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Overheating of Cities: Magnitude, Characteristics, Impact, Mitigation and Adaptation, and Future Challenges

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Abstract

Urban overheating is the most documented phenomenon of climate change impacting humans. This article presents the most recent developments on the magnitude and characteristics of urban overheating and the potential synergies with global climatic change. It analyses the latest qualitative and quantitative data on the impact of higher urban temperatures on buildings' energy supply and demand, heat-related mortality, morbidity and wellbeing, human productivity, survivability of low-income populations, and environmental quality of cities. It describes the state of the art on the development of innovative mitigation materials, advanced urban greenery, heat dissipation, and evaporative techniques as the main mitigation and adaptation technologies to offset the impact of urban overheating. It also analyses the current knowledge on the impact of each mitigation technology on energy, health, environmental quality, urban economy, and survivability. Finally, this article presents the main future challenges related to urban overheating and proposes a specific research agenda to alleviate and counterbalance its impact on human life.

Contents

1. INTRODUCTION TO URBAN OVERHEATING MAGNITUDE AND CHARACTERISTICS: IMPACTS AND POTENTIAL SOLUTIONS

Cities exhibit a higher temperature than the surrounding rural and suburban spaces. The phenomenon, known as urban heat island (UHI), is due to the positive thermal balance of cities compared to their surrounding areas. The term urban overheating is also used to characterize the overheating of cities caused by local phenomena such as the UHI, synoptic mesoscale weather phenomena like heat waves, and overheating caused by the advection of heat from high-temperature geographic zones like deserts.

UHI: Urban heat island

Additional heat gains under the form of anthropogenic heat released in cities, excess release of sensible heat from building materials and structures, advection of heat from surrounding sources and high incoming longwave radiation from the polluted urban atmosphere, as well as reduced heat losses due to limited evaporative surfaces, reduced turbulent transfer, decreased urban albedo, and lower longwave radiation losses from street canyons have the most impact on urban thermal balance (1). More than 13,000 cities are exhibiting overheating problems, and there are more than

1.7 billion people living under severe overheating conditions (2). The (average) magnitude of the phenomenon in 101 Asian and Australian and 110 European cities is found to be close to 4.1°C and 6°C, respectively, varying between 1°C and 11°C (3). The magnitude of the UHI varies depending on the synoptic weather conditions. Anticyclonic conditions favor the development of higher urban temperatures, whereas cyclonic synoptic conditions are usually associated with a lower intensity of UHI (3). The morphological and construction characteristics of cities as well as the magnitude of the anthropogenic fluxes determine the urban thermal balance and the intensity of the local overheating (4). The most critical parameters are, among others, the land use, topography, urban density and size, the optical and thermal properties of the urban materials, the existing green infrastructure (GI), and the urban landscape including the geometrical characteristics of the urban structures.

GI: Green infrastructure

HRM: Heat-related mortality

The total urban evaporation surface, made up of farms, parks, rivers, and lakes, is negatively associated with the intensity of the UHI. The vicinity of cities to sea front, dark mountain surfaces, deserts, and other heat sources or sinks increases the advection of hot or cool air and modifies the urban thermal balance (5). The thermal and optical properties of building materials, solar reflectance, emissivity, and thermal capacitance affect the magnitude of the UHI. An increase in the urban albedo decreases storage in the urban fabric, reduces the release of sensible heat, and decreases the strength of urban overheating (6). An increased urban population affects the ambient temperature in cities and tends to increase the magnitude of the UHI. Urbanization generates a significant increasing trend of the minimum ambient temperature and increases the magnitude of the UHI because of the higher release of anthropogenic heat (7). Synoptic conditions characterized by extreme high ambient temperatures significantly affect the urban climate and the magnitude and characteristics of the UHI. Synergetic results between UHI and synoptic conditions favoring extreme high ambient temperatures increase the total urban stress, defined as the state of bodily or mental tension developed through city living at a higher level than the sum of the background stress caused by the UHI and heat waves independently (8). Depending on the local conditions, increased urban temperatures may raise the cooling energy consumption, decrease the efficiency of the power plants, increase the concentration of pollutants because of the additional photochemical atmospheric reactions, raise the peak electricity demand, intensify heat-related mortality (HRM) and morbidity, lower the productivity of the population, and affect the survivability levels of low-income households (9).

To counterbalance the impact of urban overheating, urban heat mitigation techniques aiming to decrease the ambient temperature are developed and successfully implemented (10). Mitigation technologies involve the use of advanced urban materials in buildings and urban structures, the increase of the urban GI, the use of water-based cooling systems, dissipation of the excess urban heat to low temperature heat sinks like the ground (10), or a combination of the previous technologies. Performance data from numerous urban mitigation projects show an average reduction of the peak ambient temperature up to 3°C (11). The recent development of innovative mitigation technologies is expected to increase the mitigation potential up to 4.5°C. Implementation of urban mitigation technologies can decrease the cooling energy consumption, the peak electricity demand, and the heat-related mortality and morbidity (12).

Very important progress has been achieved to understand the qualitative and quantitative characteristics of urban overheating. Using experimental and numerical techniques, scientists can determine the magnitude as well as the spatial and temporal distribution of urban overheating and its association with the synoptic climatic conditions and the urban characteristics. Research has shed light on the impact of higher urban temperatures on energy, health, and environmental quality. Several advanced mitigation technologies have been developed and implemented in numerous large-scale projects decreasing the strength of the overheating while providing the required knowledge and data on their cooling potential. New challenges associated mainly with the fast overheating of the planet, the significant growth of the population, and the intensive urbanization are now emerging, and new scientific gaps become apparent.

This article highlights the recent developments on urban overheating, provides information on the quantified impact of urban overheating on urban life, describes the most recent developments on mitigation technologies, quantifies their mitigation potential as well as their impact on human life, including the potential benefits and disservices, and presents the future needs on research and development to face the current and future urban climatic problems. The article can provide useful knowledge to urban planners, city managers, architects, and engineers and assist policymakers to consider urban overheating in their environmental projects.

2. EXPERIMENTAL PROTOCOLS, ACCURACY, UNCERTAINTIES, AND INCONSISTENCIES

Although information on the magnitude and the characteristics of the UHI exists for hundreds of cities, there are concerns on the representativeness, the authenticity, the accuracy, and the validity of the provided data and conclusions. In fact, there are several inconsistencies related to the employed experimental protocols, the duration of the measurements, and the number and characteristics of the measuring stations, as only 25% of the studies succeeded in reporting quantitative data on important input parameters, such as the land and the site cover (13). Three main experimental protocols based on the use of standard and nonstandard measuring stations and of mobile traverses are used to assess the magnitude of the urban overheating and its characteristics (14).

Data from mobile traverses are of much shorter duration than the rest of the studies, whereas monitoring using nonstandard equipment is of longer duration, using more than five measuring stations to report data for 30 to 90 days (3). Data collection using standard meteorological stations is based on routine observations and is usually extended for longer time periods. Approximately half of these data cover a period between 10 to 50 years (3). However, almost half of the UHI studies based on standard meteorological equipment used data from just one urban and one rural station and failed to provide information on the spatial distribution of the UHI intensity. Monitoring using mobile or nonstandard equipment reveals a considerably higher UHI magnitude than studies using standard equipment, as routine meteorological data are recorded in mostly undisturbed areas, whereas mobile or nonstandard equipment are deployed in dense urban zones presenting a more positive thermal balance. Because of the variability of the climatic characteristics of rural areas, the diverse degree of urban influence, the land cover, the proximity to heat sinks or sources, the different topography, and the very significant warming trends observed in suburban and rural areas, the selection of reference station is the major source of potential error in calculating UHI intensity (5).

3. SYNERGIES BETWEEN URBAN OVERHEATING AND GLOBAL CLIMATE CHANGE

Urban overheating, in contrast to urban heat island (UHI = urban-rural thermal contrast), also evaluates the temperature variance between various parts of a city by including factors such as synoptic-scale weather conditions, etc., in addition to the degree of urbanization and anthropogenic heat fluxes. Urban overheating interacts synergistically with regional-scale heat waves and large-scale synoptic conditions and affects the urban climate. During heat waves, a large-scale stagnant high-pressure system delivers clear skies, intense solar radiation, and warm air from the troposphere, causing the whole region to experience scorching temperatures, altering the urban-rural thermal contrast by influencing sensible, latent, advective, anthropogenic, and storage heat fluxes (15).

The synergies between urban overheating and heat waves can be determined by computing the urban overheating magnitude difference during heat waves and a typical summer day (DUO). Under extreme heat conditions, the varying urban-rural surface features stimulate latent heat flux in rural areas, whereas greater impermeable and nongreen surfaces partition more sensible heat flux in the urban zones. The urban-rural moisture contrast was regarded as a critical synergistic interaction between urban overheating and heat waves in Nicosia (Cyprus) (16) and US cities (17), where DUO was as high as 1.3°C and 2.8°C, respectively. The higher urban-rural thermal contrast during extreme heat conditions depends on the upper soil moisture in rural areas that determines the evaporation losses. The synergies between urban overheating and heat waves may diminish as the upper soil moisture decreases in the rural areas, as this accentuates sensible instead of latent heat (17).

DUO: The difference between heat waves and normal summer urban overheating magnitudes

The impact of advective heat flux and synoptic-scale weather conditions is prominent during heat waves, especially in coastal cities. Secondary air circulation becomes more apparent during heat waves because of a more significant temperature difference between the surfaces of thermally massive sea and the urban land (18). As a result, the sea breeze cools the coastal areas, while the inland locations may remain warm due to fewer prevailing coastal breezes, as documented in Los Angeles (18). As a result, the coastal-inland thermal gradient widens tremendously. Furthermore, the DUO is relatively high in coastal compared to noncoastal cities, due to coastal wind advection and moist synoptic conditions. In Athens (19) and Shanghai (20), DUO was up to 3.5°C and 1.3°C, respectively, due to the advection of coastal winds.

In noncoastal cities, the secondary air circulation may cool down the urban zones during typical summer conditions due to the pressure gradient between urban and rural areas. Lower regional wind speed during heat waves limits the urban mixing and elevates the urban overheating magnitude. The DUO reached 4.5°C in Seoul (Korea) (21) and 1.0°C in Beijing (China) (22) under lower regional wind speeds. In contrast to regional wind speed, advection from heat sources such as desert landmass may elevate the temperature in the adjacent zones. Such synoptic conditions may become more prevailing during heat waves, disrupting the thermal contrast between adjacent and surrounding areas. These strong dry winds may halt the latent heat flux in the adjacent area by sweeping the ambient moisture.

The storage heat flux was also identified as a significant synergistic interaction between urban overheating and extreme heat occurrences. Due to increased radiative input, daytime urban fabric absorption increases significantly under intense heat conditions. Rural locations cool faster than cities during heat waves owing to radiative cooling and exacerbating the nocturnal urban overheating intensity. In Melbourne, a DUO of up to 1.4°C was documented, and storage heat flux was the key UHI–heat wave interaction (23). The heat absorbed by the urban fabric may be released during the post–heat wave period, prolonging the hot conditions in urban areas (15). Anthropogenic urban heat flux increases during extreme heat conditions due to higher air conditioning usage, elevating the urban temperature substantially and creating an urban-rural thermal gradient. In addition to latent heat flux, anthropogenic heat flux was cited as the leading cause of daytime urban overheating amplification in numerous US cities during heat waves (17).

4. METHODS AND TECHNIQUES TO CALCULATE THE CHARACTERISTICS OF URBAN OVERHEATING

When it comes to characterizing urban overheating, the main challenge is that each macrocomponent of the urban realm (e.g., buildings, streets, people, vegetation, water bodies) is a standalone

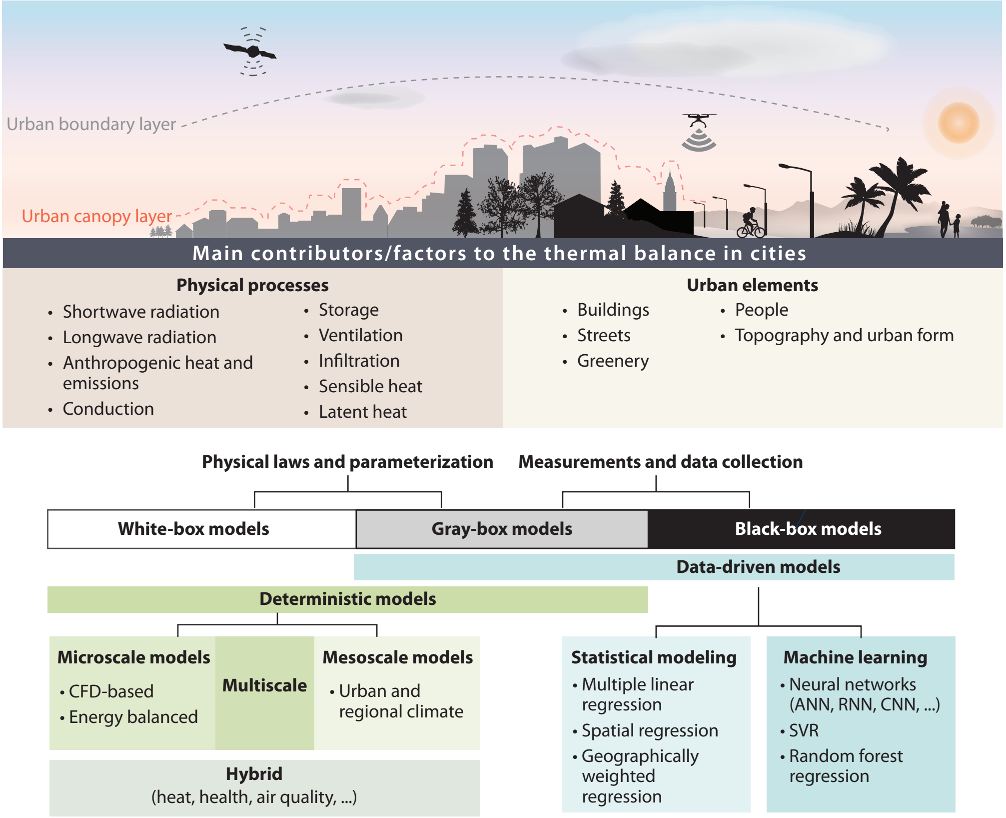


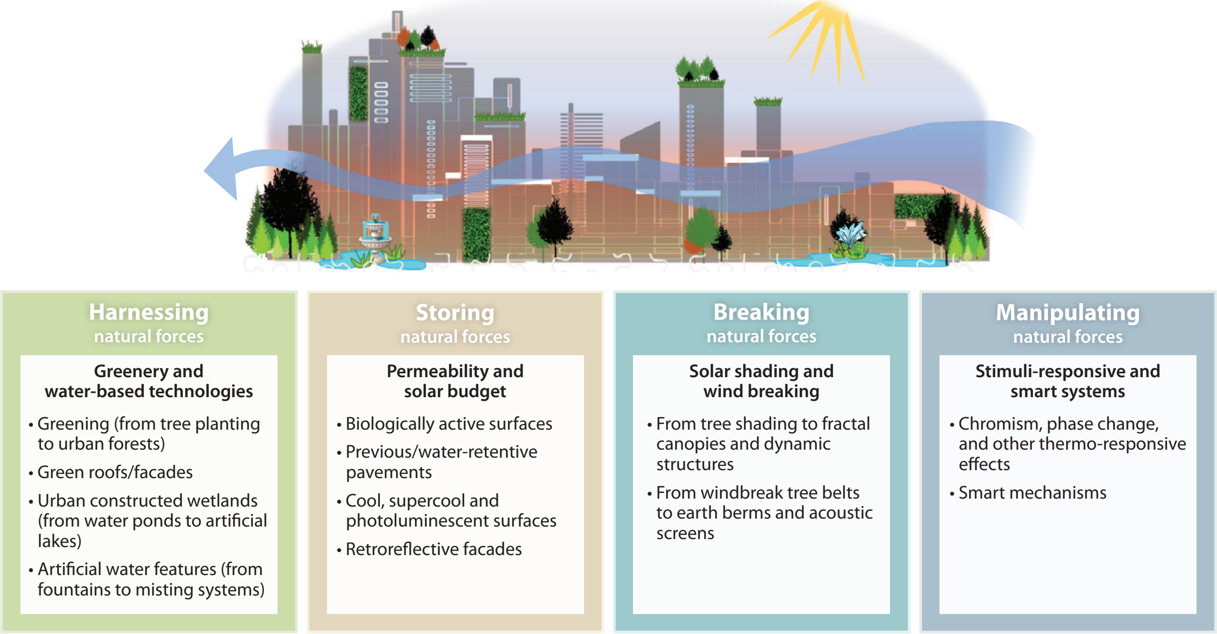
Figure 1

From urban reality to urban virtuality: classification of modeling approaches. The main elements and the physical phenomena contributing to the urban heat balance are listed in the upper boxes. These can be described through physical laws and parameterization and/or through data measurements and collection. The former description is the basis of white-box models whose inner workings are clear and transparent, whereas the latter description is used by black-box models whose only observables are input-output relationships. Gray-box models are a combination of the two approaches. Abbreviations: ANN, artificial neural network; CFD, computational fluid dynamics; CNN, convolutionary networks; RNN, recurrent networks; SVR, support vector regression.

complex thermodynamic system where multiple transfer phenomena intertwine within and across the system boundary. Characterizing the resulting heat budget and its impacts calls for combinatorial approaches crossing the domains of climate, building, and comfort physics, through either deterministic or data-driven approaches (**Figure 1**; see also **Figure 2**).

Supplemental Material >

Deterministic models (**Supplemental Appendix 1**) seek to simulate the physical world through an a priori knowledge of the thermal processes translated into parameterized mathematical equations. Typically privileged in scenario-making and large-scale studies, deterministic models owe their robustness to the level of abstraction and the soundness of the underlying assumptions (10). A certain degree of inflexibility and forcing is inborn in the use of explicit physics, which may limit room for generalization in atypical and/or extreme cases. In contrast, data-driven models (**Supplemental Appendix 2**) seek an unbiased implicit approach based on raw data from real observations, opening up the possibility of extracting unforeseen patterns in nature and performing predictions without well-established laws. However, results are intrinsically site-specific, and the quality is heavily dictated by the accuracy of the measurements, the level of



Harnessing natural forces

Greenery and water-based technologies

- Greening (from tree planting to urban forests)
- Green roofs/facades
- Urban constructed wetlands (from water ponds to artificial lakes)
- Artificial water features (from fountains to misting systems)

Storing natural forces

Permeability and solar budget

- Biologically active surfaces
- Previous/water-retentive pavements
- Cool, supercool and photoluminescent surfaces
- Retroreflective facades

Breaking natural forces

Solar shading and wind breaking

- From tree shading to fractal canopies and dynamic structures
- From windbreak tree belts to earth berms and acoustic screens

Manipulating natural forces

Stimuli-responsive and smart systems

- Chromism, phase change, and other thermo-responsive effects
- Smart mechanisms

Figure 2

Urban overheating mitigation and adaptation as a complex interaction with natural forces: classification of technologies. Depending on the causes of urban overheating, proper counteraction may rely on harnessing, storing, breaking, or manipulating natural forces. The upper part of the figure shows the key elements in this interplay: materials (represented by *gray*, *white*, *green*, and *blue* surfaces), urban layout and canopy, solar radiation, and air circulation (*blue* arrow).

data aggregation, and the robustness of the modeling architecture. Furthermore, since data-driven models learn from the past, there may be limited room for generalization in dynamically evolving systems.

Deterministic models have precise spatial constraints. Microscale models focus on the urban canopy layer and embrace the neighborhood scale thus producing detailed representations of the physical processes that occur within and above complex street canyons or building blocks. Mesoscale models span the whole depth of the urban boundary layer and can reproduce phenomena at scales of tens to hundreds of kilometers (e.g., land/sea breezes, mountain/valley winds, heat island circulations).

Micro and mesoscale phenomena are intimately connected and transcend their respective boundaries. Hence, the new rational approach in the world of deterministic modeling is represented by coupled models obtained through balancing of mass and heat transfer across the domains (24). In the same vein, hybrid models that take a transdisciplinary approach by linking aspects such as heat, pollution, health, energy, economy, mobility, and circular economy are gaining ground.

Despite the overwhelming evidence that proves the accuracy penalty associated with oversimplified urban contexts, there is no ironclad recipe to interlink the single urban macrocomponent with the heat fluxes emanating from the urban environment. The general consensus is that (*a*) physically based bottom-up methods relying on single-building representation have an edge over top-down and building block–based approaches, and (*b*) unidirectional chaining methods that cannot take into account any buildings' retroaction on climate and vice versa should be deprioritized in favor of more accurate two-way feedback approaches. Further challenges persist concerning the need to analyze and quantify the role of stochastic sources of uncertainty on the urban scale; improve the reliability of the interbuilding multiphysics, especially in dense urban environments; and better represent the synergistic, overlapping, and antagonistic effects of combined heat mitigation strategies and account for important second-order effects (25).

Data-driven models are on the rise due to the increasing popularity of the Internet of Things, artificial intelligence, and machine learning (26). Through intelligent algorithms, data-driven models can communicate the complexity of the relationship between urban overheating and explanatory variables, without requiring a large variety of input parameters and initialization data that are often unavailable or uncertain. This approach makes it also easier to realize hybrid models, by incorporating multidisciplinary inputs in the set of explanatory variables.

Novel data-driven methods and combinations are continuously proposed; hence, substantial growth and opportunities are envisioned in this research area. Nevertheless, data-driven approaches require extensive datasets to build a "story-based" understanding of the physical world. Even if trends can be captured, the absolute reliance on "past" evidence undermines the potential to truly depict a "future" whose dynamics are increasingly disrupted by climate change and other sociopolitical mechanisms. All things considered, synergizing data-driven and deterministic approaches appears to be the natural evolutionary step toward intelligent computation of urban overheating that is capable of integrating new evidence-based insights into the trustworthiness of physics.

5. IMPACT OF URBAN OVERHEATING ON ENERGY, ELECTRICITY, HEALTH, POLLUTION, ECONOMY, AND SUSTAINABILITY

As previously mentioned, urban overheating seriously impacts energy supply, demand, and infrastructure as well as health, survivability, occupational labor losses, crime, and antisocial behavior (27). In financial terms, the global cost of urban overheating in Melbourne, Australia, is estimated to be close to United States Dollar ($)1.8 billion in present value terms, and the UHI cost was close to $300 million (27). The global cost includes all additional expenses on energy, health, mobility, productivity, etc., incurred during periods of extreme temperature and heat waves; the cost allocated to the UHI refers to the estimated additional expenses in the same fields during the rest of the year.

Numerous studies have estimated the cooling penalty induced by UHI. Twenty-four studies concluded that the average additional building cooling penalty caused by UHI is close to 12%. In absolute terms, the cooling penalty varies between 0.1 and 20 kWh/m^2/year with an average close to 2.4 kWh/m^2/year, corresponding to 2.7 kWh/m^2/year per degree of temperature increase (28). Numerous studies have evaluated the UHI-induced temporal increase of the urban cooling energy demand using long climatic data series from the same meteorological station. Studies for 18 cities show that the building final cooling demand between 1970 and 2010 increased by 23% on average—corresponding to an average rise close to 11 kWh/m^2/year—the corresponding final heating demand decreased by 19%, and the sum of the cooling and heating load increased by 11% (28).

The energy impact of higher ambient temperatures on the total urban building stock is evaluated for five world cities, and for different periods and UHI intensities (28). The calculated annual average global energy penalty induced by urban overheating is approximately 0.73 ± (0.64) kWh/m^2/C, the average annual global energy penalty per person is approximately 230 ± (120) kWh/p, and the average annual global energy penalty per person and degree of temperature increase is approximately 78 ± (47) kWh/p/C (28).

Extreme heat events increase the peak electricity demand, obliging utilities to build additional power plants (29). The main parameters determining the power penalty include the penetration of the air conditioning, the quality of the building stock, the set point temperatures, the population size, and the operational characteristics of the electricity network (30). Based on data from 11 case studies around the world, it is estimated that the global urban penalty of the additional electricity demand per degree of temperature increase varies between 0.45 and 12.3%. This corresponds to an average urban penalty on the electricity demand of ~3.7% (29).

Increased ambient temperatures affect the operation of energy generation substations and transformers and reduce the generation capacity of the thermal and nuclear power plants. Increases of the ambient temperature by 1°C may reduce the output of thermal and nuclear power plants by 0.6 and 0.8%, respectively (31). The increased river temperatures resulting from the 2022 severe heat wave in France affected the operation of nuclear plants and resulted in day-ahead baseload power prices almost 10 times higher than corresponding prices from 2017 to 2021 (32).

Overheating also affects the urban environmental quality, increasing the concentration of harmful pollutants. Higher urban temperatures accelerate the formation of ozone precursors. For example, the reaction kinetics of volatile organic compounds' and NOx's combining photochemically to generate ground-level ozone speeds up with ambient temperature. Ozone is toxic and an oxidant affecting the human respiratory and cardiovascular systems (33). The first section of **Supplemental Appendix 3** provides more information on the current and future impact of overheating on the formation of ground-level ozone.

Supplemental Material >

Stagnation of air masses is favored during heat waves or in intense UHI, resulting in an increased accumulation of pollutants (34), while the sea breeze intensity in coastal cities slows down, increasing the accumulation of pollutants in the urban atmosphere (35). Increased urban temperatures may considerably increase the concentration of some components of airborne particulate matter, such as the concentration of sulfates because of the faster SO_2 oxidation (36), but not the concentration of nitrates and organic volatile particles.

Urban overheating obliges utilities to operate power plants for an extended period to satisfy the peak electricity demand. Increased operation of thermal power plants located in the urban context significantly increases the emissions of pollutants and increases the concentration of secondary pollutants like ground-level ozone (37). Each degree of temperature rise in the Eastern United States during the period between 2007 and 2012 resulted in increases of 3.35% ± 0.50% in SO_2 emissions, 3.32% ± 0.36% in CO_2 emissions, and 3.60%°C ± 0.49% in NO_X emissions (38).

Overheating affects the magnitude of the urban socioeconomic and biophysical vulnerability and has a serious impact on low-income populations (39). A considerable fraction of vulnerable populations live in districts of disproportionately high UHI intensity, excess heat stress, higher risk of heat-related mortality and morbidity, and significant socioeconomic vulnerability (40). A significant correlation between exposure to extreme heat and the corresponding socioeconomic vulnerability is reported for several cities, resulting in a mortality risk almost twice as high in the deprived districts (40) (the second section of **Supplemental Appendix 3**).

Vulnerable populations live in buildings of considerably lower thermal quality (e.g., low levels of or no insulation in the building envelope), resulting in indoor temperatures exceeding the comfort and health thresholds and excessive cooling demands (41). Extreme indoor temperatures, 35–40°C, combined with long high temperature spells, are recorded during extreme events in low-income houses (42), while just a small part affords to cover their cooling needs. Only 2% of the necessary cooling load is covered by low-income populations in Portugal (43), while in Greece the cooling cost for low-income households is approximately double the average cost (3).

Exposure to high ambient temperatures is a serious health hazard. The magnitude of heat-related mortality and morbidity is highly alarming as exposure to temperatures above a threshold defeats the human thermoregulation system, resulting in increased mortality and morbidity (44). Numerous studies have investigated the association of high ambient temperatures with hospital admissions for respiratory problems, cardiovascular deceases, acute renal failure, heat stroke, dehydration nephric syndromes, mental illnesses, and diabetes (45). Most of the studies reported an important association characterized by a considerable heterogeneity attributed to demographic differences, variable degrees of acclimatization, diversity of the used indicators, and methodological differences between the studies (46). On average, it is reported that heat-related morbidity increases between 0.05 and 4.6% per degree of temperature increase, and during heat waves the increase ranges between 1 and 11% (28). Because of the UHI effect, cities present a higher heat-related morbidity than rural or suburban areas (47). During the 1995 heat wave in Chicago, the relative risk of heat-related morbidity was 3.86 times higher than in the suburban areas (48). Studies on the intracity heat morbidity show an important variability of up to 50% among the various neighborhoods, with low-income and warmer districts presenting the highest levels (49).

Numerous studies have demonstrated the relation between exposure to high ambient temperatures and HRM (28). Demographic, socioeconomic and biophysical factors determining the magnitude of deprivation and vulnerability increase HRM levels in urban compared to suburban and rural areas (50). Meta-analysis of 26 studies has shown that the risk of heat-related cardiovascular mortality rises by 1.3% and 8.1% for the total and the elderly population, respectively (51), while the UHI increases the HRM caused by all factors other than excess heat by between 1 and 27 deaths per million (28). Analysis of 26 studies on the association between the heat exposure within an urban area and HRM shows a very considerable correlation depending on the magnitude of the distribution of the heat exposure and stress as well as socioeconomic, demographic, and health infrastructure factors (28). Meta-analysis of articles investigating the impact of microclimate on HRM concluded that living in the warmer urban neighborhoods presents an almost 6% higher risk of mortality than living in the cooler neighborhoods, while living in less vegetated urban areas presents a 5% higher mortality risk than in the greener urban districts (52).

Urban overheating is causing declining labor productivity and substantial increases in occupational injuries (53). Physiological effects of excessive exposure to high temperatures include heat exhaustion, reduced human performance, and limited working capacity (54). Under high ambient temperature and humidity conditions, sweating is not sufficient and as a result the body temperature may rise beyond 39°C, causing serious implications on human health and wellbeing (55). Under conditions of high heat stress, work intensity and productivity need to be reduced, although numerous people have to keep working beyond the safe threshold for several social and economic reasons (56). Meta-analysis of nine studies including 11,582 workers concluded that workers in heat stress conditions were almost four times more likely to suffer from occupational heat strain than workers operating under thermoregulated conditions (57). Human physiological studies show that the supplied labor time of workers—the number of hours a worker is willing and able to work during a given period—is a highly nonlinear function of the maximum ambient temperature, characterized by a very considerable decrease of the supplied labor above 30°C (58). Losses of labor time close to 40% or 60% at ambient temperatures close to 35°C and 40°C, respectively, are reported (58; see also the third section of **Supplemental Appendix 3**, which provides specific data on heat-related labor losses). Occupational injuries occur when an individual's coordination, endurance, vision, strength, or judgment are impaired by physiological changes caused by high ambient temperatures (59). Several studies have concluded that the odds ratios of acute injuries of industrial workers were 2.28 and 3.52 for temperatures between 32°C

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and 38°C and above 38°C, respectively, compared to ambient temperatures ranging between 10 and 16°C (60).

Heat-induced productivity losses and occupational injuries present a high financial cost. Meta-analysis has shown that the global estimated costs of reduced work time in 1995 and 2010 were, respectively, close to $280 billion and $311 billion, and the cost is expected to increase by up to $2.5 trillion by 2030, corresponding to 1% of the global gross domestic product (see the fourth section of **Supplemental Appendix 3** for specific data on labor and economic losses related to overheating). Several studies evaluating the direct cost of heat-related health problems are available (61–63). They typically relate to the economic consequences of heat sicknesses and mainly evaluate the cost of hospitalizations and rehabilitation, the cost of Emergency Department visits/admissions, and the cost of ambulance services. The estimated cost by each study depends highly on the size of the population considered, the period of study, and the different health outcome and exposure measures. The estimated mean cost per hospitalization due to heat-related illness in the United States from 2001 to 2010 was close to $5,359, and the total healthcare cost was close to $392.2 million (see the fifth section of **Supplemental Appendix 3** for more data and information on the current and future cost of heat-related health problems). Moreover, increases in the magnitude of overheating may significantly increase the cost of healthcare systems. Estimation of the future cost must account for major uncertainties related to future global and local climatic predictions, efficiency of the adaptation measures, increases in populations and urbanization, and healthcare costs (27, 61).

Supplemental Material >

6. MITIGATION OF URBAN OVERHEATING AND HEAT ADAPTATION: TECHNOLOGIES AND RECENT PROGRESS

Heat mitigation means acting to reduce the magnitude of overheating by limiting the global and local sources of heat and the causes of heat entrapment or by enhancing heat sinks and dispersion mechanisms. On the other hand, heat adaptation means reducing the heat vulnerability by limiting the susceptibility through, e.g., a change in behaviors or habits or by increasing the coping/adaptive capacity via early warning systems or other means. Whereas climate change action plans developed by cities have focused on the mitigation agenda predominantly, acting on both adaptation and mitigation is necessary to address climate change impacts. Equally necessary is understanding the manner in which they interact to efficiently maximize their potential.

Vegetation in the cityscape cools down the air through a combination of evapotranspiration, shade provision, and increased albedo. Similarly, water-based solutions such as constructed wetlands, fountains, and spray systems cool down the air through evaporative cooling and enhanced convective heat transfer (64). Optimal use of such nature-based solutions relies on water-sensitive urban design and low-impact development principles that pay attention to improved water permeability of the urban landscape and reduced water runoff. Infiltration-friendly and evaporation-enabling materials such as biologically active surfaces and water-retentive pavements can help mitigate both urban overheating and flooding (65).

Another critical control mechanism against urban overheating is the use of cool and super cool materials that exhibit high albedo and/or high emissivity (66). Notably, daytime radiative coolers enable subambient cooling under direct sunlight owing to the combination of close-to-unity emissivity in the mid-infrared atmospheric window and close-to-unity reflectivity in the solar spectrum. This passive technology comes with tremendous benefits in terms of urban heat mitigation, indoor comfort, and cooling energy conservation (67) and with the potential for stable and adjustable cooling power under diverse boundary conditions (68). Fluorescence- and phosphorescence-based materials can also reduce the heat gains due to their ability to re-emit a portion of the absorbed photons (69).

Regardless of the specific technology, ample scientific evidence supports three important high-level findings:

PCM: Phase change material

1. Combinatorial approaches tend to achieve greater impacts and synergies than single-measure strategies (70); however, the end result is less than the theoretical sum of the individual effects due to intercomplementarities, overlaps, and competing enablers.
2. Multiple small-scale interventions, devised in view of dominant wind patterns and synergistic cooling effects, tend to impact more than a single larger mitigation and adaptation (M&A) feature (71).
3. M&A strategies perform well in the enabling environment generated by urban planning built on the principles of mixed land use and sprawl containment.

6.1. Modifying the Urban Albedo as a Mitigation and Adaptation Strategy

Urban albedo is a major contributor to changes in outdoor surface and air temperatures, intensifying the UHI and in turn impacting outdoor thermal comfort and energy demand by urban buildings. An analysis of 14 detailed studies designed to investigate the impact of albedo changes on urban climate shows that the use of cool materials on roofs and pavements significantly reduces the magnitude of ambient temperature (72). For every 0.1 increase in the albedo, the best estimate of the afternoon outdoor air temperature drop is close to 0.09°C, which largely depends on the specific climate, landscape, and layout characteristics of the city.

Advanced light-colored, infrared-reflective coatings, phase change material (PCM), thermochromic, fluorescent, nanophotonic thin films (73), polymeric nanotextiles (74–76), and nanocellulose (77) are the most innovative developments with the highest heat mitigation capacities.

When exposed to direct sunlight, fluorescent particles convert part of the absorbed sunlight of wavelengths shorter than 450 nm into fluorescent emission, thereby increasing the effective solar reflectance and thus enhancing the overall cooling power (78). The particles can be applied to common building coating materials and can be made from TiO_2 rutile powder as well as polymer and glass microspheres. Although TiO_2 has been implemented for daytime radiative cooling since the 1970s, its practical value is limited, as it cannot achieve subambient cooling in direct sunlight. Subambient radiative cooling of TiO_2-based material under direct sunlight has been realized only recently by adding fluorescent particles to enhance solar reflectance (79). Originally, the absorptivity of TiO_2 in the range of wavelengths (0.25–0.45 μm) results in an overall solar reflectance of less than 0.9, which is not high enough to achieve subambient cooling. To address this issue, low-cost fluorescent pigments ($SrAl_2O_4{:}Eu^{2+}$, Dy^{3+}, Yb^{3+}) are added to the polymer matrix to reduce the heat generated by the solar absorption through fluorescent emission.

Meanwhile, inclusion of photoluminescence materials in the cool-paint base is an advanced technology to introduce colors into radiative cooling surfaces. This technology introduces fluorescent particles disrupting the balance in the visible spectrum (78). A recent study presented the possibility of all-color subambient radiative coolers via a general spectral design method based on metamerism that can find the ideal wavelength conversion spectrum with minimal solar absorption under strict color-matching constraints (80).

Reflective particles in coatings tend to aggregate (81), especially at high pigment volume concentration. Indeed, the higher the concentration, the worse the crowding. The aggregation of particles not only reduces the light scattering efficiency due to the overlapping of pigments but also adversely affects other physical properties of the material (82). Some researchers (83) suggest specifically designed spacers or dispersants to improve TiO_2 spacing. In a recent study, cool coatings formulated using polymer encapsulated TiO_2 resulted in improvement (up to 10%) of near-infrared reflectance and, therefore, total solar reflectance, in comparison to coatings only containing bare TiO_2, especially in high pigment volume concentration systems (84).

Replacing the pigments in cool coatings with light-scattering air voids can not only increase the optical performance of white-pigmented coatings to state-of-the-art levels of cool materials but also avoid the material, processing, and environmental costs associated with pigments (85–87). Mandal et al. (85) fabricated porous poly(vinylidene fluoride-co-hexafluoropropene) to create an excellent radiative cooling material. Solar reflectance of approximately 0.96 has been achieved, allowing for 6°C subambient surface temperature and cooling powers of 96 W/m^2 under solar radiation of 890 and 750 W/m^2, respectively. The implemented phase inversion–based technique, is compatible with a wide range of polymers, allowing optically suitable polymers to be easily transformed to excellent radiative cooling coatings with possibly improved insulation or intensity. This technique has been implemented in other porous polymer coatings (see 88–90). In another example, it is reported that nanoporous polyethylene film can improve solar reflectivity from 96% to 99%, boosting radiative cooling performance (91). Air forming porous morphology can also suppress the near-infrared absorptance (92).

At the city scale, the cooling potential (and global climatic impacts) of modified urban albedo strategies through the implementation of reflective and super reflective materials has been assessed in the subtropical desert urban environment in Dubai, United Arab Emirates. Three scenarios using low, average, and high albedo modifications are designed and evaluated, as well as a reference scenario (93). The reduction of ambient temperature during the peak of a summer day (14:00 Local Time) is shown to be 0.6°C, 1.4°C, and 2.6°C when urban albedo is increased by 0.20, 0.45, and 0.60, respectively. A much higher mitigation potential is observed for the high-density parts of the city when compared to that of the low-density parts. Irrespective of the linear relationship between the drop in ambient temperature and changing fraction of global albedo, the cooling potential of reflective materials was reported as being highly influenced by the climate, landscape, and urban characteristics of the cities (93).

6.2. Increasing the Urban Green Infrastructure and Evapotranspiration Cooling as a Mitigation and Adaptation Strategy

GI is defined as “a network of natural and seminatural green spaces such as forests, parks, green roofs, and walls that can provide nature-based and cost-effective solutions” to urban overheating (94). Common greenery-based mitigation technologies include planting street trees, building parks and watering systems, and installing green roofs and green facades. The major cooling power of GI comes from its shading effect and evapotranspiration.

Transpiration is both a physical and a physiological process where plants release water vapor to the ambient air through tiny pores, called stomata, on their leaves. From the perspective of physics, the influencing factors include surface roughness, wind speed, vapor pressure deficit, ambient temperature, as well as long-wave and short-wave radiation. From the perspective of plants' physiology, the species, growth stage, season of the year, photosynthesis rate, and water supply are the impacting factors. Usually, the transpiration process can provide water vapors from 0.28 to 12 L/m^2 per day (95), generating a cooling power that ranges between 24.5 and 29.5 MJ/m^2 per day with a sufficient water supply and dry air. In temperate climates, the transpiration cooling power can range between 0.7 and 7.4 MJ/m^2 per day (96). Transpiration plus evaporation from the land surface is called evapotranspiration. Transpiration cooling technologies influence the urban climate in multiple aspects including precipitation modification, storm formation, and cloud formation as well as near-surface weather conditions, while long-term irrigation could even impact the heat wave intensity and frequency (97).

EAHE: Earth-to-air heat exchangers

The cooling effect of GI is impacted by plant species, time and season, plant size and morphology, scale and geometry of the GI, as well as climate. Studies have shown that vegetated areas have extraordinarily lower surface temperatures, which could be 1°C to 20°C lower than nonvegetated areas (98). Since the surface cooling effect mainly comes from the shading of the GI, it is localized and is usually limited to the surface area that is under the canopy.

The summer ambient temperature reduction caused by GI is typically 2–3°C (99). Analysis of 55 articles evaluating the mitigation potential of increased urban GI has shown that the average peak daily and nighttime temperature drops may not exceed 1.8 and 2.3°C, respectively (100). During winter, the ambient temperature reduction is usually <0.5°C (101).

Generally, transpiration couples with photosynthesis, resulting in a weaker transpiration rate when the ambient temperature is far above the optimum photosynthesis temperature (25°C for most species). This results in a decrease in the transpiration cooling potential during heat extremes. Recent research (102) found that transpiration decouples from photosynthesis in extremely hot conditions, indicating that transpiration cooling may alter its magnitude under hotter conditions. Proper description of transpiration processes is crucial, as different representations of transpiration could even influence the projection of future heat wave intensity by up to 5°C (103).

Some plant species dramatically increase their transpiration rate in heat waves as a response to the urgent cooling needs in hot weather. Also, during extreme heat events, the nighttime sap flow within the stems of many tree species increases dramatically in order for the tissues to fill with water in preparation for a hot day. Furthermore, heat waves' influence on plants can last for a time that is much longer than the heat wave duration, since plants are also adapting to warmer climates. Studies (103) show that plants will remember the heat wave events and alter their transpiration behavior even after the heat wave for months to years.

Given that evapotranspiration of trees may be significantly reduced during extreme heat phenomena, irrigation is a critical parameter. Irrigation can significantly increase the ambient temperature reduction caused by GI. Typically, the extra cooling effect from irrigation ranges between 0.5°C and 3°C. Lacking enough water supply, parks and urban street trees can even intensify the urban heat (104). In Chicago, Illinois (105), replacement of the vegetated surface by drought-tolerant grass and shrubs without any irrigation was found to increase the daytime ambient temperature by 1.9°C and reduce the nocturnal one by up to 3.2°C. Similar results are also reported for Phoenix, Arizona, and Sydney, Australia (104, 105).

6.3. The Use of Low-Temperature Heat Sinks as a Mitigation and Adaptation Strategy

Urban water bodies can remove urban overheating due to their high heat capacity and evaporative cooling effects while permeable and water-retentive pavements can reduce the surface temperature by up to 12°C (106). Because of the relatively high soil thermal capacity and comparatively lower temperature than the ambient air peak temperature at deeper layers of the ground (below 3 m) over a cooling period, ground can act as an effective heat sink. Ground-based mitigation technologies involve the use of earth-to-air heat exchangers (EAHE) and heat storage-modified pavements to lower the ground surface temperature, like high-conductive, PCM-integrated, and energy-harvesting pavements (107).

High-conduction pavements transfer heat from a surface to its lower soil layers, thus maintaining lower surface temperature, while the stored heat in the upper layers is released at night.

Innovative bidirectional heat-induced asphalt pavement consists of a top layer with the lowest conductivity, a middle and bottom layer with the highest conductivity, and a reflective coating on the top. Heat is transferred to the soil while the reflective coating reduces the absorbed solar heat (108). Integrating PCM into pavements increases their heat capacity, thus lowering their surface temperature. Energy-harvesting pavements integrate photovoltaic cells and thermoelectric generators to generate electricity.

EAHE consist of buried pipes at a certain soil depth. Ambient air is passed through the pipes dissipating ambient heat to the cooler subsurface grounds (109). Backfilling the buried pipes with soils mixed with materials of thermally enhanced materials such as bentonite, graphite, silica, and carbon fibers can increase the conductivity of soil around the buried pipes by up to 50% (110).

Supplemental Material >

Ground-based systems have substantial UHI mitigation potentials (111). Although the EAHE cooling performance depends on the arrangement of pipes and the thermal properties of soil, studies have revealed that air temperature at the outlet of the EAHE can be up to 10°C lower than that at the inlet, which can lead to an ambient temperature drop of up to 0.7°C. Combining the EAHE with cool materials has resulted in a maximum ambient temperature reduction by 1.7°C. Studies show that heat storage–modified pavements present a high mitigation potential (see **Supplemental Appendix 4**, specifically **Supplemental Table 3**). Unidirectional heat-transfer pavements with a reflective coating can reduce the maximum surface temperature by 7.7°C (108). This type of cool pavement has a high real-life implementation potential, since its composition involves the combination of traditional asphalt layers with thermal conductivity ascending from the top to the bottom layer. The surface temperature reduction for a thermoelectric generator, photovoltaic-integrated and PCM-doped pavement is up to 9°C, 5°C, and 2.5°C, respectively (112, 113). However, their application to pavements requires practical considerations such as durability (during asphalt placement and exposure to the traffic loads), PCM optimization for specific climates, the complexity of the proposed system installations, and the relatively high price of core materials.

Evaporative mitigation systems such as urban blue spaces (i.e., natural and manmade water surfaces, including rivers, ponds, fountains, and sprinklers) and permeable pavements present a considerable cooling capacity (114). Existing studies demonstrate that evaporative solutions lead on average to a cooling effect of 2.5°C for ambient air and 1.2°C for surface temperature (see **Supplemental Appendix 4**, specifically **Supplemental Table 4**). While the degree of ambient air temperature reduction induced by blue spaces depends on the characteristics of the water bodies (e.g., size, shape, turbidity, and fluid-flow behavior) and the prevailing microscale weather conditions (e.g., relative humidity, wind, and turbulence), analysis of 33 articles examining the mitigation potential of water-based solutions showed a local air-cooling capacity close to 3°C (115).

Permeable and water-retentive pavements, which are constructed to maintain water for evaporative cooling, have been proposed as a UHI mitigation measure (116). However, the water in the permeable pavement is usually drained quickly, so that the potential for evaporative cooling is not retained. Therefore, the continued provision of water to the pavement surface is critical in retaining the cooling ability of the pavements. Integration of capillary columns in the aggregates of the pavement can lift stored water from lower layers to the surface, maintaining the cooling effect for more than seven days (117). Data from 10 projects using permeable and water-retentive pavements has shown that the surface temperature drop ranged between 1°C and 5°C, while the use of metal tubes to supply underground water in the pavement mass can reduce the average surface temperature up to 13°C (118) (see **Supplemental Appendix 4**, specifically **Supplemental Table 3**). Despite the successful results of the numerical and experimental studies, at this stage, this approach needs a detailed investigation of the materials used for the permeable top layer and capillary columns to provide a background for further practical implementation analysis.

7. THE IMPACT OF MITIGATION TECHNOLOGIES ON ENERGY, PEAK ELECTRICITY DEMAND, HEALTH, AND SUSTAINABILITY

There is a plethora of studies assessing the energy impact of reflective and local greenery mitigation technologies when applied on individual reference buildings. A considerable decrease of the cooling energy demand is reported, strongly depending on the properties of the implementing technology, the characteristics of the reference building, the local climate, the operational conditions, etc. Only a few studies have analyzed the impact of large-scale implementation of mitigation technologies on the energy supply and demand of buildings at the city scale (119–121). Studies assessing the impact of the albedo modification on the energy consumption of the urban building stock are characterized by a serious nonuniformity of the assessment methodology, the initial and boundary conditions, the characteristics of the building stock, and the local climatic and mitigation characteristics (119, 122). A numerical assessment of the impact of the potential modification of the urban albedo in Phoenix and Tucson, Arizona, reported that it is possible to decrease the cooling energy consumption by between 2.2% and 13.1% in Phoenix and by 2.8% and 14.2% in Tucson, depending on the magnitude of the albedo modification (119). A similar numerical analysis for the city of Riyadh, Saudi Arabia, showed that the potential for decreasing the cooling energy consumption varies between 4.4% and 5.2% (123) while an increase of the urban albedo in Sydney, Australia, can decrease the cooling energy consumption by 9% (121).

The magnitude of the albedo modification is one of the major parameters affecting urban overheating. Numerical assessments for the city of Phoenix considering increases of the urban albedo by 0.1, 0.25, and 0.4% was calculated that may decrease the total cooling consumption by 5.2, 8.5, and 13.1%, respectively (119). The magnitude of the local overheating determines the reference building cooling load, the cooling potential of the albedo modification, and the final reduction in cooling energy consumption. In Sydney, Australia, the important temperature difference, up to 10°C, between the Eastern and the Western part of the city causes a difference of the reference building cooling demand by 40% (**Figure 3*a***). The cooling conservation caused by the implementation of reflective materials on the roof of buildings and the structure of the city in the two zones differ by up to 30% for the same reference building (**Figure 3*b***) (122). The thermal characteristics of the building stock are an important parameter determining the magnitude of

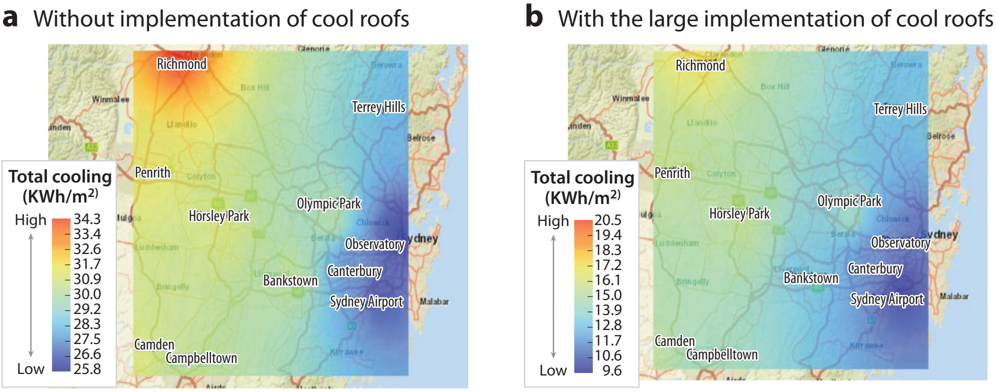

Figure 3

Spatial distribution of total cooling load for a low-rise office building (*a*) before the implementation and (*b*) after the implementation of cool roofs at the city scale. The data reflect two summer months (January and February) and are generated with weather data simulated by WRF for COP = 1 for heating and cooling. Figure adapted with permission from 122. Abbreviations: COP, Coefficient of Performance; WRF, Weather Research and Forecasting Model.

the cooling energy consumption. Numerical simulations show that the use of reflective materials at the city and building scale in Sydney may result in a reduction of the cooling energy consumption ranging between 13% and 21% for a high rise insulated shopping mall; the energy conservation for a high-rise office building without roof insulation ranges between 25% and 44% (122).

Increases in the GI in cities can result in a considerable decrease of the ambient temperature and a subsequent reduction of the cooling needs of buildings. It is predicted that an increase of the GI by 50% in the city of Tel Aviv, Israel, may result in a decrease of the mean annual temperature of 0.3°C and an energy saving of approximately 2–3% (120). Plantation of 2 million additional irrigated trees in the city of Sydney, Australia, has the predicted potential to reduce the peak daily temperature by up to 1°C, and decrease the annual cooling demand of buildings by 1.8% (121). An increase of the GI by 30% and 60% in Riyadh, Saudi Arabia, has been predicted to decrease the building cooling demand by 3.9% and 10.6%, respectively. When trees are irrigated, the corresponding cooling energy conservation for Riyadh is predicted to increase by up to 5.4% and 13.4%, respectively, compared to the reference conditions without additional trees (123).

Implementation of more than one mitigation technology, like increases of the urban albedo combined with an increase of the GI, contributes to a higher decrease of the ambient temperature and a considerably increased cooling energy conservation. The combined implementation of 5 million additional trees with a significant modification of the urban albedo and an increase of the urban evaporation through additional irrigation in Sydney, Australia, is predicted to decrease the peak annual cooling demand by 13% (121). In parallel, combination of technologies involving the use of super cool materials in the building roofs with an increase of the GI by 60% involving nonirrigated and irrigated trees was predicted to cause a decrease in the cooling load of buildings in Riyadh, Saudi Arabia, by 14.8% and 16% (123).

Implementation of mitigation technologies at the city scale could reduce considerably indoor temperatures during extreme heat events, improving indoor thermal comfort conditions and the survivability levels of vulnerable and/or low-income populations. Large-scale implementation of a combination of mitigation technologies for the city of Sydney, Australia, involving the planting of 2 million irrigated trees combined with green roofs and increased evaporation through additional irrigation, is predicted to decrease the indoor overheating hours above 30°C and 32°C in low-income homes by between 5 and 21% and 5 and 32%, respectively (121). Use of cool roofs implemented at the city and building scale in major Australian cities is predicted to decrease the peak indoor temperature in low-income housing without insulation during extreme events by between 8°C and 12°C (122).

It is argued (100) that the increase of the urban GI supports human health by decreasing the ambient temperature, modulating heat waves, and reducing the concentration of pollutants while also providing aesthetic and psychological benefits. Numerous studies (summarized in 100) have investigated the association between the increase of the urban GI and the associated decrease in heat-related mortality and morbidity. Meta-analysis of the existing data has shown that increased greenery is associated with a decreased risk of cardiovascular mortality, but there are conflicting conclusions regarding the possible decrease of all-cause mortality (124).

Despite the evident positive association of the increased urban GI with the corresponding HRM, several issues and possible uncertainties must be considered. Urban greening plans require a growing period of approximately 20 years. During this period, the urban demographic, socioeconomic, and adaptation conditions may change considerably, altering the previous association between the levels of GI and HRM and inducing a serious uncertainty on the exact future impact of urban greenery. Second, during extreme heat events, the cooling capacity of greenery is seriously reduced. Given the increasing frequency and magnitude of heat waves, trees may close more frequently their stomata while the surface temperature of their leaves may increase, contributing more sensible heat to the urban atmosphere and thus increasing the ambient temperature (100). Third, some urban trees emit biogenic volatile organic compounds (BVOCs), increasing the concentration of the ground-level ozone, which has a serious impact on human health (100).

BVOC: Biogenic volatile organic compound

GCM: General circulation models

ESM: Earth system models

Studies have shown that increased urban greenery has a positive impact on heat-related morbidity. In Phoenix, Arizona, heat-related emergency calls decreased by 17%, 35%, 53%, and 70% when the fraction of the urban vegetation increased by 5%, 10%, 15%, and 20%, respectively (125). In Darwin, Australia, an increase of the GI by 20% is predicted to reduce annual excess hospital admissions by 40.1 to 27.5 per 100,000 inhabitants, while in Sydney, Australia, planting of 2 million additional tress is predicted to decrease the excess heat-related morbidity from 3.7 hospital admissions/day to approximately 2.6/day per 100,000 inhabitants (126).

Modification of the urban albedo results in a substantial decrease of the ambient temperature and a considerable decrease of the corresponding HRM (72). Fourteen studies found that the albedo increase and the corresponding reduction of the ambient temperature may decrease the average magnitude of HRM by 9–10%, while the decrease of the ambient temperature by 1°C corresponds, on average, to 2.1 fewer deaths/day per 100,000 people, or a drop in the initial average HRM per 1,000,000 people of 19% (72). The expected drop of the HRM caused by the albedo modification presents a statistically significant association with socioeconomic parameters like urban poverty and the initial local HRM levels.

8. FUTURE URBAN CLIMATIC SCENARIOS AND IMPACT ON ENERGY AND HEALTH

Future projections of the global overheating performed by general circulation models (GCMs) and Earth system models (ESMs) lack the representation of urban areas, and provide forecasts for nonurban climates (127). A handful of studies has investigated the future impact of climate change on the urban climate and the associated UHI (127–131). Serious increases in urban and nonurban temperatures are predicted by all studies. Under a high-emissions scenario, a significant decrease of the daytime and nighttime UHI intensity is predicted for the end of the present century, given reduced evaporation rates in rural areas (128). Under a high-emissions scenario, studies concluded that cities in the United States, Northern Central Asia, the Middle East, Africa, Northeastern China, and inland South America will experience a warming of more than 4°C by the end of the century (127). Similar studies have shown that the ambient summer temperature in selected UK cities may rise by between 0.45 and 0.81°C per decade by 2080 (130). The summer daytime urban and rural temperature may change between 0.57 and 0.78°C and 0.62 and 0.81°C per decade, respectively (130). The urban nighttime warming is predicted to be higher than the rural one, increasing the intensity of the nighttime UHI by between 0.01 and 0.05°C per decade. The daytime UHI intensity is expected to decrease by 0.05°C per decade because of the faster warming of the rural areas (130). Similar warming trends are reported for the city of Paris, attributed to the faster warming of rural areas caused by decreased latent heat (131).

Future urbanization is expected to affect urban temperatures. By 2100, the urban and suburban land devoted to future developments in the United States may increase by 50% and 80%, respectively, as compared to 2010, equivalent to a surface between 500,000 and 620,000 square miles of vegetated lands (132). The urbanization-induced urban warming in China may range between 0.6 and 0.8°C by 2050 (133), while the newly developed urban zones of the future expanded city of Melbourne in Australia may increase the UHI intensity by 1.9°C (134). Increases in ambient temperature are expected to impact considerably the building energy consumption. Higher ambient temperatures may reduce the US average summer electricity transmission capacity from 1.9% to 5.8% by 2060 relative to the 1990–2010 period (135), while the peak electricity demand per capita may increase between 4.2% and 15% (135), requiring additional investments in electricity capacity of between 14% and 23% by 2055.

Prediction of the future energy consumption depends mainly on the characteristics of the future climate, the population increase, the availability and wide market adaptation of efficient energy technologies (especially air conditioners and chillers for heating, ventilation and air conditioning systems), and the trends regarding the space used per person. Studies on this subject present a very high uncertainty and a serious divergence and nonhomogeneity mainly concerning the assessment methodology, the assumptions about the future climate and about the energy characteristics of future buildings. Analysis of 144 articles investigating the impact of climate change on the future energy consumption of commercial buildings in 40 cities for the period 2030–2100 and for a range of temperature increase between 0.4°C and 5°C has shown that the expected increase of the cooling demand ranges between 1 and 86 kWh/m^2/year as a function of the future climatic scenario, current climatic conditions, and building characteristics (136). Furthermore,

- There is a strong nonlinear correlation between the reference cooling demand, Q, and the calculated absolute increase of the cooling consumption per degree of temperature rise.
- For current cooling loads close to 50 kWh/m^2/year, the estimated average increase of the cooling consumption per degree of temperature rise, Q/T, is found to be close to 6 kWh/m^2/year/K, and it is twice as much for the scenario where the baseline reference load is higher by a factor of 3, namely 150 kWh/m^2/year.
- For much higher cooling demands close to 300 kWh/m^2/year, the increase of the Q/T value is close to 17 kWh/m^2/year/K.
- The higher the current cooling demand, the lower the relative increase of the cooling consumption per degree of temperature rise.

The expected rise of the ambient temperature will increase considerably the building cooling energy consumption and probably will decrease the heating demand. Given the uncertainty about the future climatic conditions and the future building energy technologies, a quantitative estimation of the impact of climate change on energy may present very considerable uncertainties. Future increases in ambient temperature are expected to seriously impact human health. Numerous studies have investigated the association between future temperature increases and the levels of HRM (137). While most of the studies forecast a considerable increase of the future HRM, there is a large uncertainty because of the different climatic models considered, the assumed relation between temperature and mortality, future demographic conditions, the potential levels of human adaptation, and the impact of future urbanization (126). The considered emissions scenario affects seriously future predictions. Demographic considerations affect considerably the forecasts of future mortality. The significant growth of the elderly population may increase the projected number of deaths considerably.

The uncertainty related to the potential future human adaptation was found to be more significant than the uncertainty of the considered climatic model and the demographic considerations (138). Forecasts of HRM for 14 European cities for the period 2070–2099, considering five different climatic models and six different methods of human adaptation, found that consideration or not of human adaptation results in an increase of HRM by 28% or 103%, respectively (138).

9. CONCLUSIONS AND PRIORITIES ON HEAT MITIGATION FUTURE RESEARCH

Urban overheating is a major environmental problem causing a serious impact on human life. Significant scientific progress has been achieved, allowing a better understanding of the magnitude, characteristics, and impact of urban overheating. Efficient M&A technologies have been developed and implemented in order to partly counterbalance the impact of higher urban temperatures. Yet, numerous challenges around the current and future impact of overheating as well as on the technological, economic, and political ways to confront it exist, requiring further development of innovative scientific knowledge. Below, we provide a nonexhaustive, unprioritized list of emerging research topics:

1. Knowledge on the magnitude and the characteristic of urban overheating is quite rich but is overshadowed by inconsistencies. The development of objective and accurate experimental and analytical protocols is a prerequisite for improving scientific confidence in the magnitude and characteristics of urban overheating.
2. The frequency and magnitude of heat waves are constantly increasing. Heat waves act synergistically with UHI and increase the magnitude of urban overheating. A handful of studies has provided significant information and knowledge on the topic, without, however, clearly shedding light on the characteristics of the phenomena. It is reasonable to consider that such a synergy will dominate the future urban climate phenomena, and thus additional research must be carried out to better understand, analyze, and describe the synergetic interactions in urban climatic models and scenarios.
3. GCM and ESM are generally not considering urban environments. Thus, future climatic predictions rarely refer to cities, and the existing forecasts are not applicable to the urban environment. Despite the development of several techniques to overcome the problem, considerable scientific effort is necessary to integrate climatic models of different scales in an accurate and convincing way.
4. There is a need for better harmonization between urban and building models in terms of heat fluxes' representation, timescale, and dynamicity.
5. Considerable progress toward the quantification of the impact of urban overheating on energy demand and supply, environmental quality, heat-related mortality, and survivability of low-income populations has been achieved. It is evident that urban overheating has a tremendous impact on human life, which differs substantially among cities because of the variability of the climatic, demographic, environmental, energy, cultural, and infrastructure conditions. Deep knowledge and specific information are required from a high number of cities of different characteristics, to better understand and quantify the exact impact of urban overheating. There is an urgent need to document the current consequences of higher urban temperatures in the developing world.
6. Efficient mitigation technologies able to reduce the peak urban temperature by up to 2.5°C have been developed; still, this is a small fraction of the urban overheating. Development of more efficient geoengineering technologies is of very high priority. The further development of scalable super cool materials for the building envelope and urban fabric and of advanced efficient greenery technologies seems to be the most promising approach. Modulation of the optical properties of the materials to avoid winter super cooling, avoidance of glare and optical annoyance, modulation and adjustment of the quantum yield and absorption edge, ageing, and self-absorption are the main topics to be confronted. Urban greenery presents a high cooling capacity, but it is associated with side-effects, reducing considerably its mitigation capacity under extreme heat events and multiplying the emissions of harmful BVOC pollutants. Improving the knowledge on the physiology of plants as well as on their behavior under extreme heat conditions, the corresponding impact of additional irrigation, and the development of genetically modified vegetation to operate under much higher ambient temperatures seems to be the most urgent research priority.

7. Decreases in the urban surface temperature using cool materials and GI may alter the circulation in the lower atmosphere, decrease the planetary boundary layer, and increase the concentration of harmful pollutants. Research assessing the impact of low-surface temperature mitigation technologies in the lower atmosphere is needed. Existing microscale and mesoscale climatic models should incorporate spectral algorithms to assess the impact of the optically selective super cool materials, as well as advanced algorithms to evaluate the time-varying evapotranspiration of the urban greenery.
8. Transpiration cooling results from GI and transpiration patterns vary greatly among different types of GI and different types of species. To broaden our knowledge, a global database for transpiration is needed. Currently, there are efforts to establish such databases. SapFlux, for instance, is a database where researchers can upload their independent transpiration measurement results of different types of trees (139). In the field of simulation, research to establish a global leaf stomatal conductance database is required.
9. The algorithm describing transpiration in the land surface model needs updating, considering the recent findings about transpiration in extreme heat conditions. As the existing algorithm was developed partially considering that photosynthesis and transpiration are always coupled, it results in an underestimation of the transpiration rate in hotter climates.
10. Important knowledge has been developed to quantify the impact of heat mitigation technologies on energy, environmental quality, and health at the city scale. Most of the studies are based on numerical simulations and are not fully validated. It is an urgent priority to collect and provide experimental and precise information from large-scale case studies to document and validate the real impact of mitigation technologies under current and future conditions.
11. Future climatic predictions and assessment of the potential impact of urban overheating is an urgent requirement to design and implement appropriate policies counterbalancing the future climatic threat. Improved accuracy of the climatic predictions, better understanding the mechanisms of human adaptation to heat, study of the consequences of the demographic, cultural, and socioeconomic factors, assessment of the urban decarbonization paths, impact of overpopulation in the developing world, and precise assessment and documentation of the serious expected urbanization are among the main research priorities to follow. What is certain is that climatic adaptation of existing buildings using advanced energy and environmental technologies and mitigation of urban overheating are necessary policies to eradicate the expected impact of global overheating in cities as much as possible (140).
12. Public and private institutions undertake numerous initiatives to fight urban overheating. The Global Cool Cities Alliance (**https://globalcoolcities.org/**), for example, encourages and provides information about cool cities. In parallel, several cities and governments have taken important initiative to mitigate urban overheating. For example, since 2012 New Delhi requires all government buildings to have white painted roofs to improve their reflectance. Similar initiatives are reportedly in place in several first-world cities like Los Angeles and New York City. In 2016, San Francisco became the first American city to make green roofs compulsory on some new buildings (141). To support the implementation of urban mitigation technologies, the United States Environmental Protection Agency has a very useful and up-to-date advisory website for policymakers and urban planners about heat island mitigation activities in US cities (142).
13. Our current actions in relation to the urban built environment are still falling short of the Paris objectives, as they are not sufficient to ensure a trajectory that is consistent with the targets set for 2050. Having the minimization of urban overheating as a goal involves limiting the strength of warming sources and increasing the strength of urban heat sinks to balance

the urban heat budget. Achieving a zero urban heat budget requires innovative financial tools and policies:

- Change the way we design, build, and operate urban buildings, spaces, and infrastructures and transition to fewer warming and polluting patterns and policies.
- Put a value on the urban M&A capital that limits the strength of local climate change and environmental quality.
- Improve and extend urban financial tools like urban green bonds, urban sustainable real estate, urban microfinance, financing urban business-led innovation, urban public private partnerships, and investments for development of large-scale urban mitigation and adaptation projects.
- Extend the environmental, social, and governance (ESG) scheme to include activities related to urban warming.
- Put a price on urban warming. The magnitude of overheating and pollution caused by selected major urban activities has to be assessed and controlled. Liable entities exceeding the threshold and causing urban warming must pay a price for every warming/pollution unit or shortfall cost, or surrender the appropriate number of allocated units.
- It is necessary to boost sustainable urban investments. To accelerate urban cooling and finance urban heat M&A, it is critical to value urban overheating with liquidity. The development of a voluntary urban warming market could bring urban M&A investments sooner to the market and make them more affordable. The scheme will bring new sustainable urban business, will boost profits, and will skyrocket the investment of new green capitals in cities.

In conclusion, investing and counterbalancing urban climate change are the next productivity engine to drive growth.

SUMMARY POINTS

1. Urban heat islands (UHI) increase the peak temperature of cities up to 10°C, with an average between 4 and 6°C.
2. There are important synergies between extreme heat events and UHI, increasing the magnitude of urban overheating by up to 5°C during heat waves.
3. Higher ambient temperatures increase the energy demand for cooling, reduce the efficiency of thermal and nuclear power plants, enhance the peak electricity demand, raise the concentration of harmful pollutants, increase heat-related mortality and morbidity, and affect the survivability levels of low-income populations.
4. Efficient mitigation technologies based on the use of reflective materials, advanced greenery, and other dissipation techniques able to decrease the peak temperature of cities by up to 2.5–3°C are developed and implemented in large-scale mitigation projects.
5. Super cool photonic, plasmonic, and fluorescent materials can achieve surface temperatures up to 15°C below the ambient one, offering new important opportunities for heat mitigation.
6. The implementation of mitigation technologies in cities significantly decreases the energy demand for cooling, lowers the peak electricity demand, and decreases heat-related mortality and morbidity.

FUTURE ISSUES

1. It is imperative to develop objective and accurate experimental and analytical protocols to improve the scientific confidence in the magnitude and characteristics of urban overheating.
2. It is necessary to achieve a better understanding and characterization of the synergies between global and regional climate change.
3. It is highly important to enrich knowledge and information regarding the quantification of the specific impact of urban overheating on energy demand and supply, health, environmental quality, and survivability of low-income populations.
4. It is of very high importance to carry out advance research on efficient super cool materials for mitigation purposes with modulated optical properties to avoid winter super cooling, avoidance of glare and optical annoyance, modulation and adjustment of the quantum yield and absorption edge, aging, and self-absorption.
5. It is important to advance knowledge and developments on the physiology of plants and their behavior under extreme heat conditions, the impact of additional plant irrigation, and the development of genetically modified vegetation to operate under much higher ambient temperatures.
6. It is necessary to quantify the impact of heat mitigation technologies on energy, environmental quality, and health at the city scale more accurately and efficiently.
7. It is a high priority to develop accurate and efficient urban climatic prediction tools integrating climatic models of different scales, harmonized with building models in terms of heat fluxes' representation, timescale, and dynamicity, describing accurately the transpiration phenomena under high-temperature conditions and considering the spectral characteristics of mitigation materials.
8. Finally, it is widely accepted that we need to deepen the knowledge and improve the accuracy of future climatic predictions, better understand the mechanisms of human heat adaptation, assess the consequences of the demographic, cultural, and socioeconomic factors, improve the validity of the urban decarbonization paths, and evaluate the impact of overpopulation in the developing world.

DISCLOSURE STATEMENT

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