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Abstract

Overheating of cities increases the cooling energy consumption of buildings and the corresponding peak electricity demand. Advanced urban heat mitigation technologies that involve the use of super cool photonic materials combined with properly designed green infrastructure, lower the urban ambient and land surface temperatures and reduce the cooling energy consumption at the city scale. Here, we present and report the results of the world's largest heat mitigation project in Riyadh, KSA. Daytime radiative coolers as well as cool and super cool materials combined with irrigated or non-irrigated greenery, have been used to design eight holistic and integrated heat mitigation scenarios, properly assessed by mesoscale climatic models covering the whole city. We assessed the impact of the scenarios as well as the corresponding energy benefits of 3323 residential and commercial urban buildings. An impressive average decrease of the peak ambient temperature, up to 4.5°C, is calculated, for the 3323 consisting of the highest reported urban cooling performance, while the cooling degree hours in the city decrease by up to 26%. We found that innovative urban heat mitigation strategies contribute to remarkable cooling energy conservation by up to 16%, while the combined implementation of heat mitigation and energy adaptation technologies result in a decrease in the cooling demand by up to 35%. It is the first article investigating and reporting the large-scale energy benefits of modern heat mitigation technologies implemented in large cities, the dynamic and complex interdependencies between urban buildings and the urban environment as well as the suitability and the corresponding cooling and energy conservation potential of current and advanced heat mitigation technologies. It finally explores pathways to optimise urban heat mitigation and the related energy conservation strategies in cities.

Keywords: Building energy use, Urban building energy modelling, Building performance simulation, Mitigation and adaptation strategies, Advanced heat mitigation technologies

1. Introduction

Cities are one of the largest energy consuming groups and emitters of greenhouse gases in the world [1]. Urban areas offer a large potential for improvement of energy efficiency and reduction of greenhouse gases [2]. Cities exhibit higher temperatures than the surrounding areas because of their positive thermal balance [3]. Global climate change is synergistically affecting the urban temperature, increasing the magnitude of overheating [4,5]. About 13000 cities are exhibiting overheating problems up to 10.0°C, while more than 1.7 billion people live under severe overheating conditions [6,7].

Urban overheating has a serious impact on humans [8]. It increases both the cooling energy consumption of buildings and the peak electricity demand obliging utilities to build additional power plants, decreases human productivity, increases the concentration of the ground ozone, and surges heat-related mortality and morbidity while it intensifies human aggressivity and mental health problems [8], Supplement1.

Projections about the future urban climatic conditions shown that the minimum and maximum temperatures may increase substantially [9]. The projected increase of the minimum nighttime temperature may be as high as 4.0°C [10, 11], combined with a significant increase in exposure to heat waves and ground-level ozone [12, 13]. As a result, the buildings cooling energy consumption may increase between 250-1000% with the range depending on the global economic and technological developments [14].

To counterbalance the impact of urban overheating, efficient heat mitigation technologies must be implemented at the city scale. Heat mitigation research has provided innovative technologies that decrease the urban temperature substantially [15]. It is reasonably expected that the development of photonic daytime radiative cooling materials for buildings and urban structures, combined with optimised greenery solutions can substantially mitigate urban heat [16-18].

As buildings are responsible for about one-third of global energy consumption, improving building energy efficiency offers a significant opportunity to make cities more sustainable environments [19]. It is, thus, important to investigate strategies to reduce energy use and the corresponding environmental impacts.

Very little is known about the contribution of the innovative heat mitigation technologies on the climate of cities and the related energy saving potential. Studies assessing the cooling potential of conventional reflecting materials show that it is rational to achieve a drop of the peak ambient temperature up to 1.5°C and a decrease of the cooling energy demand between 15 to 35%, as a function of the climatic characteristics and the quality of the building stock [20, 21].

Given the limited number of the existing large-scale heat mitigation projects and the absence of detailed assessment studies, there is a serious lack of knowledge about the exact climatic contribution and the energy impact the innovative heat mitigation technologies and their potential combined implementation.

This article presents the methodology, characteristics, and results of the largest, to our knowledge, world urban heat mitigation project designed for the city of Riyadh, Saudi Arabia. It provides, for the first time, innovative information on a) the assessed climatic capacity of the developed innovative heat mitigation technologies and their combination, and b) their energy potential at the city scale as evaluated for a very high number, 3323, of urban buildings.

This paper delves into the compelling relationship between urban heat mitigation and energy conservation, exploring the various strategies employed to counter the rising temperatures in cities and their substantial contributions to promoting energy efficiency, sustainability, and urban resilience. Through a comprehensive analysis of the multifaceted impacts of mitigating urban heat, this study sheds light on the pivotal role such measures play in creating more liveable, energy-efficient urban environments. We believe that the article will contribute substantially to properly designing heat mitigation in cities, assess their energy potential, and contribute to improved living conditions, sustainable urban development, and urban resilience.

2. RESULTS

We assessed the distribution of the urban heat risk in the city using the methodology described in Methods.

2.1 Design of The Mitigation Strategy

The detailed analysis of the current climatic and heat risk conditions in Riyadh described in Methods, reveals that the main axes of the potential interventions to mitigate urban heat in Riyadh should aim to: a) decrease the surface, LST, and ambient temperature and reduce the heat advection from the surrounding desert, b) reduce the strength of the sensible heat in the city, c) surge the magnitude of latent heat, d) improve solar control in the city [22]

We designed and evaluated eight mitigation scenarios focusing on the above objectives, Table 1. To decrease the surface temperature in the city and reduce the release of sensible heat, reflective materials as well as passive daytime radiative cooling coatings are considered. Reflective materials are commercially available and present a high solar reflectance and a high broadband emittance and contribute to reducing the LST up to 10.0°C [23]. Super cool materials, (SCM), or photonic daytime radiative cooling coatings, are recently developed. Super Cool Coatings exhibit sub-ambient surface temperatures and depending on the local climatic conditions can reduce the surface temperature of cities up to 15.0°C [16]. By lowering the urban surface temperature, the height of the planetary boundary layer may decrease, resulting in reduced heat advection from the desert [24].

An increase in the green infrastructure in cities provides solar control and decreases the release of sensible heat, while it enhances latent heat through evapotranspiration [18]. The cooling efficacy of urban greenery under high ambient temperatures, like in Riyadh, depends highly on the proper provision of irrigation [25]. Above a threshold ambient temperature and under low watering conditions, the magnitude of evapotranspiration is reduced significantly, while the released Biogenic Volatile Compounds, BVOCs, may surge, resulting in serious air quality problems [26].

Combined scenarios considering the implementation of both reflective or super cool materials with additional irrigated or non-irrigated greenery are designed and evaluated through mesoscale climatic modelling. Table 2 provides the calculated cooling performance and the corresponding mitigation potential regarding the ambient and surface temperatures for the eight scenarios. In addition, Table S2-1 provides the calculated Mean, Maximum and Minimum average values of the main climatic parameters for the reference and the 8 mitigation scenarios. Table S2-2 presents the number of hours that the average temperature in Riyadh is above a threshold as well as the corresponding value of the Cooling Degree Hours during the whole summer period.

Analysis of the performance of the eight mitigation scenarios leads to the following main findings:

a) An almost linear association between the reference temperature (no mitigation) and the potential temperature decrease is observed for both day and night periods. This is because mitigation technologies decrease the released sensible heat which is almost a linear function of the ambient temperature. In general, and for all the mitigation scenarios, the higher the background temperature, the higher the potential temperature decrease. Figure S2-1 demonstrates the relation of the background temperature with the temperature drop for both the day and night and for the scenario 'Very Reflective Riyadh'.

b) The implementation of the super cool materials on the roofs of the buildings, combined with well-irrigated additional greenery, provides exceptional mitigation potential and contributes to the reduction of the average 24 h ambient urban temperature between 1.3°C to 7.5°C with an average close to 4.2°C. The corresponding decrease of the ambient temperature at 2:00 pm varies between 0.0°C to 3.0°C, with an average close to 1.4°C, while at 6:00 am the change of ambient temperature varies between an increase of 2.8°C and a decrease of 8.6°C, with an average close to 3°C. The reduction of the surface temperature in the city at 14:00 varies between 3.5°C to 7.3°C with an average close to 4°C. During the whole summer period, the decrease of the overheating hours above 35°C and 40°C is 23.1% and 29.4%, respectively, while the decrease of the Cooling Degree Hours, CDH, base 35°C and 40°C is 28.4% and 47.6% respectively.

c) Moderate increase of the low-level non-irrigated greenery at the city scale has a limited cooling capacity during daytime, while it may even increase slightly the temperature. This is because the top layer soil moisture decreases due to the lack of precipitation. By increasing the vegetation cover, the moisture level continues to decrease because of the larger surface of evapotranspiration. Under such soil moisture conditions, low-level vegetation with shallow roots can no longer evaporate effectively and plants cannot release latent heat, resulting in a very limited decrease or even increase of the daytime ambient temperature. Similar results were reported in [27] for Los Angeles, where it was demonstrated that replacing existing plants with drought-tolerant plants without irrigation prevents plants to relieve UHI and heat wave conditions. During the night, the cooling contribution of low-level non-irrigated greenery is more significant as plants reduce the upward heat flux from the ground, resulting in a cooler soil surface. The average nighttime temperature decrease may reach 3.0°C, in full agreement with many similar studies reporting the cooling potential of greenery in cities [28].

d) A significant increase in the cooling potential of urban greenery is observed when high-level irrigated trees are considered. The average ambient 24 h temperature is found to decrease between 0.4°C and 7.2°C with an average close to 3.5°C. The average decrease of the ambient temperature at 2:00 pm and 6:00 am is 0.6°C and 2.1°C, respectively. The overheating hours above 35.0°C and 40.0°C decrease by up to 19.1% and 14.1%, respectively, while the decrease of the cooling degree hours is 17.1% and 21.5%, respectively.

e) Although non-irrigated vegetation shows a cooling effect at night, is not effective in reducing CDHs during the daytime. Non-irrigated vegetation leads to slightly higher CDHs, base 38 C, compared to the reference scenario, while irrigated vegetation reduces CDHs during the day. Shading and evapotranspiration contribute most to the cooling effect of vegetation. The denser the plant canopy, the higher the cooling potential, as long as plants are sufficiently supplied with water. The cooling potential of trees and other vegetation is severely reduced under dry conditions when soil water is limited, which results in drought stress to the plants and lower evapotranspiration. The variation of the CDHs during the day and night-time for different base temperatures is shown in Figure S2-2.

f) An increase of the urban albedo decreases the peak daytime ambient temperature between 0.2°C and 2.2°C with an average close to 1.2°C, while the corresponding decrease of the LST is 4.8°C. Reflecting materials decrease the CDHs, base temperatures 35.0°C and 40.0°C, by 19.5% and 47.6%, respectively, while the corresponding decrease of overheating hours is 7.0% and 24.1%.

g) Implementation of passive daytime radiative cooling materials on the roofs of buildings presents a very significant heat mitigation potential because of the high reflectance and the high emissivity in the atmospheric window decreasing the peak ambient temperature at 2:00 pm between 0.3°C to 2.3°C with an average of 1.3°C, and the LST by 6.6°C. Super cool materials contribute to the decrease of the CDHs, base temperatures 35.0°C and 40.0°C, by 21.9 % and 50.8%, respectively, while the corresponding decrease of the overheating hours is 8% and 28.1%. Given the very high reflectance of the super cool materials, their use should be limited on the roof of buildings to avoid optical annoyance problems.

2.4 Impact of Heat Mitigation Technologies on the Cooling Energy Consumption of Buildings

Using the CityBES simulation platform, the cooling energy consumption of 3323 buildings located in the Al Masiaf precinct of Riyadh is evaluated for the whole summer period using weather files corresponding to the current climatic conditions as well as to the eight designed mitigation scenarios.

The average summertime cooling load of all the buildings, COP=1, is 104.6 kWh/m^2. The total summertime cooling load of all buildings is 222.3 GWh. As expected, the taller the building, the lower the cooling load. The average load for the one, two, three and four-storey buildings is 122.1 kWh/m^2, 103.3 kWh/m^2, 103 kWh/m^2 and 88.2 kWh/m^2, respectively (Figure 1).

The calculated average summertime cooling load corresponding to the eight mitigation scenarios is given in Table 3. Calculations for all cases are performed using the same building characteristics considered in the reference scenario, Table S1. The albedo of the buildings has not been modified to assess the cooling contribution caused by the temperature reduction induced by the mitigation technologies and not because of the reduced solar absorption by the structure of the building.

As shown, the mitigation scenarios investigated here result in a decrease in the average summertime cooling, ranging between 3.6% and 16%. The use of high albedo and supercool materials reduces the cooling load by 4.4% and 5.2% compared to the reference scenario, respectively. The Green and Dry and the Very Green and Dry scenarios lead to a decrease of 3.9% and 10.6% of the average cooling loads compared to the reference while this reduction is slightly higher once considering the irrigated vegetation (i.e., 5.4% and 13.4%, respectively). The combination of Very Reflective and Very Green with the non-irrigated vegetation scenario shows a 14.8% reduction in the average cooling loads. The maximum reduction, 16.0%, in the average cooling load is achieved by the combination of Very Reflective and Very Green with the irrigated vegetation scenario. Residential buildings present a slightly higher decrease of their cooling load than the commercial buildings because of the lower internal gains. The implementation of heat mitigation technologies in the considered urban area can provide a reduction of the cooling load up to 35.5 GWh during the summer period. Figure 2 demonstrates the distribution of the annual cooling load in the study area for the eight investigated mitigation scenarios.

The energy conservation potential of the building envelope related mitigation technologies is substantially increasing when the reduction of the absorbed solar radiation is considered. Tables S2-3 present the cooling load reduction in buildings of one to four storeys under the reflective and very reflective mitigation scenarios, considering both the direct and indirect benefits arising from the implementation of the reflective and super cool materials on the roof of the buildings. Under the reflective scenario, with the decrease of the absorbed solar radiation, the cooling load conservation increases on average from 4.4% to 5.6%. Under the very reflective scenario, the cooling load conservation increases from 5.2% to 6.9%. In absolute values, the total cooling load reduction in the urban area under the reflective scenario will rise from 9.8 GWh to 12.4 GWH, while for the very reflective scenario, the corresponding reductions are 11.6 GWh and 15.3 GWh. The calculated reductions indicate that for both scenarios, almost 75% to 78% of the potential conservation of the cooling load in the 3323 buildings is attributed to the decrease of the ambient temperature induced by the implementation of the mitigation technologies underlying the energy conservation impact and the considerable decarbonisation potential of urban heat mitigation technologies.

Energy retrofitting of buildings is the most efficient way to decrease their energy demand. To evaluate the combined impact of energy retrofitting and heat mitigation technologies implemented at the building and city scale, we designed and simulated the energy impact of retrofitting measures for all the 3323 buildings combined with heat mitigation technologies implemented at the urban scale. Energy retrofitting included measures to improve the thermal quality of the envelope, namely better windows, better insulation, improved solar control, cool roofs, and improved air permeability. Measures related to the

HVAC system are not considered. A list of the selected energy retrofitting measures is given in Table S2-4.

The calculated reductions of the summer cooling load in the urban area, considering the combined implementation of the heat mitigation and energy retrofitting measures (Q_{comb}) as well as the corresponding cooling benefits (Q_{mit}) when only mitigation measures are considered, are given in Table 4. Given the important thermal interaction between the energy retrofitting and the heat mitigation measures during the building operation, the difference between Q_{comb}-Q_{mit}, does not represent the exact contribution of the retrofitting measures and is lower than when retrofitting measures are applied individually. Simulation of the energy impact of the retrofitting measures under non-mitigated climatic conditions is also performed for all the buildings, and the corresponding reduction of the cooling load of the reference building is calculated (Q_{retr}). However, under the combined implementation of the mitigation and retrofitting measures, the real contribution of the heat mitigation and energy retrofitting measures are lower than Q_{mit} and Q_{retr}, respectively, because of the important thermal interaction between the considered measures. Nevertheless, a comparison between Q_{mit} vs Q_{comb} and Q_{retr} vs Q_{comb} can provide an approximate but quite realistic contribution of the mitigation and retrofitting technologies. As shown in Table 4, combined heat mitigation technologies can contribute up to 46% of the total cooling load conservation of urban buildings under the combined implementation of heat mitigation and energy retrofitting measures.

3. DISCUSSION

The temperature of cities is steadily increasing and is expected to increase further because of the intensive urbanisation, overpopulation, and global climate change [10]. To lower urban air and surface temperatures and counterbalance the impact of high temperatures on the energy demand for cooling, heat mitigation technologies have been developed and implemented. While the impact of conventional mitigation technologies is assessed for several cities, there are important knowledge gaps regarding the mitigation potential of innovative technologies like the daytime radiative cooling materials, the specific impact of irrigated or non-irrigated greenery, and the combined effect of materials and greenery as well as on the energy impact of heat mitigation at the urban scale.

This paper presents the first study, to our knowledge, investigating the large-scale energy benefits of advanced and conventional single and combined heat mitigation technologies implemented at the city scale. The results shown here provide necessary data to mitigate urban heat and reduce energy use in urban settlements based on interactions between urban building energy demand and the urban climate.

Increase in the urban green infrastructure is the most commonly considered mitigation technology. We show that the main driver for cooling is to improve the transpiration efficiency of plants so they can reduce the released sensible heat and increase the flux of latent heat flow. Transpiration can normally evaporate water from 0.28 to 12 L/m^2 per day [29], generating a cooling power ranging between 24.5 and 29.5 MJ/m^2 per day in arid environments with sufficient water supply; however, it is less than 10 MJ/m^2 in temperate climate [26]. The results from the irrigated scenarios show that irrigation is a key factor in achieving an appreciable mitigation effect for vegetation-based mitigation strategies in Riyadh and other hot arid cities. The daytime transpiration of both the low-rise vegetation and high-rise vegetation is strongly enhanced by introducing irrigation [30]. In the absence of irrigation, evapotranspiration cannot be effectively stimulated. Furthermore, the dry soil conditions prevent plants from effective evapotranspiration during the day, and most of the contribution to the latent heat flux during the day comes from direct soil evapotranspiration.

Irrigated greenery presents a considerable mitigation potential, especially during nighttime. On average, the irrigated greenery in the city may decrease the peak daily temperature up to 0.7°C and the nighttime temperature up to 2.1°C. This agrees with similar studies reported in [28, 29, 31].

High urban temperatures affect the physiological processes of greenery and their transpiration capacity, resulting in a much lower cooling potential and a non-appropriate environmental quality [32], Supplement 2. Experiments have shown that well-irrigated plants maintained their sap flow during heat waves, while non-irrigated plants reduced their sap flow by 50% [33]. Future research should aim to develop more heat-tolerant species as genetic plants engineering has progressed up to the point at which genes of proper traits are introduced and expressed efficiently [34].

Although numerous articles have investigated the impact of urban greenery on representative buildings, very few studies have assessed the benefits at the city or neighbourhood levels [35-38]. In addition, even though existing articles reflect high non-homogeneity regarding the considered urban climate, levels of urban overheating, type of greenery, quality of buildings and assessment methodology, important conclusions can be drawn:

A) The 24 h average temperature decrease induced by additional urban greenery varies between 0.2 to 2.5°C. Most of the articles report an average 24 h temperature drop between 0.7°C and 2.2°C without specifying the irrigation status. In this study, a moderate rise of urban greenery, (30%), decreases the 24 h ambient temperature between 0.7°C (non-irrigated) and 1.2°C (irrigated), while a high increase of the green infrastructure, (60%), results in a temperature decrease between 2.3°C and 3.5°C.

B) Previous studies agree that most of the cooling benefits from urban greenery occur during night-time while the temperature decrease during the peak daytime period is between 0.0°C to 1.0°C with an average close to 0.4°C. Almost all studies are performed for temperate climates and non-arid urban zones except [27], which reported a relative increase in the ambient temperature when non-irrigated plants are considered. Similar results are obtained in the present study for non-irrigated plants, while the peak temperature decrease varied between 0.3°C and 0.6°C when irrigation is considered.

C) The potential decrease of the cooling load induced by urban greenery is reported by very few articles. A direct comparison is almost impossible given the different climatic conditions, building stock and characteristics of the greenery. Annual cooling energy conservations varying between 2 to 14 kWh/m^2 are reported, close to the results of the present study for non-irrigated greenery, 4 kWh/m^2 and 11 kWh/m^2, and 5.7 kWh/m^2 to 14 kWh/m^2 for irrigated greenery.

Increase of the urban albedo contributes to decrease of the absorbed solar radiation and reduces the urban surface temperature and the release of sensible heat. Previous studies evaluating the impact of modified urban albedo reported a decrease range of the 24 h ambient temperature between 0.1°C and 0.8°C, and a peak daily temperature reduction between 0.5°C to 3.5°C, depending on the characteristics of the cities and the implemented albedo scenario [39]. It is found that an increase of the albedo by 0.1 results in a decrease of the ambient temperature close to 0.18°C (5 pm) [39]. The present study found that the average 24 h as well as the peak daily temperature decrease are 0.9°C and, 1.2°C respectively, in full agreement with the previous findings.

The recently developed daytime radiative cooling materials have not yet been implemented to mitigate urban overheating. Mesoscale simulations for the city of Kolkata, India, have shown that may decrease the peak urban temperature up to 4.5°C, imposing, however, a heating penalty during the winter [40]. Modulation of their optical properties, reflectance and emittance, could minimize the problem [41, 42]. Simulations have shown that optically modulated super cool materials can maintain their summer cooling capacity while contributing to increasing the winter ambient temperature up to 1.5°C [43]. The present study has found that the average 24 h as well as the peak daily temperature decrease are close to 0.9°C and 1.3°C, respectively. The specific values are lower than those reported in [43] as the implementation of the super cool materials is considered only for the roofs of the buildings. The development of new generation coloured super cool materials presenting a lower solar reflectance, but a similar cooling potential based on the use of fluorescent nanostructures seems to be a major future priority [44].

Although important recent advancements have been achieved in heat mitigation research, significant challenges remain, and future studies need to be developed focusing on warming climate, mitigation and adaptation technologies, and building energy consumption.

The multifaceted strategies employed to mitigate the adverse impacts of UHIs not only alleviate the discomfort caused by excessive heat but also contribute significantly to the broader goals of sustainable urban development and reduced energy consumption.

The findings emphasize the effectiveness of various urban heat mitigation techniques in curbing energy usage and can be used to design and implement heat mitigation techniques in other cities. The proposed methodology as well as the obtained results and the now generated knowledge can be implemented elsewhere to improve the performance of the considered heat mitigation techniques, lower electricity consumption, and reduce carbon emissions contributing to the overall sustainability of cities.

4. METHODS

We designed a research methodology including three main tasks as described in the Methods Chapter. First, a detailed mesoscale simulation of the climatic conditions in the city is performed and validated against extensive existing climatic data. In essence, model results validation is a critical step that underpins the credibility and utility of modelling efforts. It transforms models from theoretical constructs to practical tools that can inform, guide, and drive meaningful real-world outcomes. Further to its validation, the mesoscale model is used to populate the climate data of Riyadh at improved spatial resolution to obtain a more complete view of spatial and temporal trends and differentiations. In the second stage, based on the analysis of the climatic conditions, eight heat mitigation strategies and the corresponding scenarios were designed and evaluated in terms of their performance using mesoscale climatic modelling. Finally, detailed precinct scale cooling energy simulations are performed for the Al Massiaf central area, including 3323 urban buildings. Energy simulations are performed under the current climate as well as under the modified climatic conditions corresponding to the eight heat mitigation strategies, Figure 3.

Climatic simulations are performed using the Weather Research and Forecasting (WRF) model, Version 4.2.1 [45]. The simulation domain was centred on the city of Riyadh, and three one-way nested domains with horizontal resolutions of 4.5 km, 1.5 km and 0.5 km were used, where the innermost domain was Riyadh city. The outer two domains were used to provide boundary conditions for the innermost domain (Figures S1 and S2). Supplemental information 1 provides detailed information on the implementation of the Weather Forecasting Model. The developed mesoscale model was used to calculate the hourly distribution of the main climatic parameters for the entire summer in the city of Riyadh under the existing conditions and the eight mitigation scenarios. The hourly outputs from the nearest grid close to Al-Masiaf precinct are used to create nine weather files for the purpose of energy simulations representing the reference climate conditions and all mitigation scenarios. The results obtained from the reference scenario mesoscale simulation were validated against the observations from three existing weather stations to ensure the performance of the model. Validation has been performed for both the summer and winter periods and for the most important climatic parameters, ambient temperature, wind speed and relative humidity. We obtained a satisfactory agreement between the simulated and experimental data. In particular, the simulation results slightly overestimated the wind speed, which could result from the underestimation of building heights. Details of the validation exercise are given in Supplemental Information 1. Figures S3 and S4 present the simulated and experimental data for the three stations.

Riyadh, the capital of Saudi Arabia, has a hot desert climate, ‘Bwh’, based on the Köppen-Geiger climate classification system [46].

The magnitude of the UHI in Riyadh is persistent and well-captured by the network of stations. The temperature distribution is rather regular, with almost no outliers and high daily average temperatures exceeding 40.0°C. The differences between urban and reference contexts are systematic and stable, with frequent peaks exceeding 4.0°C and differences nearing 1.8°C for 75% of the examined period (3rd quartile) and a median of 1.2°C (Figure S6 (b)). Negative values, namely when the city is cooler than the surroundings because of the advection of cool air from the surroundings are rarely computed (Figure S6 (a)). Additional information on the climatic analysis is given in Supplemental Information 1.

The cooling degree days in Riyadh are quite consistent over the observed period, with very high values, exceeding 2000 at all locations (Figure S7) excluding stations 1 and 4, Table S2. The CDDs at urban locations are approximately 280 higher than those at reference locations. The five-year average of the CDDs at reference (background non-urban) locations is equal to 1960, while it is 2236 at urban locations. Within the city, there is a difference of 160 CDDs between the hottest and the coolest urban area. These important intra-urban and urban-reference differences point out the influence of local factors such as land cover and wind patterns, [47]

The analysis as performed on the integrated dataset (measured and simulated data) provides the following results/conclusions.

a) During the hottest conditions and considering all data points, more than 50% of air temperature data exceeds 40.0°C, and 10% of the urban area has air temperature higher than 45.0°C. In contrast, on an average summer day, only 23% of the urban data points have air temperatures exceeding 40.0°C, whereas air temperature does not exceed 45.0°C. This result shows that in the hottest climatic conditions, hot spots are not limited, and a considerable number of urban areas experience high ambient temperatures.
b) The average simulated UHI intensity of the entire urban area during the summer period, is 1.5°C, Figure S12. The southern and eastern parts have the highest UHII with an average intensity of more than 2.0°C and the highest average value of 2.5°C. The mean UHI intensity increases with the increase of urban density. The mean UHI intensity corresponding to low-density urban cells exceeds 2.0°C for 6% of the time. In medium-density and high-density areas, the corresponding percentages of time are 24.6% and 36.6%, respectively.
c) The maximum calculated daytime UHI intensity in the whole city was close to 8.5°C and appeared at 14:00, Figure S13. The southeastern part of the city experienced high UHI intensity with a magnitude of above 8.0°C. The maximum UHI intensity occurs during northern winds, while the minimum intensity corresponds to southern and southwest winds.
d) Land surface temperature (LST), in Riyadh urban zone, presents a significant variability. Up to 5.0°C, higher average surface temperatures are observed in the south and southeastern parts of the city, Figure S10. LST in Riyadh obtains values higher than 50.0°C during summer months in all its districts, whereas districts in the northeast and the southeast of the city exhibit LSTs even higher than 58.0°C. This is an important finding as land surface temperature drives the transfer of heat from the ground to the overlying air and thus contributes to higher air temperatures, and reduces soil humidity. The land surface temperature at 14:00 ranges between 46.1°C and 53.3°C. Additional data about the distribution of the LST in the city is obtained through the Landsat 8

satellite Observations at 10:30 am local time per district was used to reveal using the QGIS software, the most thermally stressed districts of the city. Figure S14 showsthe distribution of the mean daily land surface temperature per district during a hot day as calculated by Landsat 8.

High temperatures in urban areas have a direct impact on human health and are associated with heat-related stress and excess summer deaths [48]. We assessed the distribution of the urban heat risk in the city based on the collected and calculated meteorological characteristics expressing the degree of heat exposure, namely the physical characteristics and in particular, the urban planning characteristics that indicate the way the city has been built and the way it operates (building materials, buildings age, number of public facilities, etc), and the social characteristics involving demographic characteristics expressing the degree of sensitivity to extreme hot weather conditions estimated by census data such as the percentage of population over 65 or under 14 years old. Districts exhibiting high temperature values, low quality building structures and are inhabited by a high percentage of elderly people are more vulnerable to extreme heat than districts characterized by lower temperature values, high quality buildings and their population consists of younger people.

To assess the heat risk of Riyadh, the parameters presented above were combined into a composite heat risk indicator. To achieve this, each parameter was reclassified into three categories using the quantile classification, namely a data classification method that distributes a set of values into groups that contain an equal number of values. Table S3 provides the range of values for the three risk categories per parameter [49,50]. The resulting three categories are defined as: 1) Low heat risk, 2) Moderate heat risk, and 3) High heat risk. Since the relative importance of each parameter is unknown, all parameters contributed equally to the composite heat risk index. The considered parameters were reclassified into three categories using the quantile classification method, resulting in the composite heat risk index. It yields that the northeast and southeast districts of the city (in red) have higher heat risk than those to the west of the city. Several districts in the centre of the city are also exhibiting high thermal risk (Figure 4).

The 3323 buildings selected for cooling energy simulations are located at the Al Masiaf Precinct, which covers an area of approximately 2 km × 2 km (Figure S5) with a total of 3323 buildings, including residential buildings (2962 multi-family and 98 single-family houses) and office buildings (241 small, 21 medium, and

1 large offices). The simulated buildings consist of residential and commercial buildings of 1 to 4 storeys. The total area of the selected buildings to simulate is 2125820 m^2.

The simulation platform CityBES [51, 52] was used to run the energy simulations of the Al-Masiaf precinct. CityBES is a web-based data and computing platform developed by Lawrence Berkeley National Laboratory (LBNL) to evaluate the energy performance of city buildings. Figure 5 shows the key components of CityBES as organised in three layers: 1) the data layer, 2) the simulation engine (algorithm) and software tools layer, and 3) the use-cases layer. CityBES [52,53] offers detailed energy performance analysis built on the EnergyPlus engine for dynamic energy simulation of urban buildings, which offers the highest resolution due to physics-based modelling approaches capturing the full dynamic of building performance. Specific information and details about the specific simulation procedure are given in Supplemental Information 1. The most common construction and operational characteristics of the residential and commercial buildings in the Al Masiaf precinct are identified and then used to perform the building energy simulations. Table S1 lists all the main inputs used to simulate the residential and commercial buildings.

To analyse the current climatic conditions in the city, data from a network of 16 meteorological stations is used (Table S2). The dataset analysed comprises the five recent complete years of hourly averages of data from January 2016 to December 2020 representing the current conditions in the city. A detailed statistical methodology described in the Supplemental information was used to filter the data and control their quality.

We calculated the magnitude of the urban heat island in the city by considering the difference between a reference (non-urban) station and an urban station where the reference data was obtained from the average of four meteorological stations located at all four sides of the city, in this way, a reliable appraisal of the differences between the city and the non-urban surroundings is achieved. The difference is calculated considering the simple moving average over seven hours (3 hours backwards, and 3 hours forward and centred on the hour). This approach eliminates short-term differences due to atmospheric circulation conditions and better captures the general trends over the day, as performed in [8].

The climatic information provided by the ground stations was enriched with additional data regarding the spatial distribution of the main climatic parameters, the hottest spots in the city, and the distribution of the latent and sensible heat fluxes as calculated by mesoscale simulations under the current climatic conditions. The calculated spatial distribution of the ambient and surface temperature, wind speed, UHI intensity and sensible and latent fluxes are provided in the supplemental information, Figures (S8-S13).

Data Availability: All available data can be requested by the Corresponding Author.

Main Limitations of Research

The input data used for the energy simulation of the 3323 buildings are considered according to the building codes and regulations in the country and may differ from the real construction characteristics of the buildings. The used statistical data to develop the Comfort index are the latest available one, however, changes may have happened.

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Individual contributions

MS has coordinated the project, has designed the Mitigation scenarios and has analysed the data. SH has coordinated the energy study and has analysed the energy data, WZ and TH have performed the energy simulations, KG has performed the mesoscale simulations, RP has performed the local climatic analysis, CK and AP have performed the study about the Composite Heat Risk Indicator and provided the remote sensing data, AK has contributed to the Mesoscale Simulations and MA, AM, AB have provided all local data and have supervised the study. The manuscript is written by MS and SH with contributions from all authors.

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