Integrated Assessment of Urban Overheating Impacts on Human Life

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Abstract

Urban overheating, driven by global climate change and urban development, is a major contemporary challenge which substantially impacts urban livability and sustainability. Overheating represents a multi-faceted threat to well-being, performance, and health of individuals as well as the energy efficiency and economy of cities, and it is influenced by complex interactions between building, city, and global scale climates. In recent decades, extensive discipline-specific research has characterized urban heat and assessed its implications on human life, including ongoing efforts to bridge neighboring disciplines. The research horizon now encompasses complex problems involving a wide range of disciplines, and therefore comprehensive and integrated assessments are needed that address such interdisciplinarity. Here, the objective is to go beyond a review of existing literature and provide a broad overview and future outlook for integrated assessments of urban overheating, defining holistic pathways for addressing the impacts on human life. We (i) detail the characterization of heat exposure across different scales and in various disciplines, (ii) identify individual sensitivities to urban overheating that increase vulnerability and cause adverse impacts in different populations, (iii) elaborate on adaptive capacities that individuals and cities can adopt, (iv) document the impacts of urban overheating on health and energy, and (v) discuss frontiers of theoretical and applied urban climatology, built environment design, and governance toward reduction of heat exposure and vulnerability at various scales. The most critical challenges in future research and application are identified, targeting both the gaps and the need for greater integration in overheating assessments.

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Key Points:

- Urban overheating is the exceedance of locally-defined thermal thresholds that lead to negative impacts on people and urban systems
- Exposure, sensitivity and adaptive capacity of people and infrastructure, and socio-political-economic factors determine overheating impacts
- Research and application should provide integrated solutions to mitigate exposure, reduce sensitivity, and increase adaptive capacities.

Abstract

Urban overheating, driven by global climate change and urban development, is a major contemporary challenge which substantially impacts urban livability and sustainability. Overheating represents a multi-faceted threat to well-being, performance, and health of individuals as well as the energy efficiency and economy of cities, and it is influenced by complex interactions between building, city, and global scale climates. In recent decades, extensive discipline-specific research has characterized urban heat and assessed its implications on human life, including ongoing efforts to bridge neighboring disciplines. The research horizon now encompasses complex problems involving a wide range of disciplines, and therefore comprehensive and integrated assessments are needed that address such interdisciplinarity.

Here, the objective is to go beyond a review of existing literature and provide a broad overview and future outlook for integrated assessments of urban overheating, defining holistic pathways for addressing the impacts on human life. We (i) detail the characterization of heat exposure across different scales and in various disciplines, (ii) identify individual sensitivities to urban overheating that increase vulnerability and cause adverse impacts in different populations, (iii) elaborate on adaptive capacities that individuals and cities can adopt, (iv) document the impacts of urban overheating on health and energy, and (v) discuss frontiers of theoretical and applied urban climatology, built environment design, and governance toward reduction of heat exposure and vulnerability at various scales. The most critical challenges in future research and application are identified, targeting both the gaps and the need for greater integration in overheating assessments.

Plain Language Summary

Many major cities are faced with compounding effects of climate change and rapid urbanization. One of the main challenges that results is urban overheating, which leads to negative impacts on human life (deteriorating health, productivity, and wellbeing) and urban infrastructure. Heat exposure in cities, however, is only the trigger and there are other factors that influence impacts. Urban heat vulnerability exists when sensitive people and infrastructure are exposed to extreme heat, and negative impacts ensue if there is a lack of capacity to respond and adapt. Accordingly, to combat overheating challenges, it is critical that multi-disciplinary solutions are integrated to mitigate exposure, reduce sensitivity, and increase adaptive capacities.

This paper provides a review of urban overheating literature, defining pathways for addressing the impacts on human life. We review the state-of-the-art methods used to quantify heat exposure, detail the sensitivity of people and infrastructure to overheating, and elaborate on the adaptive capacities that individuals and cities can undertake in response. We provide recommendations for both researchers and policymakers that will minimise overheating impacts. These recommendations range from modifications to urban and building design to engaging citizens and informing urban overheating governance.

1 Introduction: Current and projected urban overheating in the face of future urban development and climate change

The 21st century is acknowledged to be an urban century. By 2050, an additional 2.5 billion people are expected to live in urban areas, with up to 90% of this increase concentrated in the regions of Asia and Africa, particularly in India, China and Nigeria where 35% of urban growth is projected to occur (United Nations Department of Economic and Social Affairs, 2019). This urban growth will entail considerable additions of urban infrastructure, and a larger population of urban residents vulnerable to crises or stresses such as extreme heat (Pelling & Garschagen, 2019).

The impact of such development leads to direct changes to city-scale climate, most notably manifested as the urban heat island (UHI). Defined as the increase in air and surface temperatures in settlements compared to their surroundings, the UHI is caused by physical changes in the surface energy balance of the pre-urban site upon which the city is built (Oke et al., 2017; Stewart, 2019), combined with waste heat emissions from anthropogenic sources, e.g. heating/cooling in buildings, transportation, and biological metabolism (Chow et al., 2014; Sailor, 2011). The land cover and morphology of cities further lead to substantive intra-urban variations of air and surface temperatures (Stewart & Oke, 2012). These absolute intra-urban temperatures are more directly relevant to urban residents compared to simple urban vs. “rural” temperature differences (e.g., UHI intensity; (Martilli et al., 2020)).

The UHI is driven by *separate* mechanisms than larger-scale temperature changes linked to regional and global climate change, which arise, in particular, from global anthropogenic emissions of greenhouse gases and regional land cover change. Unequivocal increases in both maximum and minimum air temperatures have been observed since the 1950s across all climate zones and regions in which settlements are located (Stocker et al., 2013). Since 1980, cities worldwide have also experienced significant increases in the number of heatwaves and hot days and nights (Mishra et al., 2015).

The combined result, i.e. the interacting impacts of the local-scale UHI with increased mean and extreme temperatures from larger-scale climate change, is projected to exacerbate overheating in cities globally (Argüeso et al., 2014; S. Chapman et al., 2017; Emmanuel & Loconsole, 2015; Kotharkar & Surawar, 2016; Krayenhoff et al., 2018; Roaf et al., 2013; Santamouris et al., 2015; Santamouris & Kolokotsa, 2015; Wouters et al., 2017). The initial use of the term “overheating” focused on building energy consumption, ambient indoor environmental conditions, and the health of urban residents from an architectural or building design perspective (Santamouris et al., 2015; Taylor et al., 2014). **Here, we define “urban overheating” as the exceedance of locally-defined thermal thresholds that correspond to negative impacts on people (e.g., health, comfort, productivity) and associated urban systems.** These thermal thresholds depend not only on local urban climates and associated exposure to heat, but also the sensitivity and adaptive capacity of people and urban systems exposed to the heat, which in turn depend on socio-political and economic factors. Figure 1 depicts the integrated framework that describes factors involved in realizing the negative impact of overheating. Heat exposure in cities is the trigger, but in itself does not lead to impacts. Urban heat vulnerability exists when sensitive individuals, populations, and infrastructures are exposed to heat. Should there be a lack of adaptive capacities to respond (both at the individual and city level), negative overheating impacts ensue. The multi-scale interactions that relate to urban overheating, from its causes to risks and impacts, represent a multifaceted and multi-disciplinary challenge.

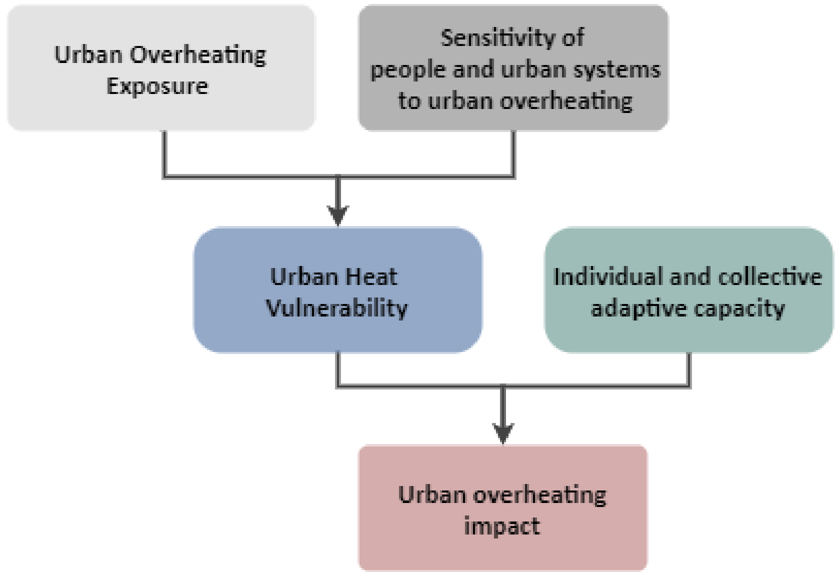

Figure 1: Holistic framework that describes factors involved in urban overheating impact.

Without local heat mitigation and adaptation, urbanization and climate change are projected to increase heat exposure. Global projections of future urban temperatures up to the end of the century indicate substantial geographic variations of added warmth in cities, including maximum air temperature increases of 0.7–7.6 °C by the end of the century (Figure 2). Urban areas sited in different geographical contexts will require unique, site-specific adaptation options to reduce exposure to the additional warmth.

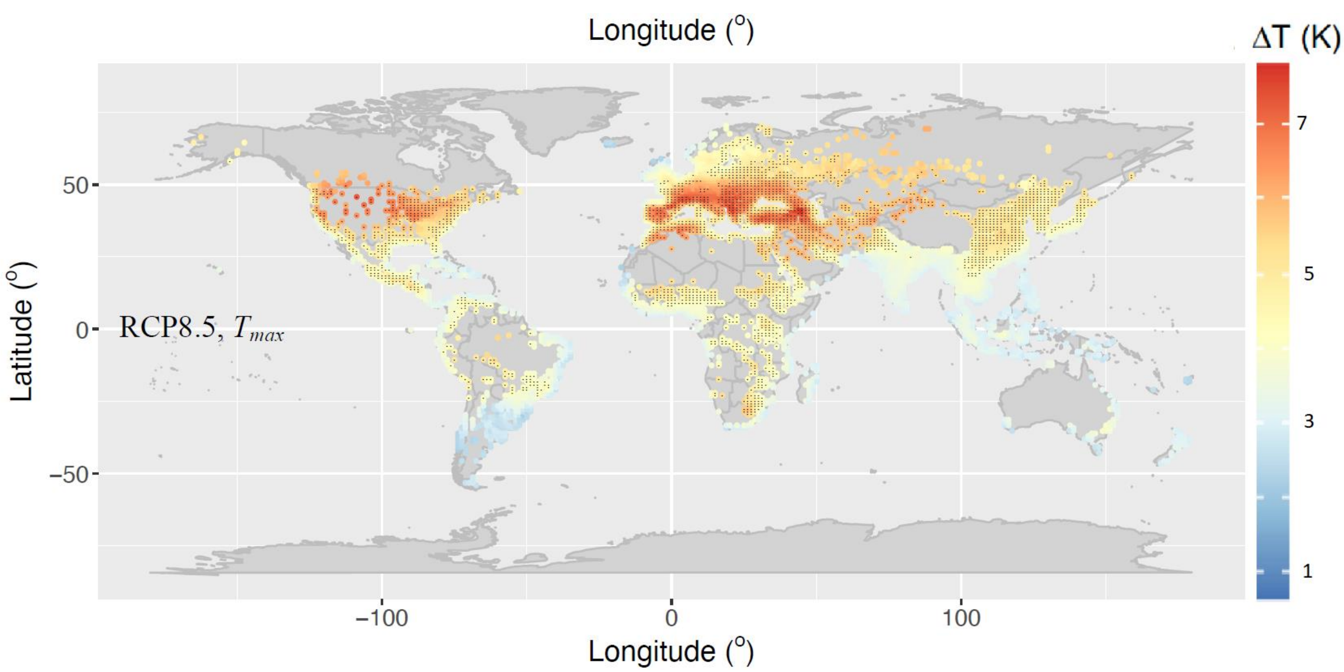

Figure 2: Projected seasonal urban warming between 2006–2015 and 2091–2100 for the diurnal maximum temperature (Tmax) under the high-emissions ‘RCP8.5’ warming scenario based on the 26-member CMIP5 earth system model ensemble in combination with an urban emulator. Stippling indicates substantial change (ΔT ≥ 4 K) with high inter-model robustness. Adapted from (Zhao et al., 2021).

Although our understanding of urban overheating has progressed, an integrated outlook and perspective on this multifaceted challenge are yet to be achieved. Previous research on urban overheating has largely focused on the UHI or climate change individually (S. Chapman et al., 2017). Moreover, assessments that include both local and global drivers of urban heating have predominantly focused on North American, European and Chinese cities (S. Chapman et al., 2017), neglecting large fractions of the global urban population, and they have rarely addressed growing urban populations (Ashley Mark Broadbent et al., 2020) or changing demographics (Dialesandro et al., 2021; Grineski et al., 2015). Furthermore, assessments rarely integrate outdoor and indoor exposures, with implications for actual individual levels of heat exposure (Kuras et al., 2017; Nazarian & Lee, 2021) and future vulnerability to urban heat (Sailor et al., 2019). Lastly, assessments of cooling from urban heat mitigation strategies (e.g., green infrastructure, shade structures and cool materials) would benefit from better integration across different scales and exposure variables (Santamouris et al., 2017a). Accordingly, we argue for a broader, multi-disciplinary approach that critically examines the emergent complexities of urban overheating towards an integrative assessment. These include:

- Quantification of heat exposure arising from urban overheating, accounting for differences in spatial (e.g. personal- to local- to city-wide) and temporal (e.g. diurnal, seasonal and extreme heat event) scales.
- Assessment of the impacts of overheating on important components of the urban environment, including physiological and psychological effects of increased exposure to heat, and impacts of outdoor overheating on indoor microclimates or building energy use.
- Robust projection of urban climates and associated exposures accounting for regional and global climate changes, local urban development, demographic changes, exposures of populations, heat mitigation strategies, and uncertainties in key parameters and projections.
- Provision of recommendations for both researchers and policymakers that account for the multidisciplinary nature of urban overheating, ranging from modifications to urban and building design to engaging citizens and informing urban overheating governance, representing an integrated approach to mitigate exposure, reduce sensitivity, and increase adaptive capacities.

These topics will be discussed in subsequent sections. To contribute to the theoretical understanding of overheating, we first provide an overview of how overheating exposure is characterized across different (human, street, and city) scales and using different observational and numerical methodologies (Sec. 2). We then focus on the human-scale impacts of overheating, noting several physiological and psychological contributors to individual sensitivities as well as adaptive capacities that individuals can afford in response (Sec. 3). At the population level, we note the integrated impact of exposure with individual sensitivities that lead to vulnerability to overheating, and set out to document two key impacts, health and urban energy (Sec. 4). Lastly, we discuss the state-of-the-art methodologies as well as future approaches and solutions in urban planning and governance that aim to address this multi-faceted challenge and mitigate exposure, reduce sensitivity, and increase adaptive capacities at the individual and population levels (Sec. 5). Each section will further identify key priorities in research (for better understanding overheating exposure and impacts) and application (for mitigating or adapting to overheating challenges). The information generated will be critical in informing holistic and integrated research in the field and will provide important discussion points to develop science-based policies for cities desiring reduction of urban overheating in the future.

2 Characterizing urban overheating exposure at different scales

In this section, we focus on quantifying and documenting the levels of thermal exposure arising from urban overheating, accounting for differences in spatial (e.g. personal- to local- to city-wide) scales. By detailing the representation of heat in indoor and outdoor urban climates (Sec. 2.1), we set out to discuss the key priorities of research in quantifying overheating intensity, location, and duration in the built environment. We then address emerging methodologies in sensing - i.e. IoT, crowdsourcing, and ubiquitous monitoring - used for infilling heat sensing networks in cities and better describing the impact on urban residents (Sec. 2.2). Lastly, we discuss numerical modeling as a powerful tool at multiple scales for characterizing current and projected urban overheating exposure in cities as well as evaluating the efficacy of various mitigation and adaptation solutions proposed to address ensuing impacts. Collectively, these sections provide a comprehensive outlook on observational and numerical methods, as well as metrics and indicators, available to characterize and quantify the extent of overheating exposure in cities, while outlining key priorities in research to better understand this challenge.

2.1 Environmental sensing of heat exposure in indoor and outdoor climates

Outdoor urban heat can be characterized in multiple ways and is often quantified by either simple temperature metrics (such as air, surface, and radiant temperature) or comprehensive indices (such as thermal comfort and heat stress indices) that aim to quantify the impact of heat on the human body. The relevance of these metrics highly depends on the underlying motivation for monitoring, assessing, or modeling the urban thermal environment, as well as the scale of analysis (Table 1).

At the city level, environmental heat has been traditionally quantified using air temperature reported by meteorological services. However, weather stations are sparse, stationary, often remote from human activities, and not representative of the complex and heterogeneous conditions in urban canyons (Harlan et al., 2006). To overcome these limitations and evaluate the microclimate variability in the built environment, two methods are often deployed: a) establishing an urban network of environmental sensors (examples included in Sec. 2.2) and b) field campaigns using mobile measurements at street level (Häb, Middel, et al., 2015; Oke et al., 2017; Seidel et al., 2016). Mobile measurements provide a finer spatial and temporal resolution of air temperature as a heat metric, but have often poor temporal resolution and require detailed post-processing for interpretation (Häb, Ruddell, et al., 2015; Middel & Krayenhoff, 2019).

A well-known metric of ambient temperature measurements to describe heat in cities is the UHI, dating back to the early 19th century in Urban Climate research (Stewart, 2019). The UHI intensity describes the temperature difference between urban and rural areas and therefore is less relevant than the absolute temperature to which people are exposed (Martilli et al., 2020). Moreover, intra-urban distributions of ambient conditions are more relevant here, as formalized in the Local Climate Zone (LCZ) scheme (Stewart et al., 2014). Inter-LCZ variability of air temperature (Fenner et al., 2017) represents a critical research direction to assess urban heat vulnerability at the neighborhood scale (e.g., as a function of urban design and socio-economic status; see Sec. 4.1), but the local nature of the scheme renders it too coarse for human-centered heat stress analyses at the street scale.

At larger scales, thermal remote sensing platforms (which use non-contact instruments to sense thermal infrared radiation) provide information on urban heat at large spatial scales. In recent decades, land surface temperatures (LST) from satellite remotely sensing products such as Landsat, MODIS, and ASTER have been widely used to assess the surface UHI (SUHI) (Imhoff et al., 2010; Voogt & Oke, 2003; D. Zhou et al., 2018), analyze the impact of urban form on land surface temperature (Bechtel et al., 2019; X. Li et al., 2016; Yujia Zhang et al., 2019), and find urban hot spots (Harlan et al., 2013; Huang et al., 2011). Satellite-based observations represent a powerful tool for assessing city-scale urban heat, but are limited by clouds and have physical tradeoffs between temporal and spatial resolution (Bechtel et al., 2012). Remotely-sensed LSTs are also subject to effective anisotropy, i.e. they vary as a function of sensor view angle due to sun-surface-sensor geometry (Voogt, 2008).

Importantly, while remotely sensed images help illustrate intra-urban surface temperature distributions, canopy layer air temperature, a key indicator for urban environmental health (Sec. 4.1) and energy (Sec. 4.2), cannot be directly inferred. It is widely acknowledged that the relationship between the two temperature types is complex (Roth et al., 1989; D. Zhou et al., 2018). The usability of satellite-based LSTs at human-relevant scales is also limited. First, the remotely sensed temperatures are based on urban objects visible to the sensor and do not completely represent canopy walls and ground surfaces (e.g., tree canopy temperature vs. surface temperature under the tree; (Krayenhoff et al., 2020)). Second, satellite-based LSTs are biased towards horizontal surfaces, and it is questionable how useful roof temperatures are to assess pedestrian overheating. Third, LSTs sensed by satellites cannot yet resolve thermal extremes at the sub-meter touch-scale relevant to human health (Vanos et al., 2016), or at the scale of individual streets relevant to personal heat exposure.

These findings indicate that at the human scale, neither air temperature nor surface temperature is sufficient for quantifying overheating in cities. Recently, human biometeorological research has highlighted the importance of the radiative environment for accurate outdoor human thermal assessments (Hondula et al., 2017; Johansson et al., 2014; Kántor & Unger, 2011; Middel et al., 2021; Middel & Krayenhoff, 2019). Mean Radiant Temperature (MRT) – a synthetic parameter that summarizes short and longwave radiation fluxes to quantify the radiant heat load on the human body – was identified as the main meteorological driver of thermal comfort in the warm season in hot dry regions and under sunny conditions (Lin et al., 2010; Middel et al., 2018). MRT observations apply different instruments with varying levels of accuracy and complexity (Höppe, 1992; Thorsson et al., 2007).

Further acknowledging the complex interaction of various environmental parameters with individual thermal comfort and heat stress response (Sec. 3), the scientific community has developed indices to better capture individual thermal sensation and provide a single integrated value that represents a more comprehensive assessment of environmental heat stress than air or radiant temperature alone (Fiala & Havenith, 2015). Potchter et al. (2018) identified over 165 thermal comfort indices developed over the past 60 years that link human thermal responses and perceptions to atmospheric conditions. Five thermal indices identified as most widely used (also see B.3) were the Physiologically Equivalent Temperature (Höppe, 1999; Mayer & Höppe, 1987), Predicted Mean Vote (Fanger, 1973; Gagge et al., 1986), Universal Thermal Climate Index (Jendritzky et al., 2012; Jendritzky & Tinz, 2009), Standard Effective Temperature (Gagge et al., 1986; Gonzalez et al., 1974) and its outdoor variant (Pickup et al., 2000), and Wet Bulb Globe Temperature (Yaglou & Minard, 1957). While these indices account for the radiative environment

– as opposed to merely temperature-humidity metrics – they all make assumptions related to clothing, activity speed, and metabolic rate. Accordingly, the ability to assess human overheating using these indices is critically limited, particularly for working populations where metabolic rate during activity is the most critical factor in predicting core temperature (Cramer & Jay, 2015). The generic assumptions of these models – often, an “average” human male, low activity, and static conditions – present a critical challenge for accurately predicting heat exposure of different individuals and populations, as detailed in Secs. 3.1 and 4.1. More efforts are needed to update these indices to account for the duration of heat exposure as well as varied physical activities (for instance, for outdoor workers), as detailed in (Bröde et al., 2016). Finally, most thermal indices do not work equally well in dry and humid conditions since the neutral or “no-stress” range varies greatly for different climate zones (Heng & Chow, 2019; Potchter et al., 2018). Therefore, indices need to be calibrated to quantify heat exposure in the context of local thermal adaptation, behavior, and differences in climatic zones (Sec. 3.2).

Table 1. summarizing the key metrics, motivations, and methods for sensing and representing urban overheating across different scales.

Scale	**Relevant Metrics**	**Motives**	**Methods**	**Reviews & examples**
City	- Land Surface Temperature - 2-m air temperature - Intra-urban temperature variability	❑ Urban energy efficiency ❑ Urban environmental health ❑ Urban heat mitigation ❑ Climate-responsive design ❑ Urban emission mitigation	➢ Remote sensing ➢ Mobile sensing ➢ Climate modeling (Sec. 2.3)	(D. Zhou et al., 2018) (Voogt & Oke, 2003)
Street	- Canopy air temperature - Mean radiant temperature - Outdoor thermal comfort/Heat stress indices - Outdoor thermal comfort autonomy maps	❑ District energy efficiency ❑ Canopy heat mitigation ❑ Promoting healthy urban lifestyle	➢ Fixed and mobile weather stations ➢ Net radiometer or globe thermometers ➢ Urban climate informatics using data sources (such as Google street view) for MRT monitoring ➢ Microscale climate modeling (Sec. 2.3)	(Potchter et al., 2018) (Middel & Krayenhoff, 2019) (Nazarian et al., 2019)
Building	- Indoor air temperature - Indoor thermal comfort indices	❑ Building energy efficiency ❑ Indoor environmental quality ❑ Work productivity ❑ Human comfort, health & wellbeing	➢ Smart WiFi thermostat ➢ Conventional or IoT environmental sensor network (Sec. 2.2)	(Rodriguez & D’Alessandro, 2019)
Human	- Indoor/Outdoor thermal comfort/Heat stress indices - Individually-experienced temperature	❑ Human comfort, health, and wellbeing ❑ Human performance (cognitive and physical)	➢ Personalized heat monitoring devices (Sec. 3.1) such as wearable sensors ➢ Personal comfort/heat stress modeling	(Kuras et al., 2017) (Nazarian & Lee, 2021)

Indoor characterization of heat exposure uses similar methods and metrics as those identified outdoors, such as monitoring microclimate parameters and calculating thermal comfort indices. However, most studies assume low wind speeds and radiant heat transfer indoors, and therefore, consider air temperature and humidity as key indicators for indoor thermal environments - a limiting assumption for naturally-ventilated buildings with large window-to-wall fractions. More importantly, most studies are focused on office buildings instead of residential heat exposure (Nazarian & Lee, 2021; Rodriguez & D'Alessandro, 2019), and a fraction of those focused on vulnerable populations detailed in Sec. 4 (White-Newsome et al., 2012). These factors - in addition to the complex and heterogeneous human behavior and adaptive capacities indoors - represent a significant gap in providing a holistic characterization of heat exposure in different cities and climates, as well as the impact on human health and energy (Sec. 4).

Despite recent advances in the development and application of methods to characterize heat exposure across different scales, several considerations persist. First, quantification of urban heat generally does not capture individual duration of thermal exposure and therefore cannot describe the cumulative effects of heat. Additionally, due to limitations in sensing methods, little is known about the real-time thermal discomfort and strain people experience as they go about their daily lives (Kuras et al., 2017; Nazarian & Lee, 2021), limiting the realistic datasets that can inform dynamic and unsteady index development. These limitations further motivate more investment in novel sensing methodologies that provide ubiquitous, real-time, and human-centric monitoring of heat exposure (Sec. 2.2).

2.2 Infilling the climate networks with ubiquitous sensing, IoT, and crowdsourced monitoring

With recent advancements in low-cost sensor solutions, Internet-of-Things (IoT), and Big Data, an innovative approach has emerged to comprehensively characterize urban heat exposure. Over the last decade, ubiquitous sensing (i.e. distributed, real-time, and spatial data collection) and crowdsourcing (in which a community is leveraging sensing devices to collectively share data) have presented a paradigm shift in heat exposure assessments (L. Chapman et al., 2017), presenting several key advantages in characterizing urban heat exposure. First, compared to traditional sensing units, a network of sensors is able to cover higher spatial and temporal resolutions at a lower cost and with less centralized effort. This further enables us to a) assess inter- and intra-urban overheating patterns (Fenner et al., 2017; Meier et al., 2017) and b) address local-scale urban effects and their spatial and temporal variation, which traditional climate station networks overlook (Oke, 2006). Second, given that sensors are distributed or carried with individuals, ubiquitous sensing provides unprecedented and dynamic information regarding the population impact of urban overheating. This advantage permits human-centric assessment of heat exposure (Kuras et al., 2017; Nazarian & Lee, 2021), in which we combine information regarding the thermal environment with a) corresponding physiological responses (Buller et al., 2018; Liu et al., 2019; Nazarian et al., 2021), b) objective and subjective momentary feedback (Jayathissa et al., 2019), and c) detailed human activity, via portable sensors or smartphones and smartwatch applications. Consequently, deeper insight into human bioclimatic impact in a real-world experiment can be obtained. Lastly, real-time and high-resolution data collection provide valuable information for developing emergency responses in the face of extreme events as well as informing and validating climate and weather modeling at various scales (Sec. 2.3).

Several successful examples of emerging methods for characterizing heat exposure can be noted. Pioneering crowdsourcing studies using Netatmo citizen weather stations (CWS) were able to characterize intra-urban air temperature variability in several European cities (Fenner et al., 2017; Meier et al., 2017; Varentsov et al., 2020; L. de Vos et al., 2020) and Oceania (Potgieter et al., 2021) at a higher resolution than otherwise achieved with traditional sensing. Other work exploited daily temperature signals from phone battery temperatures (Droste et al., 2020) and further combined them with Machine Learning algorithms (Trivedi et al., 2021) to predict ambient air temperature within 2°C accuracy. Wearable weather stations were also proposed and deployed to predict the impact of heat exposure on heat stress and perceived activity level (Nazarian et al., 2021).

Despite this significant growth, however, it appears that IoT measurements have heavily emphasized the monitoring of air temperature and humidity as proxies for the thermal environment, neglecting key environmental and personal factors that holistically link overheating to the health, wellbeing, and lifestyle (Sec. 3.1-2). This is mainly due to the fact that measurements of radiation and wind speed, as well as the physiological response of individuals to urban heat, are harder to achieve through existing low-cost and non-intrusive sensing solutions. Moreover, a fundamental question raised by (Muller et al., 2013) and (L. Chapman et al., 2017) is still far from being answered: how can crowdsourced data provide an acceptable level of accuracy, certainty, and reliability, particularly in dynamic and realistic conditions of our cities? One of the critical gaps in IoT environmental sensing arguably pertains to the quality of the sensors and the collected data, as a universally accepted set of procedures, standards, or guidelines for standardization and quality control is yet to be developed. In general, low-cost sensors tend to be less accurate than scientific and operational instruments, usually lack proper calibration, and are subject to sensor drift over time. In addition, they have errors due to inadequate or missing radiation shielding and sensor ventilation and may be sensitive to changing user context. The latter is particularly the case for sensors in smartphones and wearable devices, which fluently change between indoor and outdoor settings, pocket and palm, and are also influenced by the phone's CPU load or display intensity (Martilli et al., 2017). Moreover, the sensors usually react slowly and thus integrate over previous settings and contexts spatially and temporally. In addition to these errors, ubiquitous sensors exhibit greater variation due to realistic microclimatic effects resulting from differences in observation height, proximity to buildings, or local ventilation. In summary, there are both statistical and systematic errors, but also challenges with realistic spatio-temporal representativeness that can be considered a feature. All types are difficult to detect, distinguish, and most of all to correct. Nonetheless, more recent studies demonstrate the potential of crowdsourcing by combining various sensing methods and data layers over a wider range of meteorological parameters (including rainfall, solar radiation, air pressure, and humidity), which will pave the way towards assessment of thermal comfort (L. de Vos et al., 2020).

In addition to technological and scientific limitations of state-of-the-art IoT sensing, crowdsourcing methods face challenges in scientific communities as well as the general public. There is still a lack of acceptance in scientific communities for adopting commercially available low-cost sensors for research applications. As a result, many solutions go untested in application, creating more questions than answers regarding the capability of IoT sensing in addressing urban heat challenges. Additionally, there are concerns regarding the digital divide across age groups, income levels, and geographic location. So far, no analysis has been done to understand what percentage of IoT (or conventional) sensing for urban heat is covering low-income versus affluent neighborhoods, which can further influence the governance and policy implications of urban overheating (Sec. 5.3). Finally, justified concerns related to privacy hinder the penetration and availability of collected data. For instance, useful sensor data from mobile devices always has to record the exact position and thus can likewise be used to derive environmental information and to track individuals over days and months.

Future research should focus on merging crowdsourced and IoT environmental sensing with behavioral and mobility data, helping us better understand and characterize heat exposure and the ensuing impacts in cities. The innovations thus need to be technological, scientific, and societal. Rapid progress has been made in the past years in the development of small and low-cost sensors (mostly driven by private companies) that can similarly contribute to more comprehensive monitoring of heat exposure in the future. More importantly, critical and highly innovative research questions for inter- and trans-disciplinary work are present, which together constitute a joint agenda for science, citizens, and the public sector for at least a decade:

- Merging crowdsourced thermal environment data with behavioral and mobility data to more accurately characterize overheating exposure, vulnerability levels, and ensuing impacts. This further assists future research in quantifying how urban heating impacts people's interaction with the built environment (Sec. 3.2).
- Quality assessment to derive useful urban heat exposure information from mass data and integration of data from various sources and devices into a joint analysis system. This can include combining air temperature observations with other parameters that influence human thermal comfort.
- Further research that distinguishes errors in data (bug) from realistic microclimatic variation (feature).
- More comprehensive characterization of heat exposure both outdoor and indoor (where people spend most of their time) and better understand the relations of both (Sec. 5.2).
- Use the data for personal recommendation systems in application to enable more adaptive capacities for individuals, i.e. avoiding the heat by different routes or travel times.

2.3 Multi-scale urban climate modeling

Process-based numerical models of urban climate are generally more cost-effective and provide greater spatial and temporal coverage of potential heat exposure relative to measurements. Critically, they can be applied to evaluate future urban overheating or infrastructure-based heat adaptation scenarios (Sec. 5.1), and associated uncertainties, informing decision-makers about potential overheating exposure and adaptive responses well ahead of potential consequences (Krayenhoff et al., 2018; Martilli, 2014; Wouters et al., 2017; Zhao et al., 2017, 2021). However, numerical models rely on imperfect abstractions of the urban structure and atmosphere, and they must be appropriately tested if they are to have such utility (Krayenhoff et al., 2021). Moreover, models capable of simulating urban climates currently have varying abilities to represent actual human exposures to urban heat, which depend on multiple environmental variables (Sec. 2.1).

Numerical assessment of urban overheating must focus on the climate in the urban canopy layer (UCL), the atmosphere below the mean building height, where most of the world population spends their lives. We classify existing models that aim to capture the range of scales of phenomena relevant to UCL climates as follows:

a) <u>Microscale models</u> reproduce circulations at the scale of streets and buildings (wakes, flow blocking, channeling, etc.) and/or the complex patterns of shading and radiation exchange resulting from individual buildings. These phenomena influence heat and radiation exchanges between the atmosphere, buildings, streets, trees, and pedestrians.

b) Mesoscale models are built to represent the state of the atmosphere within and above the city (i.e., the urban boundary layer), which is characterized by phenomena at scales of tens to hundreds of kilometers, such as land/sea breezes and mountain/valley winds, directly simulating regional impacts on neighbourhood-scale climate.

c) Global-scale models simulate larger space and time scales associated with climate change and provide the context for future meso- and microscale urban climate phenomena, including overheating.

This diversity of modelling scales arises from current limitations of computational power, which render impossible the simulation of microscale features relevant to urban heat across numerical domains large enough to account for mesoscale processes. Similarly, mesoscale processes are typically not captured by global climate models, although adaptive grid-scale approaches may soon permit them to do so for selected cities. Microscale models, by virtue of their explicit representation of buildings and other urban elements, can address human-scale variability of wind and radiation (e.g., sun/shade) that is critical for personal heat exposure, whereas meso to global scale models have so far been focused more extensively on air temperature and humidity (to a lesser extent), whose spatial variation is smoother.

At broad scales, the urban overheating burden is exacerbated by two interacting effects: land cover and land use changes driven by urbanization, and global-scale climate change and associated increases to heatwave severity. Numerous meso-global scale modelling studies have quantified the substantial urban scale overheating risk from unmitigated global climate warming, including 4 K mean summer temperature increases globally (Zhao et al., 2021) and 10-fold increases in extreme heat day frequency in select regions (Krayenhoff et al., 2018), accounting for uncertainty related to greenhouse gas emissions pathways and climate model variability. Urban development includes both expansion of urban areas, and densification of existing urban areas. Urban construction on land that was previously cropland or forest, for example, generates large warming locally, especially at night, and additionally contributes smaller warming to existing urban areas downwind (Doan & Kusaka, 2018). Numerical evidence suggests that seasonal-scale urban-induced warming may either be unstable or static as a result of larger scale warming (Doan & Kusaka, 2018; Oleson, 2012); at shorter times scales, observations and modelling suggest that the UHI and heat waves are synergistic and controlled by multiple factors (Ao et al., 2019; D. Li & Bou-Zeid, 2013), in particular, the variable responses of non-urban lands to heat waves (P. Wang et al., 2019).

Meso- and global-scale models have also been widely applied to study potential reductions of air temperature in cities from the widespread implementation of heat mitigation strategies, for example, green and cool roofs, street trees, and shorter vegetation (Krayenhoff et al., 2021; Santamouris et al., 2017a), as well as their ability to offset climate change warming (Krayenhoff et al., 2018). While meso-global scale modelling can help reveal potential overheating risks based on air temperature changes and the associated cooling efficacy of infrastructure-based heat adaptation, microscale modelling more often addresses the complete heat exposure of individuals, including microscale variations of solar and longwave radiation and wind and turbulence. In particular, models at this scale have been used to assess the impacts of street-neighbourhood scale design on individual thermal exposure, using metrics that go beyond air temperature and account for radiation and wind, for example (Aminipouri et al., 2019; H. Lee et al., 2016; Tan et al., 2016); see Sec. 2.1). Here, detailed configurations of buildings, trees, shade devices, as well as the radiative and thermal effects of construction materials, can be considered in terms of their radiative impacts. Microscale computational fluid dynamics models are additionally used to evaluate wind flow and associated effects on pedestrian thermal comfort (Chew et al., 2017; Nazarian et al., 2017). However, microscale models require boundary conditions that provide information about the larger-scale meteorological conditions in which their domain is embedded. Moreover, both microscale and mesoscale modelling would benefit from better accounting for the actual or optimal locations of people who may be exposed to urban heat (Middel et al., 2017; Jiachuan Yang et al., 2019). Nevertheless, the need for careful assessment of microscale radiative and flow-based heat mitigation strategies is emphasized given the aforementioned imbalance between potential climate change warming and air temperature cooling achievable from the aggressive implementation of heat mitigation strategies (Krayenhoff et al., 2018).

The long-term goal of performing simulations that can fully resolve both meso-global scale and microscale phenomena is likely several decades away. In the meantime, paths forward should involve increasing interaction between these modeling scales, and closer attention to the complete thermal exposure of individuals within the urban environment. These new developments must be “fit-for-purpose”, e.g., tailored for assessment and mitigation of the impacts of urban overheating. In particular, we define the following medium- and short-term objectives.

As *medium-term objectives*, we should aim to develop high resolution (hundreds of meters) mesoscale models in which to two-way nest highly parameterized and fast microscale models. The main challenges for this task will be to 1) develop new multi-scale boundary-layer closures to be used in mesoscale models, and 2) identify the most relevant phenomena to be introduced in the highly parameterized microscale models.

As short-term objectives, key priorities for future research are as follows. At the <u>mesoscale</u>, of paramount importance is improvement in the accuracy of model predictions of environmental variables relevant to the estimation of indoor and outdoor biometeorological stresses (Secs. 2.1, C.2, D.1), and building energy consumption (Sec. 4.2). Models of urban canopy processes embedded in mesoscale models must be improved based on microscale simulations, in particular representations of radiation and convection fluxes in the canopy. Simplified parameterizations for evaluation of mean radiant temperature and wind speed, and their spatial variability within urban grid squares in mesoscale models, are needed. Moreover, better quantification of key parameters that characterize urban neighbourhoods are crucial requirements to take advantage of improved model physics (Ching et al., 2018). At the <u>microscale</u>, there is a need for new techniques to accurately use mesoscale model outputs to force microscale simulations (and in this way account for boundary-layer scale processes on microscale phenomena in the urban canopy layer). Moreover, it is critical that we improve surface energy and radiation budgets with detailed flow prediction. At <u>all scales</u>, future model development should include better representation of indoor-outdoor exchanges and improve the capability of the models to account for climate impacts of existing and future heat mitigation strategies (vegetation, albedo, high-performance materials, etc; see Sec. 5.1), with a specific focus on the evaluation of the sub-models introduced to represent these strategies (Krayenhoff et al., 2021). Accurate assessment of infrastructure-based adaptation effectiveness is critical for the provision of appropriate guidance to planners and policymakers tasked with addressing urban overheating. Critically, applied research based on numerical simulations should make increasing efforts to quantify and communicate uncertainty related to greenhouse gas emissions and urban development scenarios, global climate model ensemble, and modelling assumptions, with a specific focus on uncertainties related to the intensity, duration and frequency of future extreme heat and the efficacy of urban heat mitigation. Initiatives that enhance communication between urban climate scientists and municipal decision-makers are crucial to better integrate scientific knowledge in decision making, and also better target urban climate modelling to practical needs. Furthermore, linkages between climate and agent-based models can help determine probable human heat exposure based on individual agency and decision-making in addition to urban meteorological variability.

The short- and medium-term objectives mentioned above must involve rigorous and standardized model evaluation procedures that focus more on particular physical processes and less on output variables that result from multiple physical processes (e.g., air or surface temperature) where compensating errors obscure issues with model representation of processes.

3 Understanding individual sensitivity and adaptive capacity to urban heat

The following sections discuss some of the most pressing research and applied questions related to development of an integrated view of thermo-physiology, human behavior, and psychology in response to heat, such that we better understand the impact of heat exposure on individuals in the built environment. Here, we aim to extend the discussion of urban heat exposure (Sec. 2) to detail individual sensitivities that modulate the ensuing impacts of overheating. Understanding individual sensitivities - caused by physiological stress and strain (Sec. 3.1) as well as subjective, perceptive, and psychological responses to heat (Sec. 3.2) - is also critical for understanding available adaptive capacities at an individual scale.

3.1 Biometeorological strain and physiological responses to heat exposure

Heat stress refers to the combination of environmental conditions, metabolic heat production and clothing characteristics that alter human heat balance and ultimately contribute to the accumulation of heat energy inside the human body. Heat strain refers to the resultant physiological responses from heat stress, such as the rise in thermal strain, cardiovascular strain, and dehydration (Fig. 3) (Sawka et al., 2014). Accurate risk assessment of human heat strain requires a comprehensive and in-situ representation of all four parameters that define a thermal environment, namely air temperature, mean radiant temperature, absolute humidity and wind speed. Often these parameters are integrated into a single thermal comfort or heat stress index (Sec. 2.1). However, environmental determinants alone are insufficient to understand the implications of urban heat exposure; physiological responses must also be assessed to fully understand the impact of overheating on individuals and populations. Figure 3 outlines the environmental drivers of heat exposures across different scales (Sec. 2.1) with human behavioral and physiological responses that lead to individual sensitivity to heat exposure and ensuing impacts.

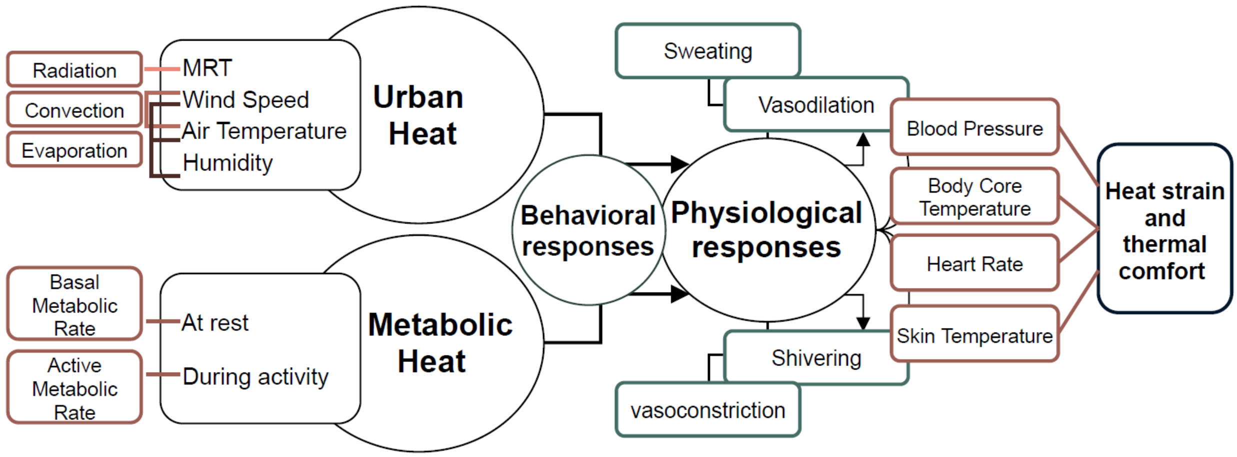

Figure 3. Physical, physiological, and behavioral mechanisms in response to heat.

Human core temperature is tightly regulated at around 37 °C, despite variations in environmental conditions (Parsons, 2014). The maintenance of thermal homeostasis is achieved through both physiological and behavioral responses (Flouris, 2019). During heat exposure, increases in deep and peripheral tissue temperatures are sensed by thermoreceptors and integrated in the hypothalamus to activate heat loss (mainly cutaneous vasodilation and sweating (Fig. 3). Behavioral thermoregulation reduces the need for autonomic thermoregulation as humans consciously engage in actions (e.g., moving to the shade, removing or putting on more clothing) to maintain thermal equilibrium, based on perceptions of thermal comfort and sensation (Schlader & Vargas, 2019). (Sec. 3.2). This suggests that our behavioral responses are triggered by sensations of thermal discomfort (Schlader et al., 2010).

There is robust epidemiological evidence demonstrating the negative health effects of hot weather and heat extremes (Bi et al., 2011; Kovats & Hajat, 2008; Luber & McGeehin, 2008; Semenza et al., 1996). These impacts are predominantly concentrated within specific clinical and socio-economic sub-groups (Sec. 4.1). Focusing on individual health, people with cardiovascular or renal diseases are at an elevated risk of heat-related mortality/morbidity during heat extremes (Hansson et al., 2020), while people who do not own or cannot afford to operate air-conditioning have a significantly higher chance of heat-related illness during heatwave (35-times higher risk of heat-related illness reported during the 1999 heatwave in Cincinnati, Ohio (Kaiser et al., 2001)). Extreme heat is often reported to acutely worsen these diseases, so understanding the specific physiological pathways for the increased heat sensitivity of people with specific diseases is essential for identifying the optimal heat mitigation strategy. For example, people with cardiovascular disease may not be able to tolerate the increased cardiovascular strain associated with the elevated skin blood flow required for heat dissipation, thus increasing their risk of cardiovascular collapse (Ebi, Vanos, et al., 2021). In this scenario, an intervention or a drug that increases skin blood flow to promote heat loss may be counter-protective as it may inadvertently exacerbate cardiovascular strain; instead, skin cooling strategies that reduce skin blood flow requirements may be a more suitable heat mitigation strategy, regardless of its efficacy in reducing core temperature (Jay et al., 2021).

Besides heat-related illnesses, urban heat stress can also exacerbate underlying health conditions and adversely impact fertility (Grace, 2017), work productivity (Kjellstrom et al., 2016), work-related accidents (Morabito et al., 2006), and decision-making (C.-H. Chang et al., 2017; Obradovich et al., 2018). Understanding the biophysical aspects of heat exchange between the human and surrounding environment is essential for determining the efficacy of various cooling strategies under different environmental conditions, thus informing evidence-based heat-health advisories. For example, many public health authorities currently recommend against the use of electric fans when ambient temperature exceeds 35˚ C (skin temperature), as it would increase convective heat gain (Hajat, O'Connor, et al., 2010). However, this does not consider humidity and a person's ability to sweat, which influence the rate of evaporative heat loss (Jay et al., 2015; Morris et al., 2021). Research has demonstrated the cooling benefits of electric fan use at ambient temperatures of 42°C with 50% relative humidity in healthy, young males with intact sweating responses (Ravanelli et al., 2015). However, fan use under similar ambient conditions may not benefit individuals with reduced sweating ability (e.g., elderly, people taking anticholinergic medications) (Gagnon et al., 2017; Morris et al., 2021). Therefore, advice concerning fan use during heat exposure (particular in indoor spaces as detailed in Sec. 5.2) should be specific to the population and humidity levels (Jay et al., 2015; Morris et al., 2021).

Furthermore, strategies designed to alleviate physiological strain (mainly by altering core temperature) associated with exertional heat stress can potentially be adapted to combat urban heat stress. Individuals performing physical activity (e.g., occupational work, exercise) are at an increased risk of heat illnesses as heat stress from the environment is compounded by increased metabolic heat production (J. K. W. Lee et al., 2010). A common behavioral adjustment is the use of work-rest cycles (alternating periods of work and rest) to prevent excessive body heat storage (J. K. W. Lee et al., 2013). This strategy is particularly relevant for outdoor workers who are specifically vulnerable to urban heat challenges but are underrepresented in research (Nazarian & Lee, 2021). Physiological strategies such as improving aerobic fitness (Alhadad et al., 2019), heat acclimatisation (J. K. W. Lee et al., 2012), pre-exercise cooling (J. K. W. Lee et al., 2012, 2015) and fluid ingestion (Luippold et al., 2018) are also often used to optimise work productivity and performance in the heat (Fig. 4). However, it is important to note that the most appropriate strategy for combating urban heat stress must be tailored according to context and needs, particularly in extending their efficacy in vulnerable populations. For example, aside from questions regarding the sustainability of air conditioning use, being sedentary indoors for prolonged periods will potentially degrade habitants' aerobic fitness and heat acclimatisation status, therefore reducing their heat tolerance. These factors are currently neglected in heat-health advisories and should be considered to increase the population's resilience to urban overheating.

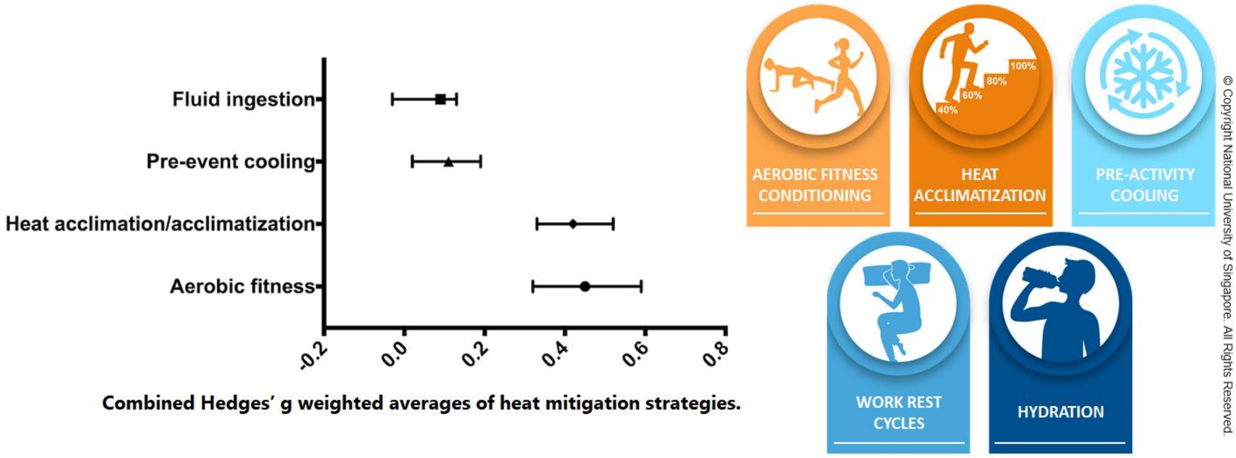

Figure 4. Overall efficacy of physiological strategies to reduce heat strain and augment work productivity and performance, based on a meta-analysis of 118 studies (Alhadad et al., 2019). Figure shows the overall effect sizes (Hedges' *g*) of each strategy in altering body core temperature during exertional heat stress. Values are interpreted as trivial (<0.20), small (0.21–0.49), moderate (0.50–0.79) and large (≥0.80) effects, respectively. Diagram adapted from (Alhadad et al., 2019).

To reiterate, heat-health advisories that are solely based on climatic conditions have limited efficacy. Given the subjectivity of thermal comfort, future research should focus on the development and implementation of personalized heat mitigation guidelines that are tailored according to an individual's health, environment and adaptive capacity. This can be achieved by coupling climatic data with biophysical inputs and known influencing factors of heat illnesses (e.g., sex, age, body size, aerobic fitness). With emerging IoT and wearable devices (Sec. 4.2), this is becoming increasingly feasible. Besides personalization, the physiological capacity of the population of interest must also be considered, to improve the accuracy of future projections of work capacity and heat-related health outcomes (Byrne & Lee, 2019). For example, (Cramer & Jay, 2015) and (Notley et al., 2019; Vanos et al., 2020) noted that several inter- and intra-individual factors (e.g., age, sex, aerobic fitness, hydration status) that influence a person's physiological strain (thus, risk of heat-related illness) for a given level of heat stress are neglected in current heat exposure limits for exertional settings. Consequently, the current "one size fits all" approach may induce unnecessary productivity losses for heat-tolerant individuals while under-protecting heat-intolerant workers who may suffer heat injury under moderate heat stress. This further underscores the importance of developing personalized heat mitigation strategies to optimise human health, well-being and productivity in the face of urban overheating. However, to do so effectively, further research is warranted in several areas, including (but not limited to) potential interactions among the various individual factors on heat strain and the relative importance of each factor in determining heat illness risk (Notley et al., 2019).

3.2 Biometeorological stress and psychological response in the face of urban overheating

In addition to environmental heat exposure and physiological responses, behavioral and psychological determinants are critical components of urban overheating. From the perceptual point of view, the individual sensitivity to urban overheating is related to the difference between the thermal environmental conditions at hand, and those normally expected of the city in question. For example, typical urban meteorological conditions in Shanghai during summer are readily accepted by the residents of that city who have no difficulty going about their day-to-day routines under those conditions. But were the same climatic conditions to occur in say, London UK, they would greatly exceed expectations of Londoners who would rate them 'off the chart' and deem them unacceptable, if not debilitating. This relativity in thermal perception is the phenomenon known as adaptive thermal comfort in which there are no absolutes, and comfort perceptions are benchmarked against climatic expectations (Brager & de Dear, 1998). The empirical evidence for adaptive comfort has largely evolved in indoor settings (De Dear et al., 2020; Nicol & Humphreys, 2002), but the underlying principles are equally relevant at the urban scale and recent field studies in outdoor settings confirm this generalization in the literature (Jendritzky et al., 2012; Lin et al., 2011). The adaptive model of thermal perception indicates that the psychological response to thermal exposure as well as the zones of "no heat stress" for thermal comfort indices (Sec. 2.1) should be explored and calibrated in cities with different climates to reflect local thermal adaptation strategies, behavioral patterns, and differences in climatic zones (Heng & Chow, 2019; Potchter et al., 2018). Such adaptive considerations of heat exposure are yet to be quantified and documented for all climate classes in both northern and southern hemisphere, and in developing countries susceptible to heat-health impacts (Baker & Standeven, 1996).

Additionally, it is critical to recall that thermal comfort of individuals is defined as "the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (Standard 55, 2017). Various studies have confirmed that approximately 50% of a person's thermal sensation can be explained through environmental factors, while the other 50% are induced by personal, psychological, and physiological characteristics. These components can only be assessed through mixed methods combining subjective and objective evaluation (Chen & Ng, 2012; Johansson et al., 2014; Middel et al., 2016; Nikolopoulou et al., 2001) or personalized assessments that monitor physiological and behavioral responses of individuals, as detailed in Secs. 2.2 and C.1 (Kuras et al., 2017; Nazarian & Lee, 2021).

Furthermore, people's perceptions of heat and their psychological responses drive their behavior, which then modulates the indirect and direct impacts of urban overheating (Sec. 4). In the absence of outdoor adaptation and mitigation strategies for heat exposure, the default behavioral response to perceived urban heat discomfort is often the minimization of exposure, i.e. reduced time outdoors and correspondingly increased time indoors and an increasingly sedentary lifestyle (Nazarian et al., 2021). This further results in over-reliance on air-conditioned indoor comfort and preference for private vehicles over the active modes of transport, particularly in developed countries, with life-style-related health impacts ensuing (i.e. cardiovascular, obesity, and diabetes). This hypothesis of obesogenic cities, and the deleterious impacts of urban overheating on walkability of the city, raises important multidisciplinary research questions that are yet to be addressed. Empirical verification of causal links between urban heat and residents' behavior, their sedentariness, and heat-health impacts at the individual and population levels are essential directions for future research such that evidence-based urban planning and policy can be effective in a warming urban world.

Implementing this knowledge in practice, adaptive opportunities that individuals can afford to reduce heat exposure require more explicit consideration. Adaptive options for an individual to control their local environment (Baker & Standeven, 1996) are circumscribed by the built environment (Baker 1996). For instance, in the humid tropics, the key urban adaptive opportunities relate to wind resources available at the pedestrian level to enhance the body's convective and evaporative heat losses (Ng & Cheng, 2012), and in the hot-dry climatic setting, pedestrian thermal comfort relies primarily on solar shade opportunities afforded by the urban geometry, street furniture, verandas and overhangs, and trees (Hwang et al., 2011). Additionally, greening of streetscapes, precincts, and facets of individual buildings - which can also reduce canopy-level ambient air temperature in hot-dry climates - can create thermally pleasant conditions in adjacent residential and commercial precincts if implemented at sufficient scale (C.-R. Chang & Li, 2014). Green infrastructure integrated in design further improves the walkability of urban precincts and increases the likelihood of outdoor spaces being used by residents. Enhanced city walkability and livability promotes higher levels of outdoor activities that, in turn, facilitate deeper thermal adaptation and acclimatization through a variety of physiological, psychological, and behavioral interactions which ultimately reduces heat strain risks in individuals (Sec. 3.1).

Beyond the passive urban design approaches described above are the active engineering solutions, such as mechanical ventilation to enhance convective and evaporative cooling of pedestrians, misting to enhance evaporative cooling of air in outdoor urban settings, and even energy-intensive air-conditioning of semi-outdoor urban spaces. For example, in Qatar where the average outdoor dry bulb temperature is 34°C, an outdoor air-conditioning system was designed and installed into the perimeter of a football field. The system projected conditioned air at 14°C into a vast, open space occupied by about seven thousand attendees at a live-streamed FIFA World Cup match (Ghani et al., 2021). As effective as these brute-force design strategies for urban thermal comfort may be, they carry considerable financial and environmental costs that need to be carefully weighed before being implemented in workplaces (such as construction sites) as well as on precinct and urban scales. A more parsimonious and environmentally responsible approach to the design and implementation of active outdoor comfort conditioning may be to think of it as temporary thermal respite such that outdoor activities are encouraged despite higher heat exposure projected in cities.

To better utilize outdoor spaces, urban planning solutions (Sec. 5) could also be developed by incorporating adaptive behaviors in addition to environmental determinants (such as MRT and wind speed) responding to urban morphology and local climate (Nazarian et al., 2019; Ng et al., 2011). Further examples of strategies that can promote climatically adaptive comfort behaviors at the individual scale include pedestrian routing recommendation engines to maximize exposure to shade resources (Deilami et al., 2020), development of cool street furniture (high thermal mass, low surface temperature, with vegetated awnings or shading), and active engagement in water-based recreation. Accordingly, in addition to city-scale urban heat mitigation efforts, localized cool oases in hot environments, or cool refuges, are needed to tap into adaptive opportunities in the built environment.

4 Assessing the impacts of overheating on populations

Understanding the key sensitivities to urban heat at the human scale (Sec. 3.1-2) is fundamental to characterizing and addressing population-level vulnerability and impacts in the face of extreme heats. To further clarify the negative impacts of heat, this section details the ways in which the impacts are realized at the population and city level, particularly with regards to urban environmental health and energy. Here, we focus on urban dwellers - 55% of the global population now and 67% by 2050 (Ritchie & Roser, 2018) - exposed to and often negatively affected by extreme or chronic urban heat (i.e., urban overheating).

4.1 Urban Environmental Health

Urban Environmental Health & Heat Epidemiology

Urban environmental health focuses on the health of people as it relates to environmental conditions in cities (e.g., water and air pollution, greenspace, hazards such as flooding or heat). Recent definitions of "health" focus on a state of complete physical, mental, and social well-being, and not merely the absence of disease (World Health Organization, 2021). Despite this definition, extreme heat impacts have generally been studied as either the presence or absence of a heat illness or heat death as opposed to assessing well-being and liveability. In recent years, worker productivity and economic losses related to heat exposure have been used to quantify the intermediate impacts of heat (Lucas et al., 2015; Vanos et al., 2019; Zander et al., 2015), with a focus on developed countries in the northern hemisphere. Yet globally, reduced well-being and death from heat stress are common, and the associated vulnerabilities are often poorly documented in the research (Ebi, Capon, et al., 2021).

Epidemiology applies various methodologies for quantifying the contribution of *extreme heat* to human health outcomes at a population-scale across cities or counties, both *directly and indirectly*. At finer scales (e.g., neighborhoods), studies apply vulnerability indices that can explicitly assess social vulnerability, thus focusing on those demographic and socioeconomic factors that may increase or attenuate the hazards (such as heat) on a local population (Tierney et al., 2002). Common country-, city-, or neighborhood-level methods to quantify direct heat-health impacts are listed in Table 2. The literature strongly demonstrates positive associations between heat and mortality or morbidity in large cities (Gasparrini et al., 2015; Guo et al., 2017), regardless of climate zone or country income level (H. Green et al., 2019). Heat vulnerability studies at census tract or neighborhood scales are better able to ascertain location-specific factors such as income, poverty, social isolation, education, race/ethnicity, age (elderly) and vegetation as important predictors of heat death or illness during locally-defined heat events (Harlan et al., 2006; Reid et al., 2009), resulting in the creation of numerous city-specific heat vulnerability indices (HVIs) (Harlan et al., 2013; Rey et al., 2009; Wolf & McGregor, 2013).

Table 2: Common methods used to quantify the contribution of extreme heat to human health across spatial and temporal scales, often with historical data.

Methods	Description	Examples (citations)
Years of Life Lost (YLL)	A measure of premature mortality, in this case, due to heat mortality.	(Sewe et al., 2018) (Yunquan Zhang et al., 2018)
Heat Vulnerability Indices	Summarize the key socioeconomic and physical factors that may increase or attenuate the effects of heat. The weighting (importance) of different factors will differ by location. Often mapped across spatial scales, such as zip code or neighborhood.	(Reid et al., 2009) (Harlan et al., 2013) (Conlon et al., 2020)
Time-series Epidemiological Approaches	Used to estimate temporal changes in relative risk (RR) of short-term mortality associated with increased temperatures (e.g., min, mean, max, range); account for confounding of effect modifiers; assess lagged and/or cumulative effects; often at city- or county-scale. Also used to assess change in RR over time (years), evaluate heat warning systems, and applied in climate projections.	(Bobb, Obermeyer, et al., 2014) (Petkova et al., 2014) (Gasparrini et al., 2015) (Benmarhnia et al., 2016)
UHI Attribution	Assess heat-related impacts with and without UHI impacts caused by urban development (see Sec. 5.1).	(Dang et al., 2018) (Heaviside et al., 2017)
Climate Change Attribution Studies	Determines whether climate change has contributed to observed changes in a given outcome (e.g., the number of deaths with or without a change in climate)	(D. Stone et al., 2013) (Vicedo-Cabrera et al., 2021) (Ebi et al., 2017)

Heat-related health issues are better understood in high-income countries due to data availability and more advanced health systems (H. Green et al., 2019), and thus greater challenges to heat adaptation exist in low- and middle-income countries (LMICs). Within developed countries (e.g., Australia, Italy, Czech Republic, South Korea, United States, Sweden) heat-related mortality has been steadily declining in large cities over the last 30+ years (Bobb, Peng, et al., 2014; Coates et al., 2014; J. Ha & Kim, 2013; Kyselý & Plavcová, 2012; Petkova et al., 2014; Schifano et al., 2012) while the rate of decline varies regionally and across different population groups (Sheridan et al., 2021). Reasons for the recent decline in developed countries may include increasing adaptive capacity, such as heat warning systems, air conditioning prevalence, education, and behavioural modifications. Nonetheless, many heat-related mortality projections for the coming century point to substantial increases (Hondula et al., 2015). Whether or not declining trends will continue in high-income countries depends on continuing and advancing these adaptation strategies, population demographics, migration, urbanization rates (Heaviside et al., 2017), climate change mitigation, and heat adaptation strategies, all of which must be considered in future pathways to project heat related mortality (Gosling et al., 2017). However, a recent study shows that 37.0% (range 20.5–76.3%) of warm-season heat-related deaths across 43 countries (many high-income) globally from 1991-2018 can be attributed to climate change (Vicedo-Cabrera et al., 2021); hence, even with adaptive capacity increases, 1/3 of lives lost may not have occurred without climate change. Such trends, both past, current, and future, are largely unknown for LMICs.

While population-level epidemiological studies in urban areas are a critical starting point, they can only provide a broad overview of potential individual-level challenges outlined in C.1 (i.e., thermal discomfort, physiological strain). There are well-known physiological limits related to heat strain and sensitivities to heat (discussed in **C.1)** that can substantially increase vulnerability even at lower heat exposures and that should be considered in heat projections (Vanos et al., 2020).

Direct and Indirect Health Impacts of Urban Heat on Humans

In addition to the direct physiological impacts of heat exposure (Sec. 3.1), numerous indirect impacts (e.g., cardiovascular events, respiratory distress, and inhibition of sleep, learning, mood, and behaviour) are linked to extreme heat (see review by (Jay et al., 2021)). Each case of heat illness or death is highly individualized and context specific, based on a person's activities and "pathway" to heat exposure, as discussed in Sec. 2.

The patterns of personal heat exposure can vary considerably between individuals and between urban versus rural locations. Certain advantages may be present within urban versus rural environments, specifically a greater access and ability to find cooling centers; a higher presence of shading in some instances (e.g., desert regions); greater access to clean water; more access to transportation; proximity to hospitals and emergency personal; and closer social ties, among others, that directly or indirectly affect heat vulnerability.

Vulnerable Sub-Groups within Cities

Population sub-groups that are more physiologically or psychologically vulnerable and more likely to experience heightened levels of heat include children and infants, athletes, outdoor workers, warfighters, those with pre-existing illnesses and/or on medication, homeless, and the elderly (Ebi, Capon, et al., 2021). While many urban amenities (shade, water, cooling) help support the homeless population, they can be at higher risk because of challenges including barriers to accessing sufficient healthcare and community cooling centers, or compromised physical and/or mental health, making them one of the most at-risk populations to heat deaths (Nicolay et al., 2016).

Athletes and outdoor workers are more likely to experience exertional heat stroke (EHS), which typically strikes active and young athletes and workers when coupled with high metabolic loads and clothing/equipment that impair heat loss (Hosokawa et al., 2019). Within these groups, those at the highest risk of exertional heat injury are already compromised by illness, large body type, recent illness, and/or medication (Hosokawa et al., 2019).

Children's activity patterns and access to (or use of) heat adaptive strategies within urban environments are important factors in their personal heat exposure and thus health outcomes. At the population-level, studies in children point to a higher risk of heat morbidity rather than mortality (Bartlett, 2008; Knowlton et al., 2009; Kravchenko et al., 2013). Within many contemporary playgrounds, extreme surface temperatures may cause thermal burns (e.g., from sun-exposed plastic, rubber, metal; (Pfautsch et al., 2020; Vanos et al., 2016)). Infants and children face the greatest risk to the dangers of pediatric heat stroke (PHS) in overheated vehicles, which is an ever-present, critical concern: in U.S. cities alone, 888 children died of PHS since 1998 (Null, 2021; Vanos et al., 2016).

Finally, excessive heat exposure to pregnant women during the later stages of pregnancy is associated with increased risk for still- and premature-births (Chersich et al., 2020; S. Ha et al., 2017), yet moderate bouts of exercise in the second and third trimester was recently shown to not pose a greater risk to pregnant women in their second and third trimesters (Smallcombe et al., 2021).

Challenges and recommendations

Studies must also address adaptive capacity, which is strongly associated with heat-related illness and death, rather than rising temperatures alone, in order to improve the ability to predict individual or population-level health detriments deriving from overheating in cities. The following recommendations in research and application are suggested:

- Collect appropriate data (health and weather) to conduct research into heat-health associations in LMICs and lower SES communities.
- Develop and validate more rigorous approaches to account for adaptive capacity and demographic change in projecting future heat-health impacts.
- Research indirect effects of heat and include well-being more broadly.
- Create city-specific early warning and response systems for heat extremes that are supported by heat vulnerability maps and that are more tailored to specific individuals; evaluate all such systems.
- Develop and implement passive (i.e., sustainable) cooling strategies to support heat mitigation in cities and in homes (Sec. 5.2), as the cost of AC often leaves the most vulnerable without power ((Jay et al., 2021), and as detailed in Sec. 4.2).
- Improve resources, policies, public health messaging, and technologies that are needed for the most vulnerable populations to respond appropriately to heat (e.g., to prevent PHS or isolated heat deaths in elderly populations), leveraging spaces, tools, and resources already present in urban areas.

4.2 Urban Energy

Urban energy systems both impact and are impacted by urban overheating. Urban overheating results in higher cooling energy needs, while urban energy systems release anthropogenic sensible heat and moisture into the urban atmosphere, increasing urban temperature. High urban temperatures further decrease the performance of photovoltaic modules and air conditioning (AC). Thus, urban energy systems represent a cascade of integrated systems, where the consequences of design and planning decisions and inefficiencies rapidly propagate, pushing socio-economically-disadvantaged urban populations into energy poverty. With the term "urban energy systems", we refer to the interconnected components of energy generation, distribution, and end uses in the built environment, together with buildings and human users. Here, we discuss the challenges in addressing these cascading systems in relation to urban overheating.

In the context of urban overheating, urban energy systems should also be critically assessed when they fail to provide the indoor thermal comfort they were designed to offer (Sec. 5.2). For increasing fractions of the urban population, the failure arises from transient or permanent exclusion from the energy system itself, and thus increased exposure to heat-related health outcomes. This is the condition faced by the energy poor, who are defined as having energy expenditures that exceed 10% of their household income (Moore, 2012).

Urban energy systems often reach a critical state at the occurrence of extreme heat events that act in synergy with local contributions to overheating, both inland (Zhao et al., 2018) and in coastal areas (Khan et al., 2020). Under stress conditions, thermally-inefficient buildings are subject to inadequate indoor conditions, even in developed countries (Thomson et al., 2019). Another relevant risk comes from food safety, when inadequate temperatures during transport and storage lead to the biological proliferation of mycotoxins or pathogenic bacteria in food (Miraglia et al., 2009), while exposure to hotter temperatures reduces food safety inspections (Obradovich et al., 2018). This risk is especially increased during heatwaves for the energy poor, whose dwellings show high indoor air temperatures, impacting the performance of refrigerators, even in the absence of black or brownouts. Chillers and condensing units of air conditioners see their performance decrease with increasing temperature and humidity (Kabeel et al., 2017), and the same dynamic applies to photovoltaic solar panels (Skoplaki & Palyvos, 2009). Therefore, building-integrated PV may decrease the electricity output during heatwaves, thus resulting in increased demand from the power grid. As less solar radiation is converted into electricity, more is dissipated as heat, thus worsening the contribution of photovoltaic panels to urban overheating, as documented at utility scale (Ashley M. Broadbent et al., 2019).

The last of these highly non-linear dynamics relates to anthropogenic sensible heat and moisture, which is released into the built environment contributing to increases of the ambient air temperature and humidity (Sailor, 2011). Mesoscale climate modelling coupled to building models estimate an increase of the ambient temperature by 1-2 °C in peak conditions in most cities driven by exhaust heat from condensing units (Sailor, 2011; Salamanca et al., 2014). Instead, evaporative cooling towers can decrease urban temperatures, even by 1.5 °C in the evening, although with a substantial increase in specific humidity, which then may worsen thermal comfort and increase the energy needs for dehumidification (Y. Wang et al., 2018). During heatwaves, the release of anthropogenic heat from buildings may increase by more than 20%, of which more than 85% is contributed by air-conditioners (Luo et al., 2020), due to reduced efficiency and increased demand. Also, during heatwaves, air conditioners fail to provide comfort conditions or may not operate because of blackouts (B. Stone et al., 2021).

To design and manage building stocks for resiliency in the context of worsening urban overheating, it is necessary to manage them as connected systems rather than individual buildings. This vision, among other technological advancements, requires granular energy utility data to better understand and quantify interconnected impacts of urban energy systems. However, often utility datasets are neither easily accessible nor include appropriate and consistent contextualized metadata in non-smart grids (Nagasawa et al., 2013; Yu et al., 2015). Consequently, the development of district-scale electricity demand models capable of high-resolution assessments in different boundary conditions is complicated. Moreover, the uncertainty in the definition of the population in small areas is an intrinsic issue (Tayman, 2011), which prevents a detailed understanding of the semi-hourly demand, area by area (Bhattarai et al., 2019), without a widespread implementation of smart metering.

Realistic representation of the complex meteorological boundary conditions for building simulation has been addressed with increasingly convergent efforts by the building simulation and urban climatology communities (Ferrando et al., 2020). Still, practitioners consider shadowing by nearby buildings at most, with a deterministic input in response to a probabilistic problem, and use typical weather data from airports that exclude climate anomalies. Further, while heating energy needs can be robustly estimated with typical weather years, cooling energy needs are strongly affected by heatwaves, therefore resulting in a significant bias (Paolini et al., 2017). Practitioners also model individual buildings, despite the growing opportunities for urban energy modelling (Hong, Chen, et al., 2020). The availability of reliable 3-D stock models, now limited to a few cities (Evans et al., 2017), may overcome the limitations of archetypes (i.e., typical buildings) to represent the whole building stock (Ferrando et al., 2020). Additionally, urban energy codes could offer a pathway towards collaborative energy design of buildings, no longer treating buildings as stand-alone entities.

Perhaps the most significant gaps in model assessment of urban overheating impacts on urban energy (and vice versa) concern the interconnections of urban energy systems, especially at the neighbourhood scale. First, disentangling the connections between the layers of urban energy systems entails addressing a problem affected by high uncertainty, and focusing on the links between the different parts (Pappaccogli et al., 2020). Notably, the quantification of anthropogenic heat and moisture emissions is one of the terms in the urban energy balance showing the greatest variability depending on the model and assumption (Sailor, 2011; Y. Wang et al., 2018). Specifically, even very detailed bottom-up models (Hong, Ferrando, et al., 2020) do not take into consideration the thermal dissipation from different components of the electrical grids (e.g., transformers), which requires attention in the future.

On the other hand, the synergies between urban overheating and heatwaves have been investigated (Zhao et al., 2018), but the current framework does not support the quantification of the chain of effects involving the electrical grid, buildings, and air conditioning, which can lead to reduced energy performance and energy poverty. In fact, only a limited number of studies have addressed this frontier (Luo et al., 2020) despite its critical impact on health outcomes of overheating.

The second cluster of gaps relates to the fragmentation of the study of energy transformation and uses, social inequality, and spatial differentiation (Bouzarovski & Thomson, 2018). High cooling energy consumption in wealthy areas drives demand and energy prices, harshening energy poverty in less affluent and denser suburbs (Simshauser et al., 2011), where the vulnerable population is confined to thermally unsafe and inefficient buildings. Further, to achieve net-zero energy cities, net-zero energy users and constant metering are needed (Yan Zhang et al., 2018), motivating further research on citizen engagement together with technological advancements. Furthermore, climate extremes, and consequent blackout and brownout models need to inform the design process of urban energy systems, with a balanced approach to energy curtailment, and enforcement of maximum cooling set points during extreme heat events. Other possible solutions include heatwave shelters and energy sharing during non-extreme conditions, which can mitigate inequalities (Salvia & Morello, 2020), with people’s affiliation networks driving remarkable energy savings at building scale (Xu et al., 2012), especially in plug loads.

In conclusion, the urban energy problem should be reframed to support human health, in addition to reduction of energy use. Otherwise, there is a risk of further polarisation and increasing energy poverty (Santamouris, 2020), with only the wealthy dwelling in net-zero energy buildings equipped with on-site renewables. Cities should be designed and managed as complex systems, and while the single components have been developed, the response of the integrated model is not known. Therefore, to develop new knowledge, first, a new integrated energy space has to be developed so that new applied research can find novel opportunities and solutions to the energy problem.

5 Multidisciplinary solutions to address urban overheating

This section discusses the state-of-the-art methodologies and solutions for mitigating heat exposure, reducing sensitivity, and increasing adaptive capacities at the individual and city levels. We focus on cooling strategies that can be implemented in urban design (Sec. 5.1) or indoor spaces (Sec. 5.2) as well as urban heat governance (Sec. 5.3) needed to mitigate or adapt to this multi-faceted challenge.

5.1 Heat mitigation strategies integrated in urban design

Urban design and architecture have traditionally been developed to enhance immediate thermal environments of individuals, a design process that has since been obscured due to the prevalent use of air-conditioning and cheap fuel (Pearlmutter, 2007), exacerbating urban heat challenges in cities (Sec. 4.2). Inspired by traditional interventions and novel technologies, various heat mitigation methodologies have been developed over the last three or more decades (Akbari & Kolokotsa, 2016; Rosenfeld et al., 1995), aiming to decrease the local ambient temperature using solar control, reflective and green roofs (D. Li et al., 2014; Santamouris, 2014), urban greenery (Santamouris et al., 2018), water and irrigation (Coutts et al., 2013) and the use of light color materials for urban facades and pavements (Santamouris, 2013). Apart from these traditional methods, several new and efficient mitigation technologies presenting a high cooling capacity are developed and used in large scale urban projects. Most of the newly presented technologies deal with the development of advanced materials for the urban fabric and building envelope, as well as with scientific developments to enhance the cooling potential of urban greenery (Akbari et al., 2015). In parallel, significant new knowledge has been generated on the optimum use of water and evaporation systems in cities (Gao & Santamouris, 2019).

A combination of advanced and traditional mitigation technologies and systems can be considered in urban design, selected based on the urban morphology, local climate class, water availability, and seasonal climate variability. On average, it is feasible to decrease the peak air temperature of cities up to 2.5-3 °C (Feng et al., 2021; Santamouris et al., 2017a, 2020). Addition of green infrastructure often represents a re-integration of landscape elements better able to store precipitation and fuel evapotranspiration and reduce temperatures during hot spells. Examples include green roofs and green building facades, trees, and ground-level vegetation such as parks, lawns, and gardens (Bowler et al., 2010). Street trees not only evapotranspire, but provide shade to pedestrians, buildings, and heat-absorbing ground-level infrastructure, dramatically reducing radiation and consequently overall daytime heat exposure and nighttime heat release (Coutts et al., 2016; Oke, 1989). However, trees can warm temperatures at night (Gillner et al., 2015; Krayenhoff et al., 2020) and slow winds and prevent dispersion of pollutants emitted at ground level (Santiago et al., 2017; P. E. J. Vos et al., 2013), such as those from vehicle tailpipes, and interfere with subsurface infrastructure. Surface and air temperature cooling from green roofs and low vegetation, and to a lesser extent, trees, is critically dependent on adequate soil moisture, either from precipitation or irrigation (Heusinger et al., 2018; Krayenhoff et al., 2021). Nevertheless, to date there is evidence that urban trees are most effective for pedestrian-level cooling, followed by ground level vegetation, and finally by green roofs (Krayenhoff et al., 2021; Santamouris et al., 2017b; Shashua-Bar et al., 2009); however, green roofs can have greater impacts on building energy and/or internal thermal environments (Sailor et al., 2012). Reviews of vegetation cooling effectiveness suggest about 0.1-0.3°C of cooling per 0.1 plan area increase in vegetation area (Bowler et al., 2010; Krayenhoff et al., 2021). Recent observational results suggest that trees may reduce air temperature much more effectively as total canopy cover increases (Ziter et al., 2019).

Critically, each urban vegetation strategy has copious non-climatic benefits and, in some cases, select drawbacks, related to aesthetics, function, hydrology, health, historical context, etc, that will differ with local context (Krayenhoff et al., 2021; Santamouris et al., 2018). There is opportunity to better optimize urban vegetation combinations and arrangements accounting for all impacts, including adaptation to urban overheating.

However, the intensity of contemporary and especially projected urban overheating exceeds the potential of existing heat mitigation technologies, especially at night when the canopy urban heat island is maximized, and when heat mitigation approaches that rely on solar radiation (e.g., increased albedo or evapotranspiration) are less effective (Krayenhoff et al., 2018). This requires that we consider more efficient mitigation technologies with a considerably higher cooling capability. Therefore, achievements in the field of heat mitigating materials are the focus of the remaining discussion in this section.

Materials used in the urban fabric and building envelope absorb solar radiation, absorb and emit infrared radiation, store and release heat via conduction, and exchange heat with the air through convective processes. Materials that exhibit high radiation absorptivity have a high surface temperature during daytime, heating the ambient air, emitting large amounts of longwave radiation, and deteriorating thermal comfort. To decrease the materials' surface temperatures several principles are used separately or in a combined way:

- Increase the reflectivity of the materials in the visible, infrared or both parts of the solar radiation spectrum,
- Increase the thermal inertia of the materials (however, doing so warms evening and nighttime periods),
- Exploit fluorescent materials to enhance their thermal losses,
- Exploit chromic materials to adjust their reflectivity according to the climatic conditions,
- Increase the emissivity of the materials in the whole infrared spectrum, or
- Increase the emissivity of the materials in the so-called atmospheric window.

White artificial materials of extremely high reflectivity in the visible solar spectrum may present up to 6°C lower surface temperature than white natural materials like marble (Synnefa et al., 2006). However, reflectivity decreases considerably over time because of the deposition of dust and other atmospheric constituents and the effects of UV radiation. Near-infrared reflective colored materials present a much higher broadband solar reflectivity than conventional materials of the same color, increasing broadband reflectivity by up to four times (Levinson et al., 2005), and lowering surface (air) temperature by as much as 10°C (1.5°C) compared to conventional surfaces of the same color (Santamouris, 2016; Synnefa et al., 2007). Ageing and deposition of dust are issues that can potentially be mitigated by self-cleaning IR reflecting coatings (Kyriakodis & Santamouris, 2018).

The addition of phase change materials (PCM) in the mass of reflecting coatings, which store latent heat, can increase material thermal storage and consequently decrease the release of sensible and longwave heat, and reduce material surface temperature by up to 2.5°C (Karlessi et al., 2011). Use of thermochromic materials, which change color and reflectivity as a function of surface temperature, may be an excellent mitigation solution for temperate climates. Leuko dye-based thermochromic materials (Ma et al., 2001) are found to yield surface temperatures up to 22°C lower than conventional surfaces of the same color (Karlessi et al., 2009), however the use of optical filters is required to protect them when exposed to the sun (Karlessi & Santamouris, 2015). Modern chromic materials appear to provide a high potential for efficient deployment for cooling in cities (Garshasbi & Santamouris, 2019). Fluorescent materials absorb solar radiation and re-emit photons at longer wavelengths, enhancing thermal losses. Materials based on ruby fluorescent crystals, for example, showed surface temperature about 6.5°C lower than conventional samples (Berdahl et al., 2016). Preliminary testing of mitigation materials based on quantum dots, another chromic material, showed spectacular cooling effectiveness, however several problems with their ageing are yet to be solved (Garshasbi & Santamouris, 2019).

Daytime radiative cooling materials presenting an extremely high reflectivity to solar radiation and a very high emissivity in the atmospheric window can reach sub-ambient surface temperatures while sunlit (Zhai et al., 2017). Metamaterials, photonic, and plasmonic materials, when used to form active or passive daytime radiative cooling coatings and components, may present surface temperatures up to 17°C below ambient (Santamouris & Feng, 2018). Overcooling of surfaces during the winter period and reduced performance in humid climates seem to be the main limitations of this technology. The use of variable emissivity materials like PCMs to control the temporal variation of the emissivity of radiative coolers (Ono et al., 2018) may be an efficient way to overcome these problems.

Future Research Priorities

The emerging energy and environmental problems in cities that arise from regional and global climate change require optimal application of existing climate moderation strategies such as urban vegetation, combined with development and implementation of advanced technologies able to further enhance urban cooling.

<u>Development of innovative mitigation technologies.</u> Current mitigation technologies may decrease the peak ambient air temperature by up to 2.5 – 3.0°C Given the projected magnitude of urban overheating, research efforts should concentrate towards the development of more efficient mitigation technologies able to decrease peak ambient temperatures by up to 5°C. The main research priorities and developments should target the following areas:

- Development of sub-ambient temperature materials. Photonic and plasmonic technologies used for daytime radiative cooling exhibit large potential for functional improvement and technology simplification. Passive radiative cooling technologies in the form of paints, sprays or simple coatings may decrease the surface temperature of roofs and pavements up to 10°C below the ambient temperature. In parallel, the development of photonic shading devices can reduce surface temperatures (and associated mean radiant temperature; see Sec. 2.1) in open spaces, reduce the ambient temperature, and improve outdoor thermal comfort.
- Further development of fluorescent materials combined with thermochromic or photonic substrates may yield high cooling potential.
- Development of alternatives to leuco dyes thermochromic materials may be a high research priority. Recent research demonstrated that thermochromic quantum dots, plasmonics, photonic crystals, conjugated polymers, Schiff bases and liquid crystals offer fascinating and impressive mitigation characteristics and potential.

- More integrated analyses of plant ecology together with urban climate measurements and modeling, such that we understand the desired traits and locations of green infrastructures for relevant city climate and resources (such as access to water).
- Continued re-integration of vegetation into urban landscapes, including tree planting, green roofs, and added ground-level vegetation, particularly when it provides co-benefits (e.g., recreational greenspace, urban agriculture, etc).
- Continued research into effective methods for cooling cities during evening and nighttime.

Large scale urban projects demonstrating the use of efficient technologies may further enhance our knowledge and understanding of the best way to implement these new technologies for improved heat resilience. Additionally, the specific impact and the potential improvements achieved through the implementation of efficient mitigation technologies have to be assessed through well defined evaluation protocols to better understand their impact.

5.2 Indoor thermal environment and innovative cooling strategies

In addition to mitigating overheating outdoors, it is important to quantify and address indoor thermal exposure to minimize the negative impacts on humans. In the United States, for example, people spend 90% of their time indoors, on average (US Environmental Protection Agency, 1989). Even in moderate heat periods, people may experience elevated indoor temperatures in both workplace and residential buildings (Kjellstrom & Crowe, 2011; Uejio et al., 2016; White-Newsome et al., 2012), which could lead to significant impacts on people's health, safety, finances, and well-being (Sec. 4).

Raising outdoor air temperature increases the indoor air temperature and/or the energy demand for cooling. The relationship between outdoor and indoor temperatures is influenced by many factors, such as building design and operation (e.g., full glass building vs well insulated building with external shading device) and cooling strategy (e.g., air-conditioned vs naturally ventilated buildings). The ASHRAE Global Thermal Comfort Database II (Földváry Ličina et al., 2018) is largest thermal comfort field survey database that can provide insight on how the outdoor air temperature (T_o) is related to the indoor air temperature (T_a) in both air conditioned and naturally ventilated buildings (Fig. 5). From simple weighted linear regressions, we find an increment of 0.1 °C and 0.4 °C, respectively for air conditioned and naturally ventilated buildings, for every degree Celsius increment in outdoor temperature. It is clear that indoor temperature can be regulated through heating and cooling in air-conditioned buildings regardless of the outdoor environments; but a slope of ~0.4 in naturally ventilated buildings suggests that the indoor temperature does not follow exactly the outdoor conditions. We observe with concern that in some naturally ventilated buildings (above the yellow dotted line in Fig. 5), the indoor temperature is higher than the outdoor temperature, which itself is elevated. This indicates that outdoor temperature may in some cases underestimate the overheating exposure and that there exist other heat sources that are yet to be characterized.

Indoor temperature is increased by heat gains via conduction from the building envelope, convection from outdoor hot air, direct or indirect solar radiation through windows and openings, and heat released from occupants and equipment within the space. Indoor overheating challenges, particularly for vulnerable and socio-economically-disadvantaged urban populations, are more likely to occur in thermally-inefficient buildings (Sect 4.1). Thermal exposure perceived by humans, however, does not only link to air temperature, it also relates to mean radiant temperature, relative humidity, airspeed, and occupant's clothing insulation and activity level (Fanger, 1970; Standard 55, 2017). Moreover, as noted in Sec. 4.2, it is important to assess the ability of a building to provide passive survivability during extended power outages in peak summer conditions (LEED BD+C, 2021).

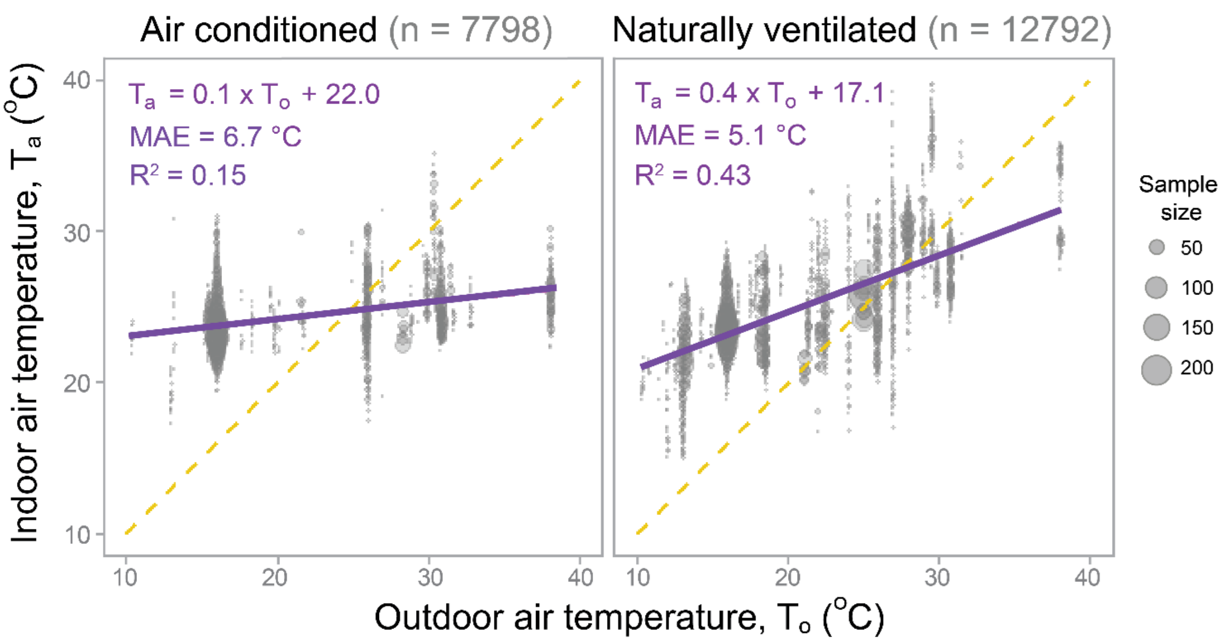

Figure 5. Indoor and outdoor air temperature relationships in air conditioned and naturally ventilated buildings obtained from the ASHRAE Global Thermal Comfort Database II (Földváry Ličina et al., 2018). The yellow dotted line indicates the hypothetical line where $T_o=T_a$. n indicates the number of measurements.

Indoor heat exposure can be minimized by two major strategies: Reduce heat gains and actively remove indoor thermal load. Heat gains can be reduced by building design and effective operation with established strategies, for example: avoid direct solar heat by altering building orientation (Axaopoulos et al., 2014), block solar radiation by installing outside shading (Cheung et al., 2005; Chua & Chou, 2010), reduce heat gain by applying insulation in the building façade (Fang et al., 2014; Schiavoni et al., 2016) and install cool roofs or green roofs (Junjing Yang et al., 2018), use high performance glazing (Karlsson & Roos, 2001), and maximize natural ventilation to remove indoor heat by advanced building design and control (Etheridge, 2011). There are also more innovative solutions not yet ready for implementation, such as terrestrial radiative cooling (X. Yin et al., 2020; M. Zhou et al., 2021) and cooling textiles (Hsu et al., 2017; Zeng et al., 2021).

Air conditioning is most effective in removing indoor heat load and regulating the indoor environment, but its applicability is limited by financial and resource constraints, especially for mid- and low-income communities, and by the possibility of power outages during heat waves. Moreover, air conditioning has a high negative environmental impact. It is energy intensive, and it releases heat to the outdoors, increasing temperature at different scales (Sect 4.2). It also increases pollution from refrigerants, and if the space is not ventilated, it leads to high indoor CO-2 levels if people close windows to save energy (Dahl, 2013; Gall et al., 2016).

In practice, there are several energy efficient strategies that can reduce cooling loads and relieve occupants' thermal discomfort in buildings, for example: thermal mass and storage (Faraj et al., 2020; Yau & Rismanchi, 2012), evaporative cooling (Y. Yang et al., 2019), free cooling at night

(Solgi et al., 2018), and water- / air-side economizers (Habibi Khalaj & Halgamuge, 2017; Ham et al., 2015). Among all potential strategies, an affordable, effective, scalable and market-ready solution is to increase air movement in built environments with fans in both indoor and outdoor areas (Jay et al., 2019). Subjective thermal discomfort under a high temperature environment can be offset by an elevated air speed due to the fan-generated cooling effect (Arens et al., 1998; Schiavon & Melikov, 2009; Tanabe et al., 1993). The increased air movement is perceived as pleasant and is aligned with the physiological principle of alliesthesia (Cabanac, 1971; Parkinson & de Dear, 2015). The main advantage of this solution is that the energy used to increase air speed is much lower than the energy used to lower the temperature while maintaining an equivalent thermal comfort condition (Hoyt et al., 2015; Rim et al., 2015; Schiavon & Melikov, 2008). It may also potentially provide better air quality (Pantelic et al., 2020). In addition, this solution can be easily adapted to different ventilation types (i.e., air-conditioning, natural ventilation or mixed mode) in both new and existing buildings. Evidence from the literature suggested occupants were thermally more satisfied in a condition of higher indoor air temperature (e.g. 26 °C) with fans than a condition of lower air temperature (e.g. 23 °C) without fan, in both a climatic chamber experiment (Schiavon et al., 2017) and a field study (Lipczynska et al., 2018).

Despite the energy saving benefits and increased occupant satisfaction, we find that the implementation of this higher temperature cooling with elevated air movement strategy is not common in commercial buildings, while it is in residential buildings. Possible barriers could relate to air-conditioning being perceived to be of a higher quality than fans (Chappells & Shove, 2005; Lorch & Cole, 2003), the aesthetic concerns related to having an object spinning in the space, the reduced effectiveness of convection for occupants with formal office dress (e.g. long sleeve and trousers) (Holmér et al., 1999) the lack of open source guidelines to inform adequate elevated airspeed system design, and operation and maintenance concerns (noise, dust and wobbling) (Present et al., 2019). To address the benefit of fan usage, more research regarding elevated airspeed cooling strategies in different building types and climate zones are needed to demonstrate their efficacy with respect to energy efficiency and indoor thermal comfort improvement. In addition, practical guidelines should be developed to encourage system deployment in actual buildings and facilitate building practitioners' needs.

5.3 Addressing sensitivity and adaptive capacity: Governance, policy, and citizen engagement

The wide suite of impacts of overheating on urban systems, as well as the array of tools and solutions for understanding and reducing adverse impacts, raises important questions related to governance and community engagement. Among them: Which actors and institutions are responsible for the governance of urban overheating? How do they interact with each other, and with the public at large? What is the contemporary state of urban overheating governance, and what may be in store for the future?

Conceptually, governance of urban overheating can be framed as an extension of—or perhaps even an explicit component of—climate change governance more broadly defined (Fröhlich & Knieling, 2013). In the case of urban overheating, the drivers and impacts of climate change occur at local and regional scales, rather than global, which alters the magnitude of collective action challenges posed for global climate change mitigation and adaptation (Georgescu, 2015; Georgescu et al., 2014; Jay et al., 2021). However, many other governance challenges for urban overheating closely parallel those framed for global climate change, including those related to geographic scale and boundaries, participation and needs of a wide range of sectors and stakeholders, time horizons for decision-making, and uncertainty (Fröhlich & Knieling, 2013). Urban overheating governance can also be framed as an aspect of climate adaptation, for which a rich suite of definitions, conceptual models, and theories have been proposed (Keith et al., 2021; Moser & Ekstrom, 2010).

Within climate adaptation literature, scholars are increasingly examining barriers to effective adaptation. Among the barriers particularly relevant to urban heating are those related to authority, responsibility, agreement, resources, and path dependency (following (Moser & Ekstrom, 2010)). While public sector leaders are in many cases detecting problems related to urban overheating, and indicating that those problems are crossing thresholds for concern and response needs, tackling urban overheating remains a relatively new challenge for traditional governance actors. As such, ambiguity regarding responsibility and accountability structures, access to financial, human, and regulatory resources, and a legacy of institutional non-attention to problems associated with urban overheating, are hindrances to successful implementation that many actors have yet to overcome (Keith et al., 2019). While preferred models for urban overheating governance have not yet been clearly articulated, it is clear that any contemporary models are relatively immature compared with those established for other chronic environmental hazards, including air pollution (e.g., strong national to local regulatory structures, financial incentives, and explicitly named responsible governance institutions) (Keith et al., 2021), and noise (e.g., local regulatory structures, workplace protections).

Contemporary examples of urban overheating governance reflect attention to two key impact domains —health and energy. At the international scale, the World Health Organization and World Meteorological Organization have collaboratively authored guidance for implementation of heat-health warning systems, which aim to lessen the public health burden of heat events even beyond the urban context (McGregor et al., 2015). There is widespread evidence of local implementation of such systems (Casanueva et al., 2019; Hajat, Sheridan, et al., 2010; Hess & Ebi, 2016). National governments and non-governmental organizations have also offered a wide range of guidance documents and technical assistance related to management of various aspects of urban overheating, including implementation of urban heat countermeasures and health-protective resources (as detailed in several use cases compiled by (Global Heat Health Information Network, 2020)). At the local scale, some jurisdictions have produced different types of planning documents and strategies for tackling aspects of urban overheating, and in some cases these documents are approved by a local commission or council, with varying degrees of regulatory authority (e.g., (Ahmedabad Heat Action Plan, 2016; The Nature Conservancy, n.d.). In other cases, regulations and ordinances related to urban overheating appear in a more ad hoc nature in local policy, and elsewhere, measures related to urban overheating are included as components of broader plans, including general plans, sustainability plans, and/or resilience plans (Gabbe et al., 2021). Yet it is also clear in examination of local efforts to govern urban overheating that tensions and barriers arise that are consistent with those identified in the climate change governance and adaptation literature. Among them, (Mees et al., 2015) and (Guyer et al., 2019) report disagreement and ambiguity in practitioners' understanding of their roles and responsibilities with respect to urban climate governance. (Mahlkow et al., 2016) suggest challenges with respect to authority of urban development in the context of urban overheating and the ability of governance actors to influence those processes. (Birkmann et al., 2010) further posit that these tensions and barriers may be particularly impactful in the context of developing countries, where rapid population and infrastructure growth create even greater challenges for coordinated and comprehensive governance.

While literature continues to accumulate related to how urban overheating governance is functioning today, there are many examples of historical analyses, modeling studies, and visioning and scenario exercises from which recommendations can be drawn regarding how urban overheating governance could evolve in the future. There is now relatively widespread acknowledgement that urban overheating is another lens by which inequities in urban systems are revealed. Governance actors must recognize that contemporary conditions are products of legacies of planning and investment that did not sufficiently prepare cities for challenges they currently face with respect to urban overheating, especially for historically marginalized communities (Grineski et al., 2015; Harlan et al., 2007; Wilson, 2020). In some cases, actors working today to reduce the challenges of urban overheating must reverse the legacy effects of intentional practices that placed certain populations at greater risk of harm from heat and other environmental hazards (Harlan et al., 2019; Wilson, 2020). Beyond acknowledging and reducing the total and inequitable distribution of harms associated with urban overheating, public leaders are also challenged to improve engagement strategies in the pursuit of participatory justice (Baldwin, 2020; Chu & Cannon, 2021). Residents who have been excluded from decision-making processes in the past can and should meaningfully contribute to the planning and implementation of urban overheating solutions moving forward, bringing critical domain expertise from their lived experience (Guardaro et al., 2020; Marschütz et al., 2020). Scenario planning and visioning workshops have shown promise as a tool for both engagement and shaping governance strategies related to the future of urban climates (Iwaniec et al., 2020). Participation of the private sector and private landowners in the implementation of urban overheating countermeasures will be critical, owing to the relatively limited spatial extent of land owned by governmental agencies in many urban settings. Public-private partnerships, financing and incentive mechanisms, and other tools that accelerate collaboration may all accelerate the timeline for realizing solutions to urban overheating. The role of technology, specifically concerning ubiquitous sensing and Internet-of-Things connectivity will need to be carefully balanced (Sec. 2.3). Governance actors can benefit from access to increasingly precise data about urban climates and urban systems that influence and are influenced by the urban climate (Hamstead et al., 2020; Hondula et al., 2015; Y. Yin et al., 2020), but widespread sensing raises potential social and legal challenges concerning privacy and security, institutionalization of bias, and more. Given the complexities and interrelationships of the challenges associated with urban overheating, adaptive governance may be the most promising model for localities to adopt as they move forward. Adaptive governance embraces principles of iteration, flexibility, and learning, and has been advocated as an appropriate model in the context of urban heat (Hess et al., 2012) and other urban environmental domains including ecology (O. Green et al., 2016) and water (Bettini et al., 2013; Larson et al., 2015). Finally, as jurisdictions continue to evolve their approaches to governing urban overheating, we encourage attention to the "five Ws" for urban resilience posed by (Meerow & Newell, 2019). Efforts to address urban overheating cannot be detached from the underlying socio-political structures and processes that shape cities. As such, all involved in efforts to address urban overheating must consider for whom, what, when, where, and why those efforts are being directed.

6 Conclusions and key ways forward

We provide the first integrated outlook for characterizing, evaluating, and addressing overheating in existing and future cities. We discuss how overheating exposure is characterized using different observational and numerical methodologies across different scales (ranging from human to street and city scales). At the human scale, we then detail several physiological and psychological pathways that lead to individual sensitivities to overheating, as well as adaptive capacities that can be promoted to reduce sensitivity or exposure. At the population level, the key impacts of overheating on health and urban energy are documented for vulnerable groups. Lastly, we discuss state-of-the-art methodologies as well as future approaches and solutions in urban planning and governance that aim to address this multi-faceted challenge by mitigating exposure, reducing sensitivity, and increasing adaptive capacities at the individual and city levels.

Key priorities to better assess overheating impacts as well as potential solutions can be condensed into seven multidisciplinary **research directions**:

1. **Develop a new paradigm for heat exposure characterization:** More comprehensive characterization of heat exposure in cities is an ongoing focus in research. While both measurements and modeling practices need to quantify overheating at higher spatial and temporal resolutions, it is critical that exposure is better characterized focused on where people are located, encompassing more diverse and targeted indoor and outdoor spaces. Additionally, metrics and indicators that fully characterize heat exposure (including relevant meteorological factors such as wind and radiation, as well as duration and intensity of exposure) should be integrated into sensing and modeling of thermal environments based on fit-for-purpose evaluations.

2. **Determine adaptive capacities at the individual level to reduce exposure and sensitivity:** Future research should provide a more expansive and inclusive knowledge of the physiological and psychological/behavioral pathways that lead to increased sensitivity and exposure of individuals and populations. This knowledge can then inform the evaluation of adaptive capacities that can be afforded at the individual level to reduce either sensitivity or exposure. Inclusive evaluations include consideration of different clusters of personal or professional profiles (covering different professions, health conditions, and socioeconomic status) that may be more vulnerable to heat exposure.

3. **Prioritize personal heat exposure assessment over one-size-fits-all approaches:** More human-centric assessment of heat exposure, i.e. personal heat exposure, is a key priority in several subfields. A ‘receptor-oriented’ approach to heat is suggested, in contrast with existing ‘source-oriented’ assessments, to quantify the heat exposure in the immediate environment of humans as well as the impacts on human comfort, performance, well-being, and health. Future research in personal heat exposure requires not only targeted spatial coverage in data collection and modeling, but also better integration of knowledge and datasets that detail behavioral patterns and individual sensitivities in response to heat.

4. **Quantify the indirect health and wellbeing outcomes of overheating:** More human-centric assessment of heat exposure permits quantification of the links between heat exposure and indirect health and wellbeing outcomes. Empirical verification of causal links between urban heat and residents’ behavior, their sedentariness, and heat-health impacts at the level of the individual and the urban population at large are essential directions for future research, such that evidence-based urban planning and policy can be more broadly effective at maintaining and enhancing well-being in a warming urban world.

5. **Develop equitable urban energy systems for human health and wellbeing:** For a more integrated assessment of overheating and urban energy, future research should consider the non-linear interactions between overheating and urban energy systems - involving electrical grids, buildings, equipment, energy production (e.g., photovoltaics), and air conditioning - that lead to reduced energy performance and energy poverty with adverse effects on heat exposure

indoors. In other words, urban energy research should be framed to better support human health, particularly in vulnerable populations, moving beyond the focus on building-level energy computation or city-level CO2 emissions.

6. **Develop guidelines for heat mitigation and adaptation strategies:** In addition to the continued development of novel materials and strategies with greater cooling potential, future research should focus on the development of regionally- and climatically-adaptive guidelines that optimally combine infrastructure-based heat mitigation strategies (e.g., green infrastructure, cool materials) and heat adaptation strategies (e.g., cooling centers), considering multi-faceted impacts of urban canopy air temperature, wind, humidity, and radiation on buildings, pedestrians and air quality. The efficacy of these guidelines should be evaluated in the context of contemporary and future extreme heat, and additionally with respect to their performance in cooler seasons. Further development of infrastructure-based approaches for evening and nighttime cooling are also important.

7. **Expand time and space horizons in overheating analyses:** In many research directions noted above, there is a need to consider global assessments of municipal-level temperatures and extreme heat levels (beyond air temperature) under different global climate change and urban development scenarios during the period 2030-2080. Furthermore, future research should focus on areas with high (current and projected) urbanization in developing countries as well as informal settlements that have traditionally been neglected in the urban climate literature. An estimated 25% of the world’s urban population live in informal settlements and slums (UN-Habitat, 2013) with distinct urban climate characteristics, design, and sensitivity profiles to heat that have not been documented before. This calls for urgent attention in future research, further contributing to global environmental justice with regards to heat.

Additionally, further advancements in **research tools and methods** are needed to achieve the emerging research directions, including:

I. **Evaluate and advance smart technologies for heat exposure assessments:** The emerging IoT/ubiquitous sensing field can overcome the limitations of conventional methods to provide real-time and high-resolution/personalized heat exposure data, but still requires more focus on combining different sources of data (particularly on human behavior, activity, response) to holistically quantify exposure and health outcomes. To do this, we need technological, scientific, and societal advancements as well as open-access datasets, algorithms,and analytics that ensure not only data quality and completeness, but also digital inclusion and privacy.

II. **Develop high fidelity climate models suitable for integrated system analyses:** Overall, climate models should focus more on the multidisciplinarity of heat exposure, integrating existing knowledge from urban climatology, plant ecology, energy system analyses, and behavioral modeling to better uncover synergies, co-benefits and tradeoffs in drivers of overheating and associated adaptive responses. Furthermore, better numerical representation of infrastructure-based heat mitigation strategies is needed to inform urban and building design in practice. Finally, simulation studies should make increased efforts to quantify uncertainties in projected overheating and heat mitigation effectiveness.

Furthermore, we summarize existing **priorities for policymakers, planners, and government managers**, such that we address, mitigate, or adapt to overheating challenges in current and future cities:

a. **Implement strategies for climate change mitigation**: It is critical that we continue to reduce greenhouse gas emissions (from transportation, building, and other sectors), plant trees, and undertake related climate mitigation strategies locally and abroad, to help reduce long-term global climate warming and the intensity, frequency, and duration of future extreme heat events.

b. **Implement strategies to cool the built environment:** In addition to large-scale climate change mitigation strategies, implementing street- to city-scale cooling strategies (including green and blue infrastructure and advanced materials) in harmony with local climate and resources are critical for mitigating the intensity of urban overheating, particularly in ways that target heat where vulnerable populations reside and work and that are developed collaboratively with local residents.

c. **Provide behavioral options for reducing exposure:** Adaptive opportunities should be considered in urban design such that individuals can reduce their heat exposure as they go about their lives in the city. In this context, **strategies should focus on changing the environment to provide behavioral options for reducing heat exposure in addition to cooling the built environment.** These options range from local design elements such as cool furniture or green and blue infrastructures to building cool refuges for reducing the duration of heat exposure. These strategies should be implemented in collaboration with local residents and initially focus on neighborhoods with the highest densities of heat-vulnerable individuals.

d. **Provide evidence-based personalized heat-health advisories:** Building on personal heat exposure assessments, evidence-based heat-health advisories can be developed that are suitable for identifying optimal personalized heat risk mitigation strategies for sensitive individuals, as opposed to taking a one-size-fits-all approach. This can further lead to city-specific early-warning and response systems for heat extremes that are supported by heat vulnerability maps and more tailored to specific individuals.

e. **Provide personal recommendation systems to reduce heat exposure:** Human-centric data collection in the built environment can further promote personalized recommendation systems to enable more adaptive capacities for individuals, i.e. avoiding the heat by different routes or adjusting activity level to overheating intensity.

f. **Promote and incentivize the use of sustainable heat adaptation solutions:** While promoting cooling strategies in cities, it is also critical to overcome the barriers related to the use of more energy-efficient and sustainable adaptation solutions, such as fans for indoor cooling or shading for outdoor cooling. These barriers may relate to various aspects ranging from perceived effectiveness to aesthetic concerns that can be overcome through more public engagement and education.

g. **Future directions for policy and governance**: Developing urban overheating governance, in combination with climate change governance and policy across different scales, is one of the most critical pathways for reducing negative impacts of overheating on human life. These governance frameworks should embrace principles of iteration, flexibility, and learning, i.e., adaptive governance, and integrate engagement strategies in the pursuit of participatory justice, allowing residents to bring critical domain expertise from their lived experience. Moreover, legacy effects of practices that placed certain populations at greater risk of harm from heat and other environmental hazards must be identified and rectified.

The present work describes a multidisciplinary outlook on urban overheating research and application, while detailing several existing gaps that are yet to be addressed. In addition to knowledge gaps detailed here, it's critical to note that economic assessments of urban overheating (covering a holistic calculation of economic burden of impacts as well as cost-benefit analyses of various overheating countermeasures) are yet to be fully determined and have not been addressed here.

Furthermore, the primary focus of this contribution has been on understanding and responding to overheating challenges, depicting cities as the epicentre of the developing situation. While this view accurately reflects contemporary and projected urban climates in the context of ongoing climate change and urbanization, alternative perspectives should not be overlooked. Responding to increasing temperatures, cities can potentially be envisioned as places of refuge from overheating and extreme events, where more thermally acceptable conditions can be achieved through climate-sensitive design and planning. Cities have the opportunity to cool built environments more than surrounding rural areas especially during afternoon periods when potential heat exposure is maximum (for instance, taking advantage of urban shading and ventilation that have long been embedded in traditional architecture), and in doing so, can influence a larger number of inhabitants due to higher population densities. Urban areas may also provide opportunities to host outdoor workers (for instance, in urban agriculture) that can benefit from cooling mitigation and adaptation strategies otherwise not afforded in non-urban areas. Accordingly, further research and implementation measures are needed to assess the opportunities embedded in cities to expose fewer people to projected overheating and climate extremes.

Data Availability Statement

No dataset was used to prepare this manuscript.

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