
Quantifying the energy impact of heat mitigation technologies at the urban scale

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SUPPLEMENTAL INFORMATION

Description and Details on the WRF Implementation

The Weather Research and Forecasting (WRF) model, Version 4.2.1, was used to simulate the climatic conditions in Riyadh. The Mellor-Yamada-Janjić scheme (MYJ) [1-3] was used for the planetary boundary layer parameterization, combined with the Rapid Radiative Transfer Model for Global Circulation Models (RRTMG) scheme for longwave and shortwave radiation [4]. All grids in the domains were created following the Lambert projection. The Noah land surface model (LSM) coupled with single-layer urban canopy model (UCM) was used for Land surface parameterization [5-6]. Modified Tiedtke scheme was applied for Cumulus parameterization [7-9]. Janjić surface-layer scheme [10] based on the Monin–Obukhov similarity theory was employed for the surface layer parameterization and Thompson scheme [11] was used for microphysics.

The datasets of Moderate Resolution Imaging Spectroradiometer (MODIS), i.e., 15s resolution land surface datasets, were used to represent the land surface. The urban grid cells were remapped using the remote sensing products from the U.S Geological Survey [12]. The Landsat 8 – with a resolution of 30m (spectrum band 1 to 11) were used to remap the urban categories from year 2015 to 2017. The urban geometry parameters and anthropogenic heat flux numbers were assigned to

each of the three urban categories based on the existing literature. The meteorological boundary condition and initial condition are extracted from ERA interim datasets. Simulations were performed for three months during the summer period from 12:00 June 1st, 2018, to 18:00 Aug 31st, 2018.

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. The outer two domains were used to provide boundary conditions for the innermost domain (Figures S1 and S2).

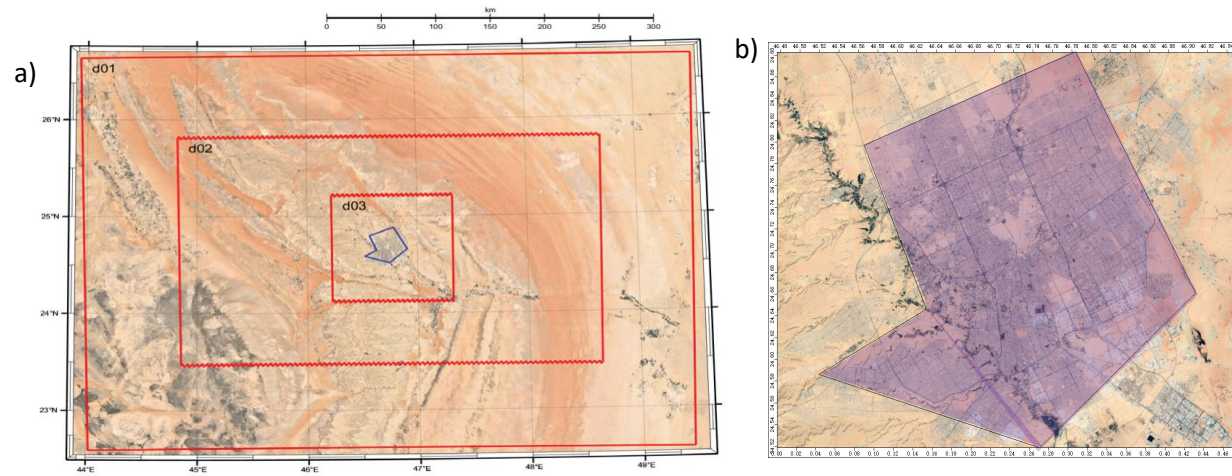


Figure S1. The Boundaries of the WRF domains (a),
Boundaries of the urban area (b).

	Domain 1	Domain 2	Domain 3
Spatial resolution	4500m	1500m	500m
Grid size(west-east*south-south)	125*101grids	259*175grids	223*241grids
Spatial Scale	562.5km*454km	388.5km*262.5km	111.5km*120.5km
Location of domain origin on parent domain	(1,1)	(20,22)	(94,49)

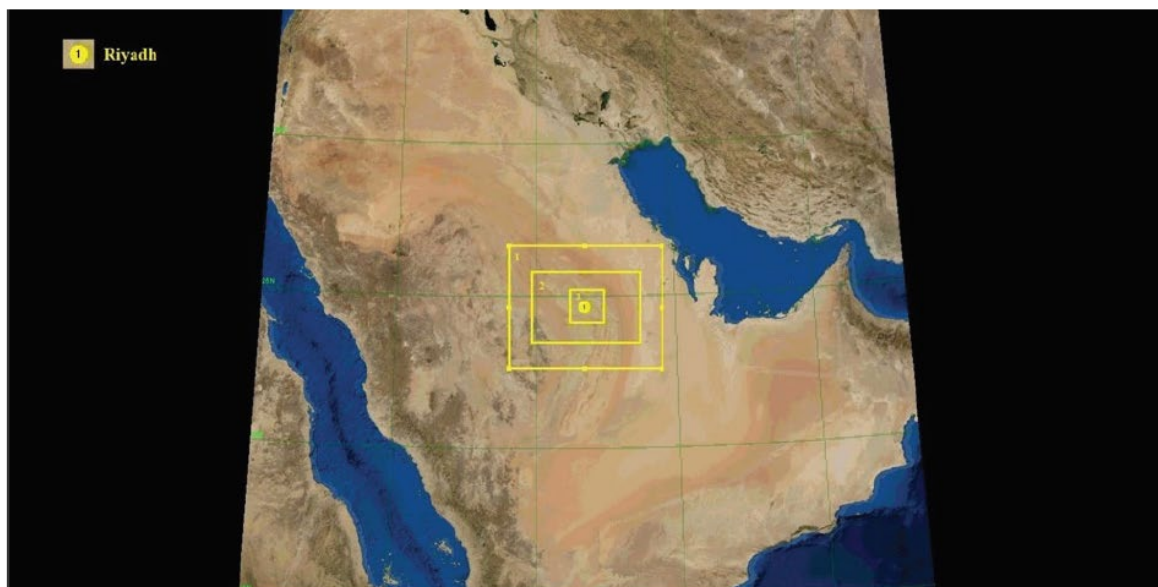
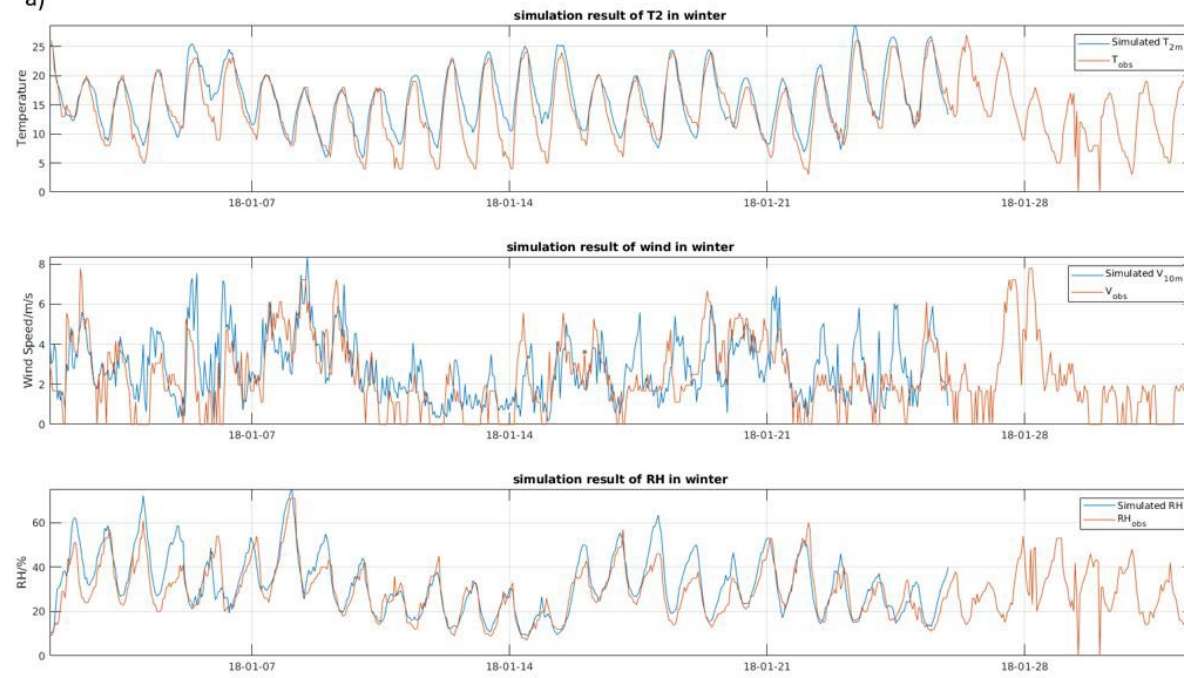


Figure S2. Details on the Boundaries of the WRF domains

Validation Data of the Reference Case

a)



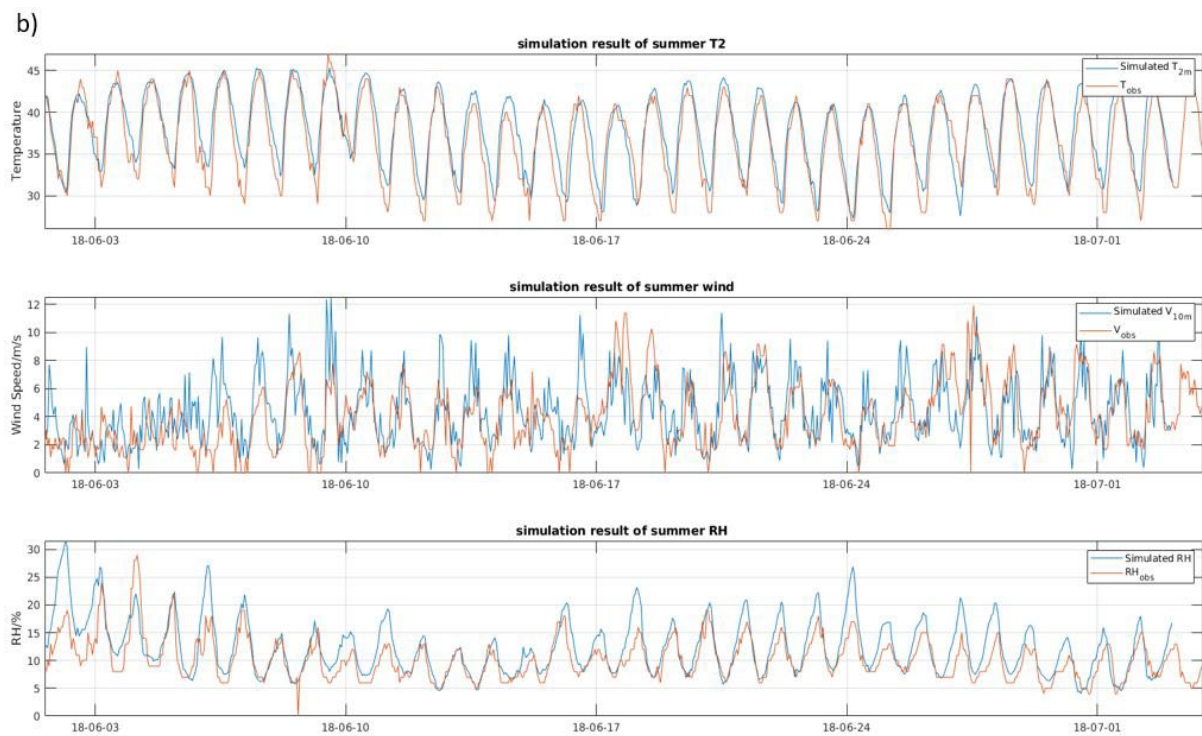
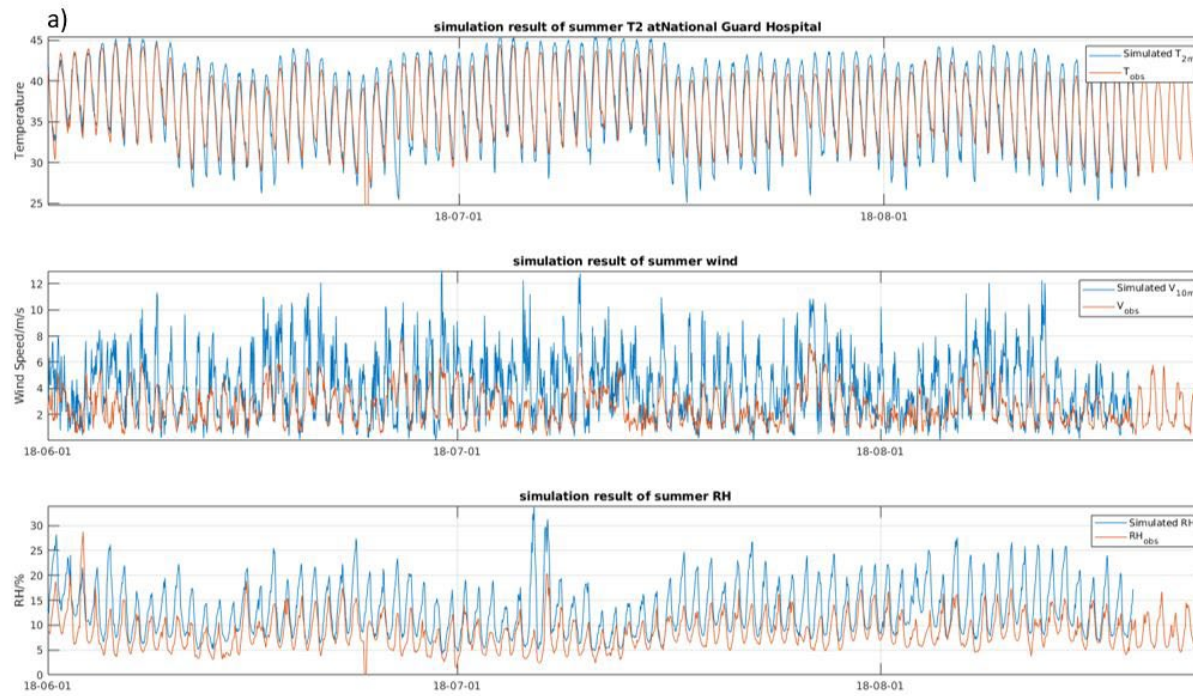


Figure S3. Khalid International airport station. Comparison of the simulated and measured ambient temperature, wind speed and Relative Humidity during a) The winter and b) the summer period



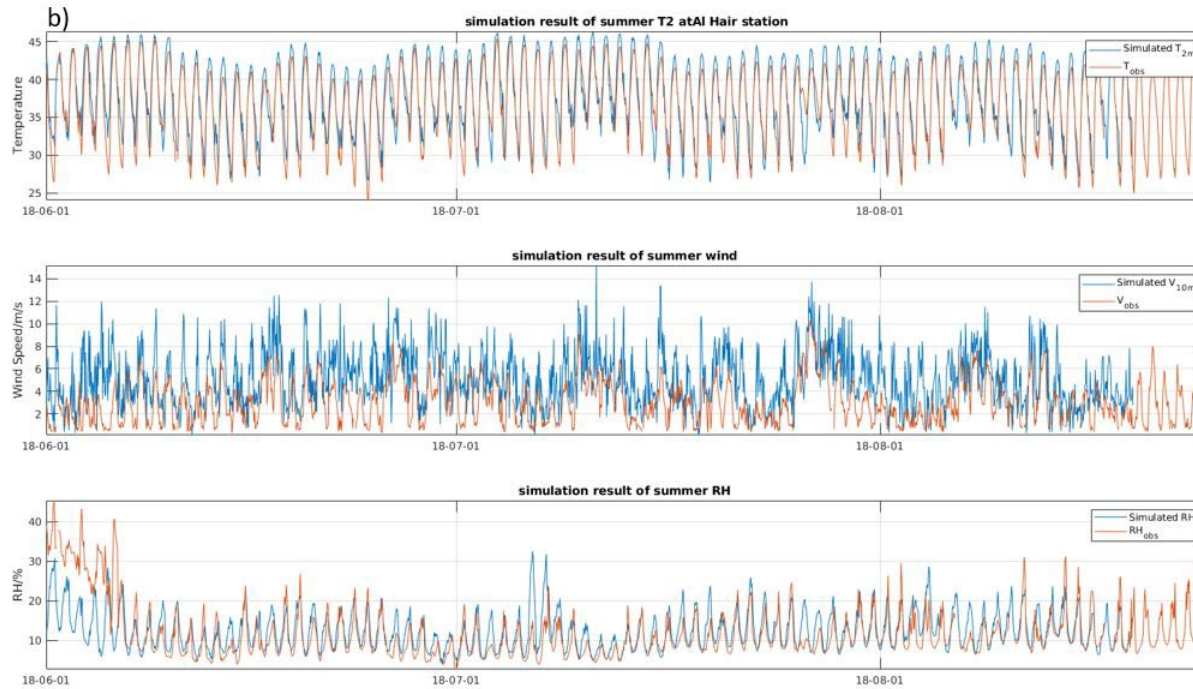


Figure S4. Measured and Simulated data of the summer ambient temperature, wind speed and relative humidity for a) The station at Guard Hospital and b) the AI Hair Station

Additional Data of Climatic Analysis

In addition to the urban heat island, a less known but not less relevant phenomenon is the urban moisture island. In desert climates, urban areas can be more humid than the xeric surroundings, while in temperate climates cities are typically drier than the non-urban adjacent zones. Here, we computed that the city is systematically drier than the reference non-urban areas, as captured by the reference stations. On average, the urban area contains less humidity than the air out of the city by 0.58 g/m^3 of air, which corresponds to approximately 2.8% in relative humidity computed at 23.0°C . Drier conditions can be explained by increased

evaporation within the urban area because of higher temperatures and the prevalence of impervious surfaces, with limited moisture capacity. Urban areas are also drier because the UHI induces the deviation of low-pressure circulation and therefore rainfall.

Study Area

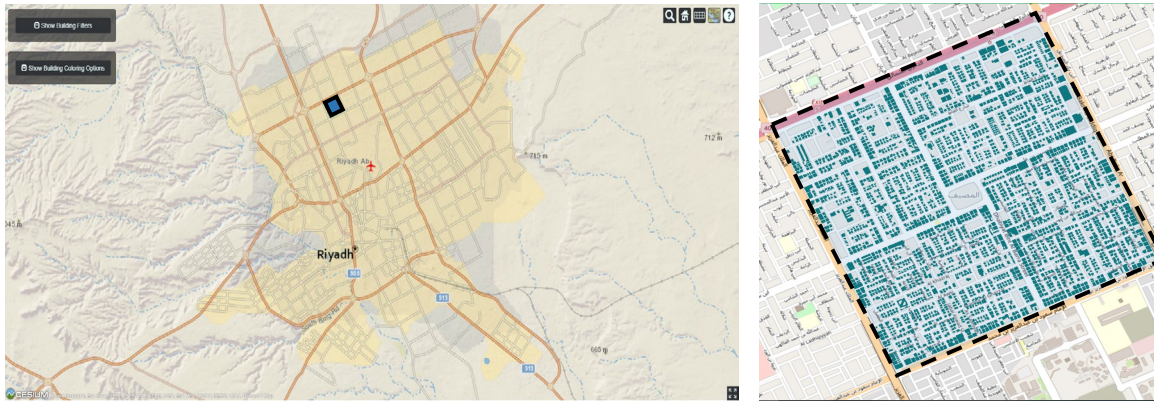


Figure S5. Location of Al-Masaf precinct in Riyadh (left), distribution of buildings in Al-Masaf precinct (right). Source: <https://citybes.lbl.gov/>

Implementation of CityBES

First, we created building dataset using GIS dataset in GeoJSON format, which consolidates city data in a format that can then be imported into the energy modelling tool. Table S1 shows the inputs used in the building dataset for the residential and office buildings in the selected precinct. CityBES processes the city GIS data to determine the buildings, shared walls, and weather file for each building. Then, each building is assigned the associated weather file and neighbourhood buildings as well as the GIS-based building footprint, year built, building type, building height, and number of stories. The neighbourhood buildings are modelled as shading surfaces in EnergyPlus to consider the solar overshadowing effect between buildings. The building performance is visualised by color-coding the 3D view

of the buildings based on annual cooling electricity use intensity. CityBES generates sub-hourly load profiles for each building which we used to calculate cooling electricity use intensity during summer period.

Table S1. Building characteristics and inputs used for energy simulations in CityBES

Parameters	Residential	Office
Lighting power density (W/m ²)	5	12
Equipment power density (W/m ²)	5	10
Occupancy density (person/m ²)	0.02	0.14
Outdoor air flow per person (l/s.person)	7	7
Infiltration flow rate per exterior wall area (l/s.m ²)	0.49	0.49
Roof insulation R-value (m ² K/W)	2.2	2.2
Roof solar reflectance	0.20	0.20
Wall insulation R-value (m ² K/W)	1.3	1.3
Window u-value (W/m ² K)	5.6	5.6
Window SHGC	0.36	0.36
Window visual transmittance	0.7	0.7
HVAC system type id	Packaged single zone rooftop heat pump	Packaged single zone rooftop air conditioner
HVAC cooling COP*	2.2	2.5
HVAC heating efficiency*	1.5	1.5
HVAC fan efficiency*	1	1
Heating setpoint (°C)	20.0	20.0
Cooling setpoint (°C)	24.0	24.0

**Note: Simulations were performed to calculate both cooling load (using cooling coefficient of performance (COP) of 1) and cooling energy use (normal/assigned COP reported in Table 2). In the simulations performed to derive cooling load, we considered HVAC cooling COP, HVAC*

heating efficiency, and HVAC fan efficiency equal to 1. All other parameters were kept unchanged.

Characteristics of the Local Climatic Stations and Analysis of Data

Table S2. Meteorological stations and metadata (gaps for air temperature). Metadata from provided by ArRiyadh Air Quality (http://195.66.100.41/aq/?site_id=5015).

Type	Station	Station name	Height (m)	GapsT _{air}
Background	1	Prince Sultan Humanitarian City	685	16.5%
	2	National Guard Hospital	579	12.1%
	3	Al Hair	498	9.4%
	4	Wadi Hanifa	672	15.4%
Suburban	5	Al Aziziyah hospital	585	12.8%
	6	Al Shifa	616	7.4%
	7	Al Zamroud	632	7.8%
	8	Al Amal	591	12.7%
	9	Al Zahrah	655	12.4%
	10	Al Mauroj	638	7.0%
	11	King Faisal	626	15.2%

Four of these stations measure the background at the boundaries of the city, while seven more urban stations collect data within Riyadh. Unrealistic values (i.e., wrong readings) were filtered performing the validation procedures detailed by Estevez et al. [13] performing the following tests, with context specific values:

- Range tests (e.g., relative humidity comprised between 0.8 and 100%);
- Step tests (e.g., ait temperature change of less than 12 °C in one hour, or relative humidity variation not exceeding 45% in one hour);

- Persistence tests (e.g., steady values for long periods are filtered as equipment failure);
- Relational tests (i.e., if the wind speed is null, then the wind direction cannot be different from 0°).

To deal with the missing values [14] in the raw data recorded by weather stations, we linearly interpolated between values if the gaps accounted for maximum three hours similar to Paolini et al. [15] who used a Back-Propagated Neural Network to infill the gaps in the data series. For longer gap in the data series, we found an analytical relation between a quantity (e.g., air temperature) at one station and the same quantity measured by the three closest stations triangulating the target station, also as a function of the previous hours. We found these relations by means of the genetic programming software tool Heuristic Lab [16,17].

Magnitude of Urban Heat Island

To analyse the urban heat island intensity (UHII) in Riyadh, we compared the temperature of the urban areas against the reference location which presents a lower ambient temperature.

The reference location is selected based on a site with the lowest average air temperature during the entire simulation period located in the northwest of the city (46.29E, 24.9N) about 40 km from the city centre..

The average UHI intensity of the entire urban area during the summer period is 1.5°C. The southern and eastern parts have the highest UHI with an average intensity of more than 2°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 when UHI intensity exceeds 2.0°C are 24.6% and 36.6%, respectively. This pattern of UHI with respect to urban type is similar to the pattern of air temperature in relation to urban type,

The maximum daytime UHI intensity of 8.5°C appeared at 14:00 on 22nd July, which is referred to daytime Max UHI Time (dMUT). This relates to a specific area, which explains why the maximum magnitude of the UHI observed through the network of weather stations is of 6.5°C, with frequent peaks above 4.0°C.

The whole middle and southwest region of the city showed a UHI intensity of more than 4°C during the night. It started to shift to the southern parts from around 0:00

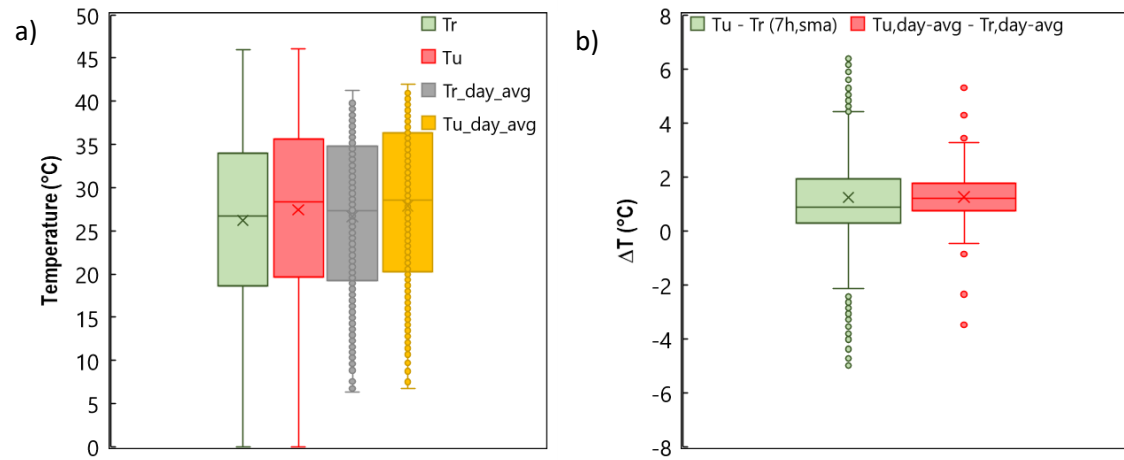


Figure S6. Boxplots of the ambient temperature in Riyadh. Temperature out of the city (T_r , average of the temperature recorded by the four reference stations), temperature within the city (T_u , average of the urban records), and daily averages of the reference and urban data ($T_{r_day_avg}$ and $T_{u_day_avg}$) (a). Boxplot of the temperature difference ($T_r - T_u$, based on the 7-hour simple moving average of the urban and reference data) and difference between the daily averages (b). Data refer to 365 days, (size of sample-365 for S6a and S6b). Reference to the box plot: The lower and the upper end of the lines presents the minima and the maxima. The Centre line represents the median value. The upper and lower bounds of box and whiskers represent the 75 % and 25 % of the values respectively.

Cooling Degree Hours

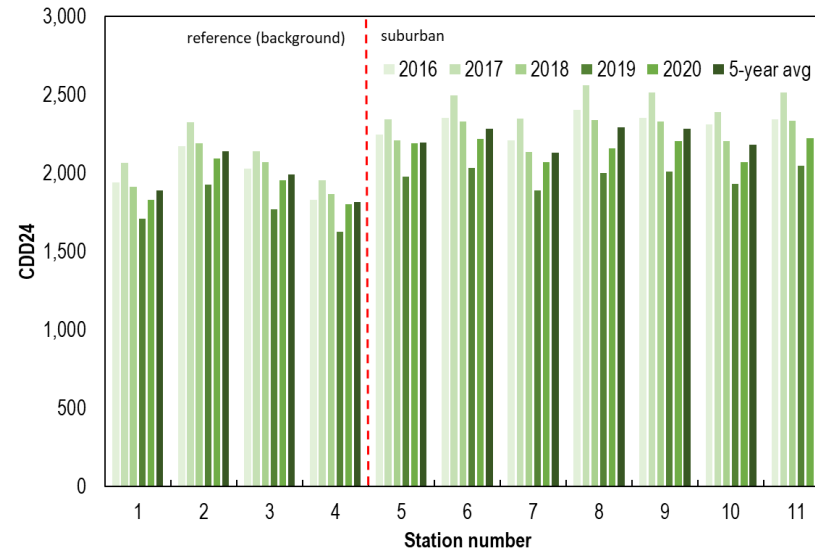
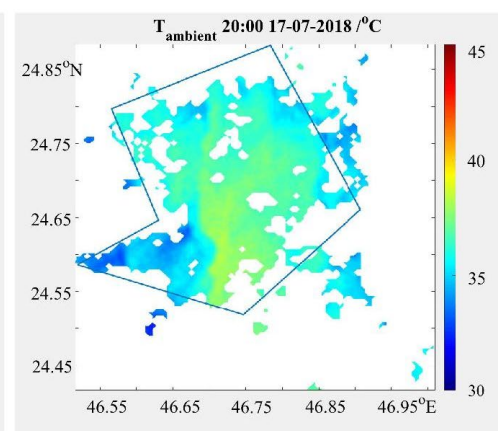
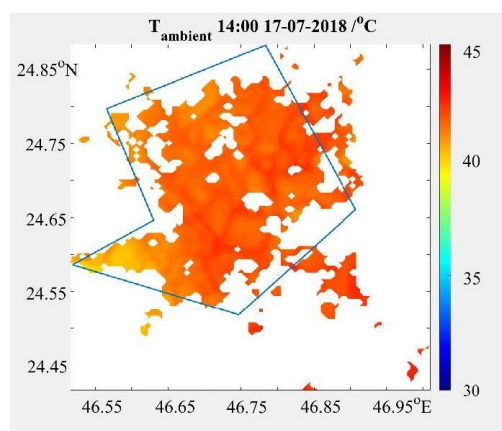
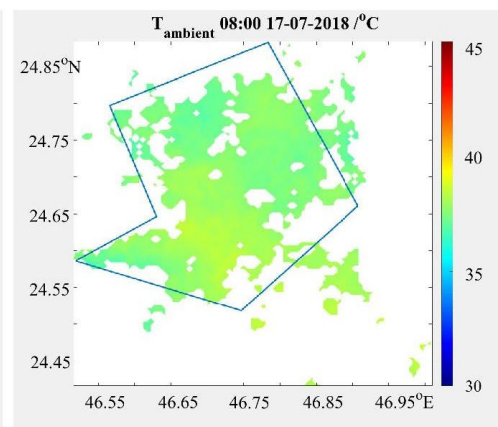
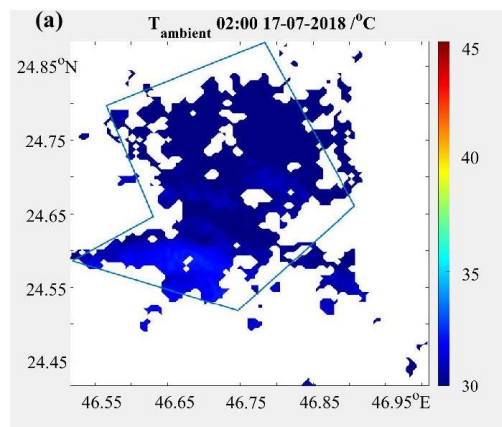


Figure S7. Bar plot of the Cooling Degree Days with base temperature of 24 °C (CDD24) for the five complete years of temperature records and the five-year average for the reference locations (background, Stations 1-4, Table S2) out of Riyadh and the suburban locations within Riyadh (Stations 5-11, Table S2)

Spatial Distribution of the Main Climatic Parameters Calculated by the Mesoscale Mode



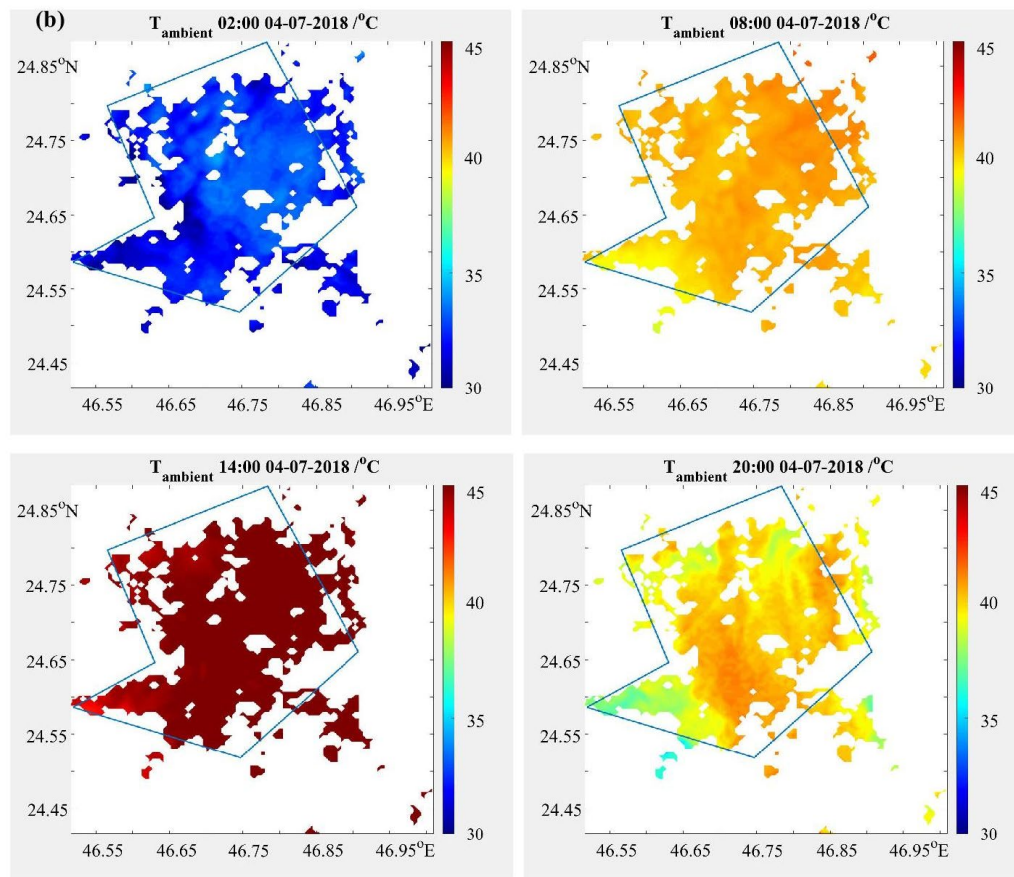


Figure S8. Air temperature distribution in the average summer day (a), in the hottest day (b).

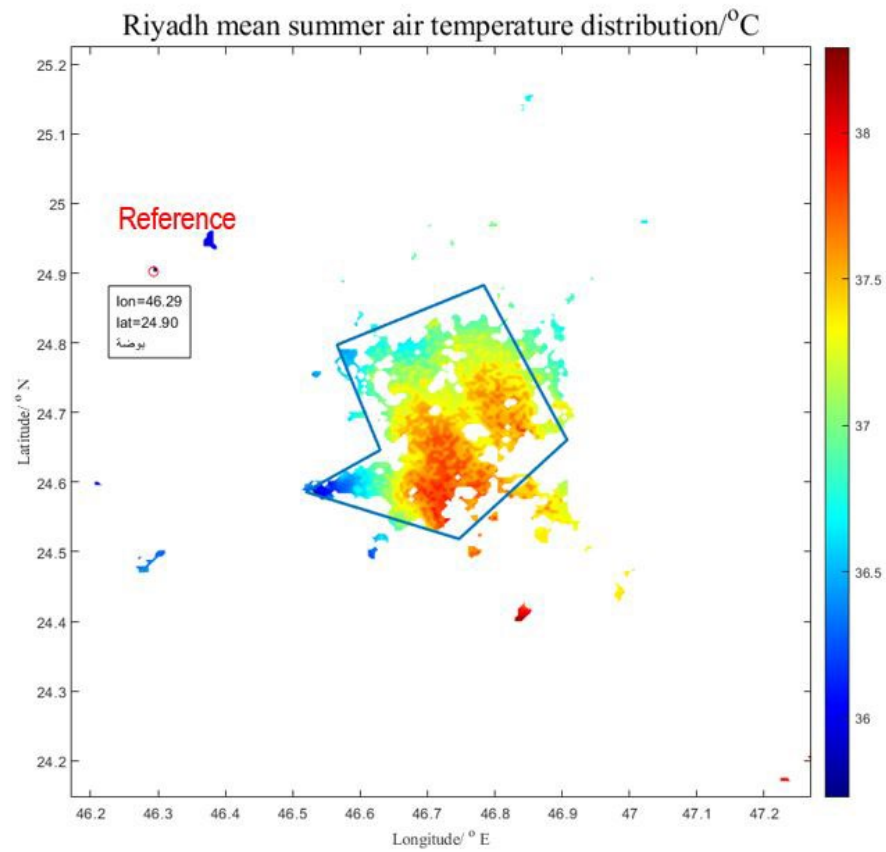
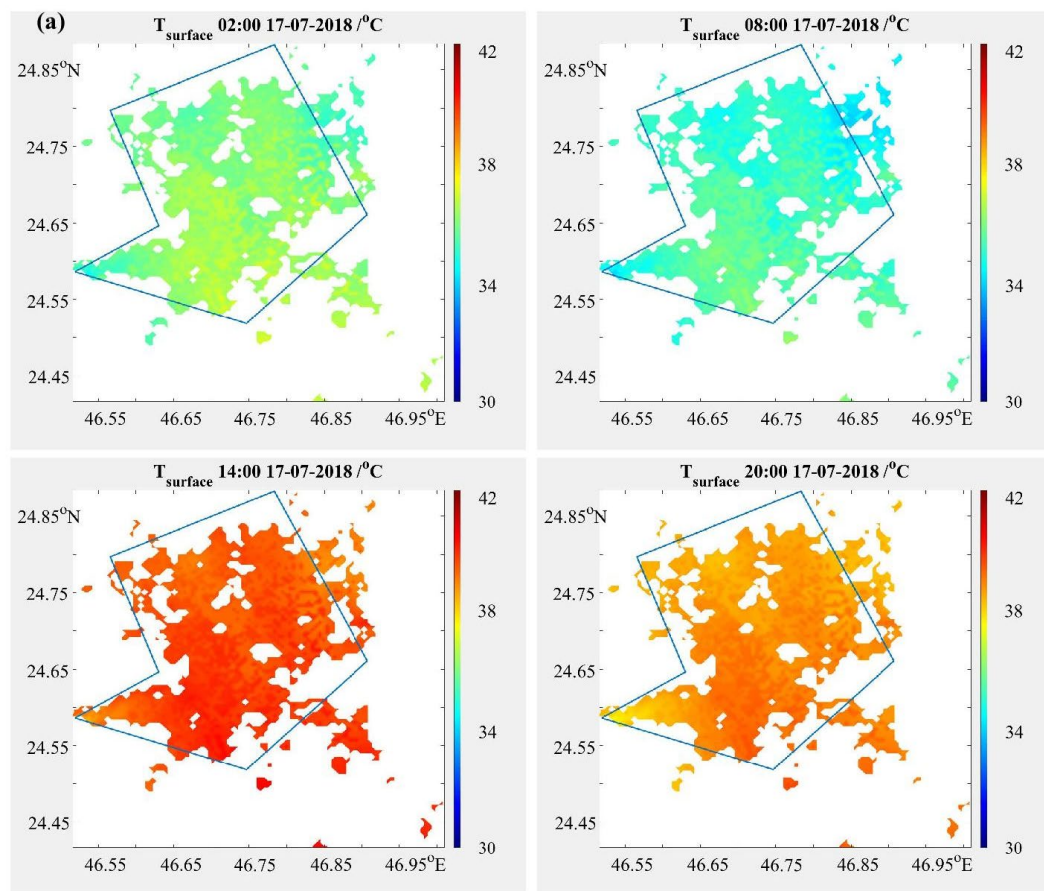


Figure S9. Average ambient temperature distribution during the entire simulation period



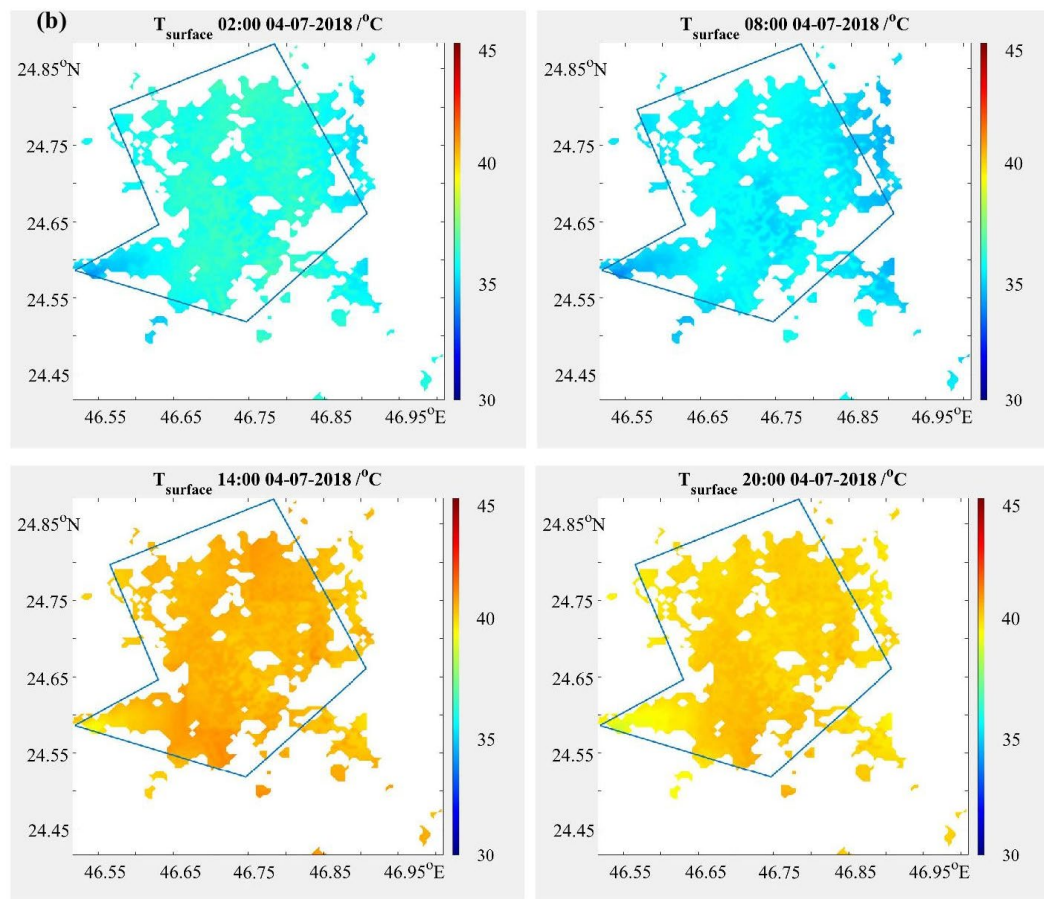


Figure S10. Surface temperature distribution in the average summer day (a), in the hottest day (b).

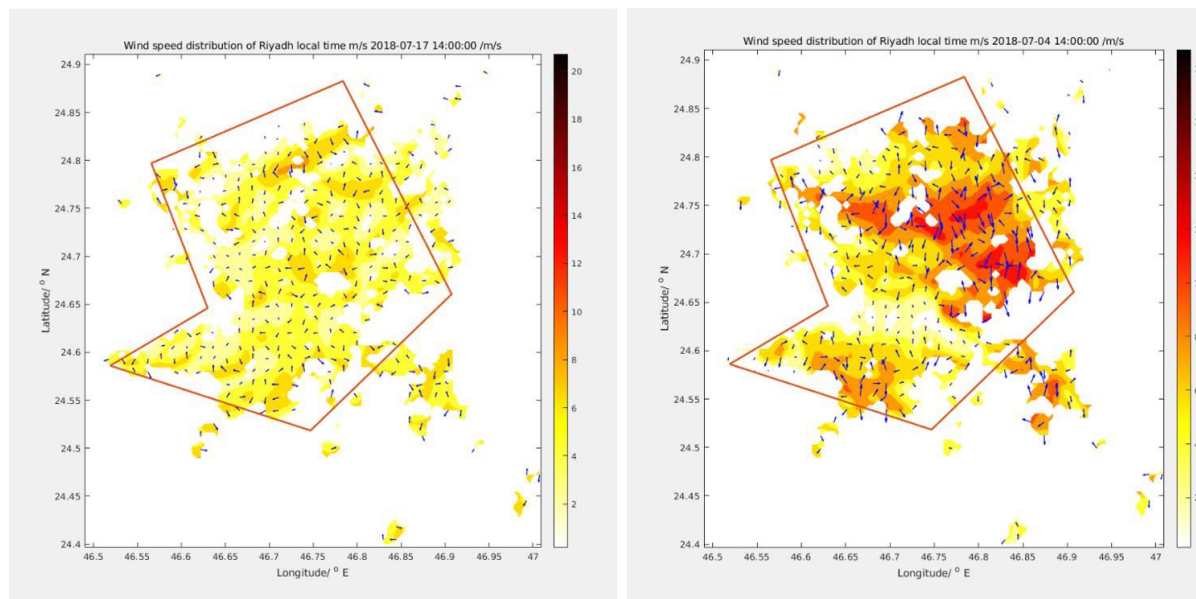


Figure S11. Wind speed/direction at 14:00 on July 17 (left)- average summer day and July 14 (right) hot summer day.

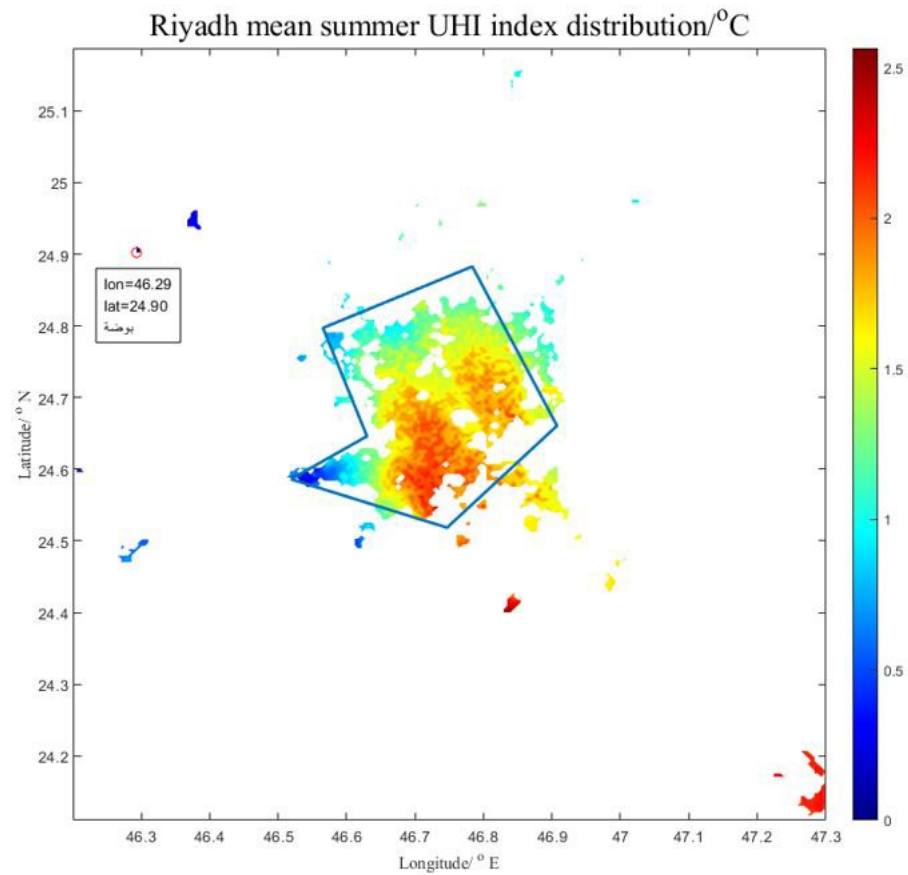


Figure S12. Average summer UHI intensity distribution

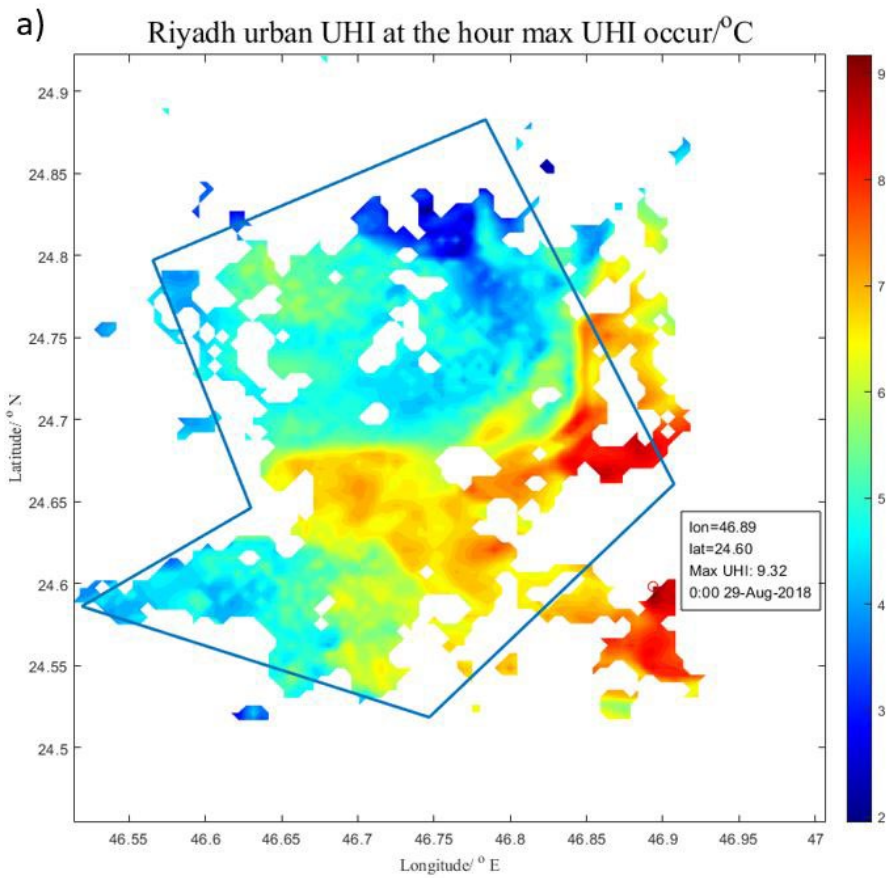


Figure S13. Spatial Distribution of the maximum UHI values.
Satellite Images

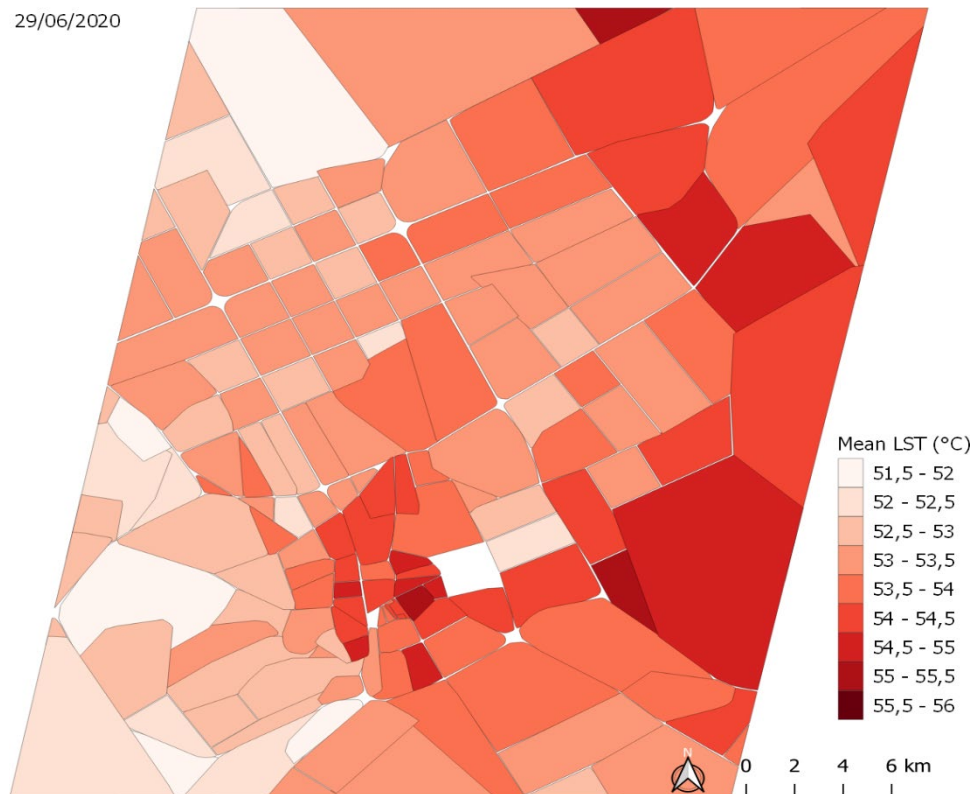


Figure S14. Mean daily Land Surface Temperature per district on 29/06/2020

Calculation of the Composite Heat Risk Indicator

To evaluate Riyadh's heat risk, several factors, including daytime land surface temperature (Figure S15), Thom discomfort index (Figure S16), air temperature (Figure S17), the percentage of residents under 14 years old (Figure S18), the percentage of residents over 65 years old (Figure S19), and building density (Figure S20), were computed for each district. These factors were then integrated to create a composite heat risk indicator. To achieve this, each parameter was categorized into one of three groups using the quantile classification method, which divides data into groups containing an equal number of values. The range of values for each risk category per parameter is provided in Table S3. The resulting categories were defined as follows:

- 1=Low heat risk
- 2=Moderate heat risk
- 3=High heat risk

Since the relative significance of each parameter is unknown, all parameters were given equal weight in the composite heat risk index. The sum of all parameters was then classified into three categories using the quantile classification method, resulting in the composite heat risk index. The analysis revealed that the northeastern and southeastern districts of the city have a higher heat risk compared to those in the western part of the city. Additionally, several districts in the city center also exhibit a high level of thermal risk.

Table S3. Parameter values used for the quantile classification.

	LST (°C)	DI	T2m (°C)	YP<14 y.o. (%)	OP>65 y.o (%)	Buildings per sq. m. (BD)
Less risk	<47.2	<28	<40.6	<23	<1	<66
Moderate risk	47.2≤ LST ≤47.9	28≤ DI ≤28.2	40.6≤ T2m ≤40.8	23≤ YP ≤28	1≤ OP ≤3	66≤ BD ≤109
High risk	>47.9	>28.2	>40.8	>28	>3	>109

LST: Land Surface Temperature in degrees Celcius; DI: Thom Discomfort Index; T2m: temperature at the height of 2m; YP<14 y.o. (%): percentage of young population less than 14 years old; OP> 65 y.o. (%): percentage of population above 65 years old; BD: Building Density in square kilometers.

Additional Maps Supporting the Calculation of the Composite Heat Risk Indicator (Figures S15-20).

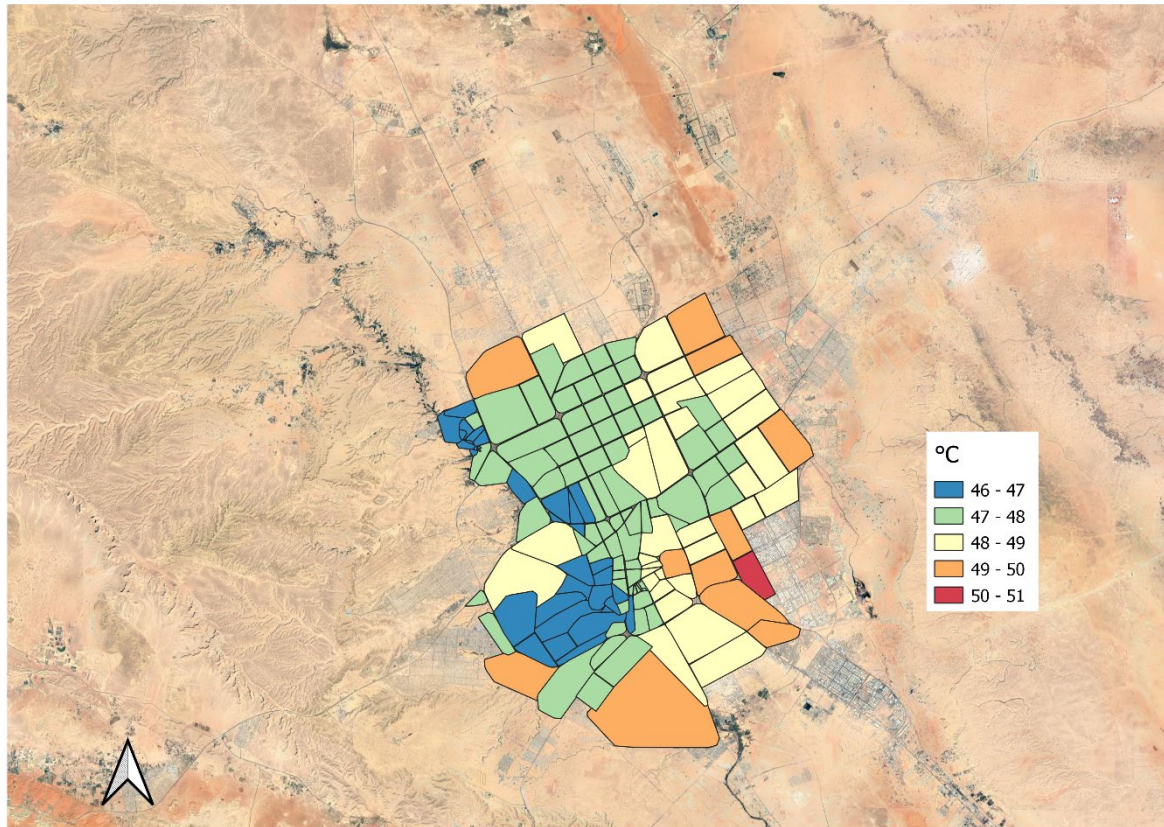


Figure S15. Mean daytime land surface temperature in degrees Celsius (satellite derived) per district.

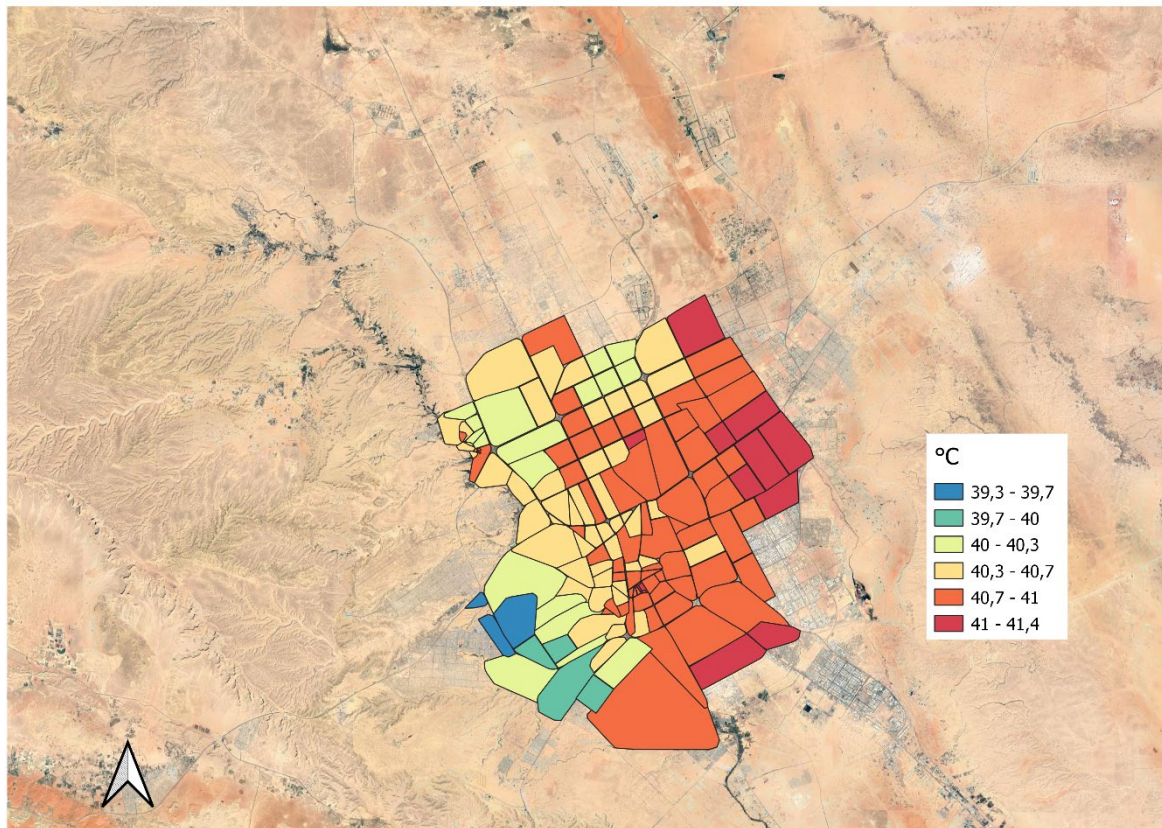


Figure S16 Mean daily air temperature in degrees Celsius (WRF derived) per district.

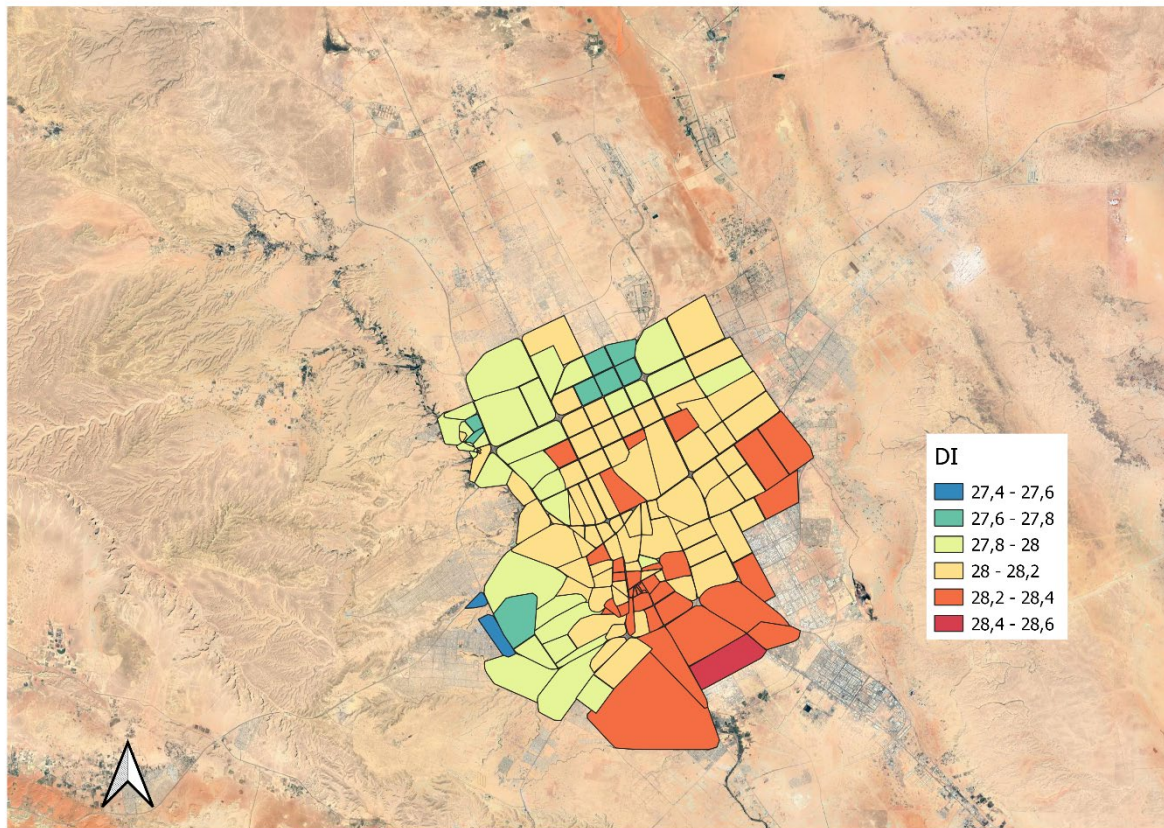


Figure S17. Mean daily Thom's discomfort index per district as estimated from WRF outputs for relative humidity and air temperature.

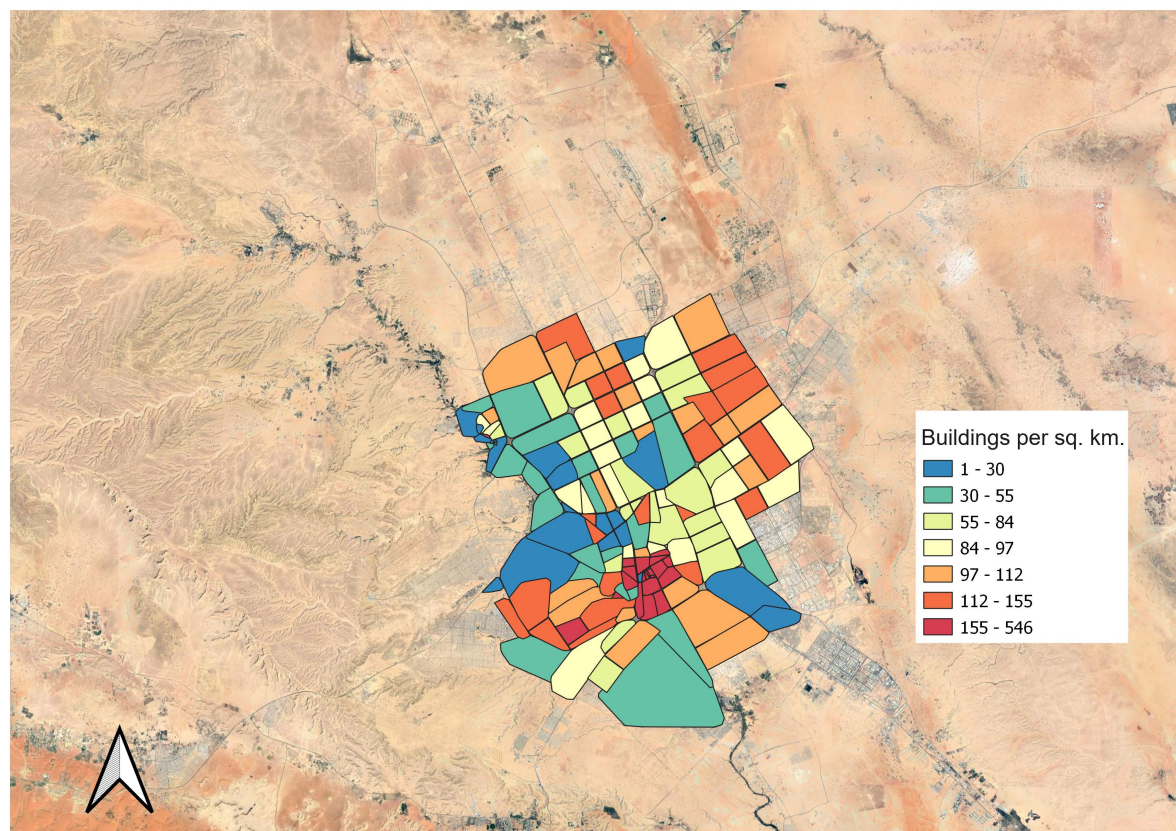


Figure S18. Building density per district (data as of 2016).

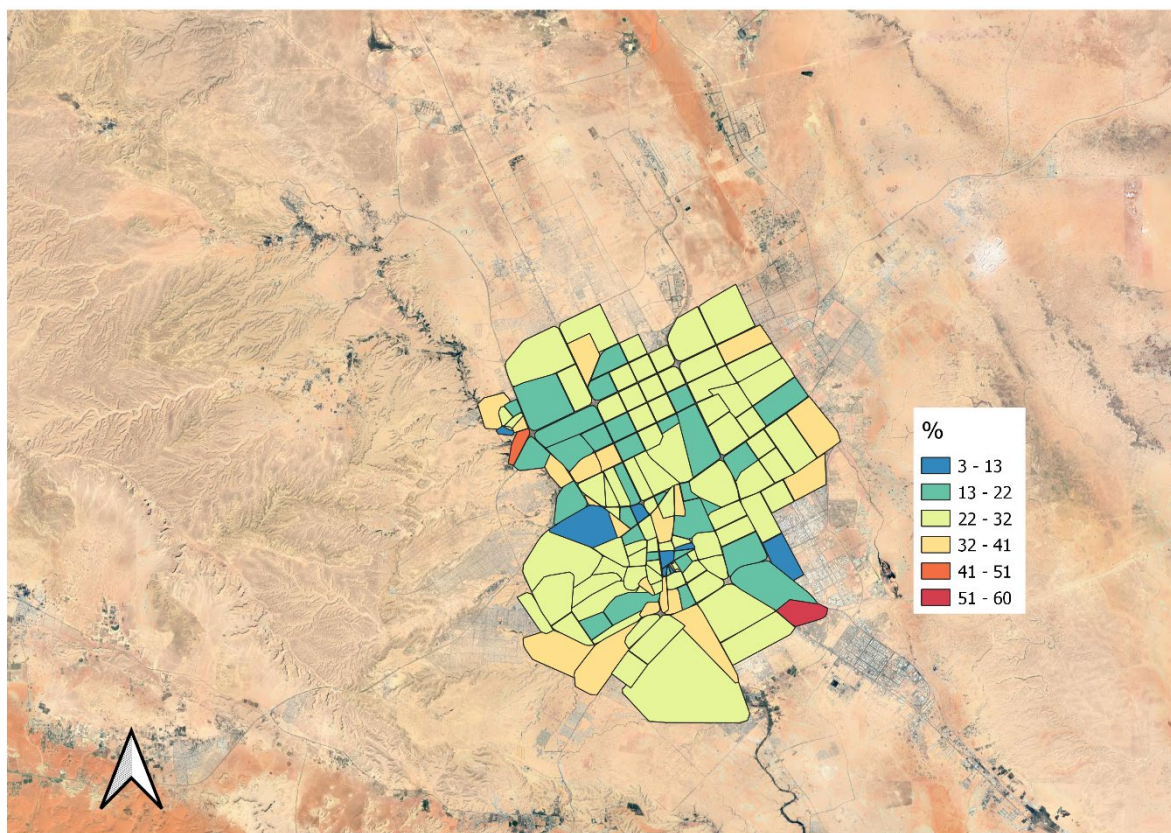


Figure S19. Percentage of residents under 14 years old per district (data as of 2016).

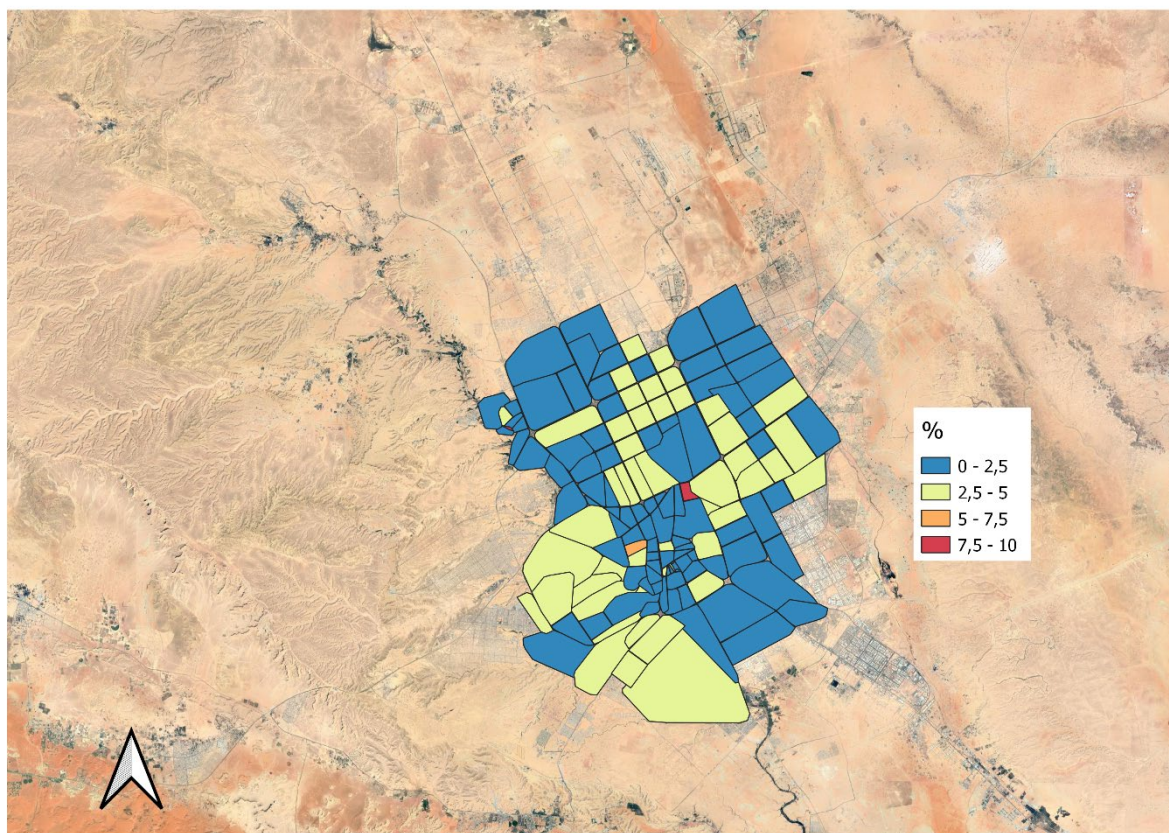


Figure S20. Percentage of residents over 65 years old per district (data as of 2016).

Additional Information on the Impact of Urban Overheating

Several studies have been performed to analyze the characteristics and the impact of the urban overheating in the Gulf area, (18, 19).

Assessment of the cooling penalty induced by urban overheating involving data from 18 world cities has shown that the cooling energy demand of representative buildings has increased by 23% between 1970 and 2010, while the corresponding average energy penalty at the city scale caused by the increased

urban temperatures is approximately $0.73 \pm (0.64)$ kWh/m²/°C, the average annual global energy penalty per person is $230 \pm (120)$ kWh/p, and the average annual global energy penalty per person and degree of temperature increase is $78 \pm (47)$ kWh/p/°C [20].

Increased urban temperatures result in a substantial surge in the peak electricity demand during the summer period. Data from 11 urban studies revealed that the average power penalty and the corresponding additional electricity demand induced by urban overheating is close to 21 Watts (± 10.4) per degree of temperature increase and per person [21].

Overheating affects the generation capacity of the power plants and increases the total number of major electrical grid failure events. An increase of 1°C in the ambient temperature decreases the output of thermal and nuclear power plants by 0.6% and 0.8%, respectively [22]. According to (23), the major electrical failure events in the USA have increased from 45 to 125 in the period 2015-2020.

Extreme ambient temperatures affect the price of electricity. During the 2022 heat wave in France, increased river temperatures seriously reduced the operational capacity of the nuclear power plants and resulted in day-ahead baseload power prices about 10 times higher than the prices between 2017 and 2021 [23].

Results of the Mesoscale Simulations for the Reference and the Eight Mitigation Scenarios During the Summertime

Table S4. Average Calculated values of the Mean, Max, and Min Values of the main climatic parameters for the reference and the 8 mitigation scenarios at 14:00 and 6:00.

Scenario	Reference Riyadh	Reflective Riyadh	Very Reflective Riyadh	Green and Dry Riyadh	Green and Irrigated Riyadh	Very Green Non-Irrigated (Dry) Riyadh	Very Green and Irrigated Riyadh	Very Green – Very Reflective and Dry Riyadh	Very Green – Very Reflective and Irrigated Riyadh
Max Summer Ambient Temperature at 14:00 pm	46.9	45.6	45.6	47.0	46.5	47.1	46.2	46.2	45.6

Mean Summer Ambient Temperature at 14:00 pm	42.9	41.8	41.7	43.1	42.6	43.2	42.3	42.4	41.6
Min Summer Ambient Temperature at 14:00 pm	39.1	37.9	37.8	39.2	38.8	39.5	38.4	38.8	37.6
Max Summer Ambient Temperature at 06:00 am	38.6	37.1	37.1	38.5	37.3	39.0	38.1	38.3	37.4
Mean Summer Ambient Temperature at 06:00 am	33.0	31.7	31.7	32.7	31.8	32.1	30.9	30.9	30
Min Summer Ambient Temperature at 6:00 am	27.2	26.0	26.0	26.7	26.2	25.1	23.8	23.7	22.6
Max Summer Surface Temperature at 14:00 pm	53.3	48.4	48.4	54.1	52	55.1	42.3	51.5	52.3
Mean Summer Surface Temperature at 14:00 pm	49.7	44.5	44.5	50.0	48.2	50.4	33.8	47.0	44.7
Min Summer Surface Temperature at 14:00 pm	46.1	40.8	40.8	46.1	44.2	45.8	23.5	42.6	37.3
Max Summer Sensible Heat at 14:00 pm, (W/M ²)	449.0	165.2	165.2	474.9	374.2	466.8	438	266.7	325
Mean Summer Sensible Heat at 14:00 pm, (W/M ²)	329.2	120.6	120.6	344.9	262	357.7	221.8	212.0	101.8
Max Summer Latent Heat at 14:00 pm, (W/M ²)	29.8	17.3	17.3	19.8	153.9	17.5	349.9	17.4	300.8
Mean Summer Latent Heat at 14:00 pm, (W/M ²)	17.2	15.4	15.4	13.8	102.6	10.3	142.1	10.2	128.8

Table S5. Calculated Number of Hours above threshold ambient temperatures and the corresponding number of Cooling Degree Hours as calculated for the Reference and the eight Mitigation scenarios, during the summer period.

Scenario	Reference Riyadh	Reflective Riyadh	Very Reflective Riyadh	Green and Dry Riyadh	Green and Irrigated Riyadh	Very Green Non-Irrigated Riyadh	Very Green and Irrigated Riyadh	Very Green – Very Reflective and Dry Riyadh	Very Green – Very Reflective and Dry Riyadh
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									Irrigated Riyadh
Number of Hours above 27 °C	2176	2163	2156	2032	2048	1683	1678	1682	1682
Number of Hours above 30 °C	1987	1918	1901	1757	1746	1481	1476	1455	1454
Number of Hours above 35 °C	1399	1304	1286	1295	1257	1093	1131	1071	1075
Number of Hours above 40 °C	761	577	547	753	701	753	649	641	537
Cooling Degree Hours Base 27 °C	909	831	818	842	811	736	713	692	672
Cooling Degree Hours Base 30 °C	647	573	562	605	575	537	516	496	475
Cooling Degree Hours Base 35 °C	292	235	228	284	261	268	242	233	209
Cooling Degree Hours Base 40 °C	65	34	32	69	56	73	51	50	34

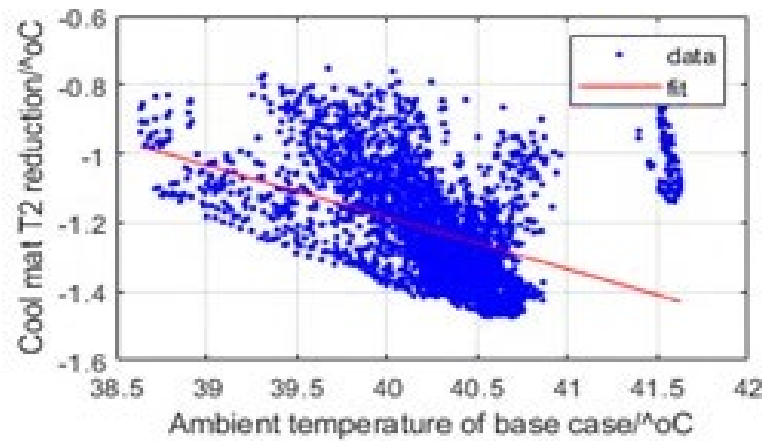


Figure S21A. Association between the background ambient temperature and the temperature drop during the daytime for the scenario of Very Reflective Riyadh

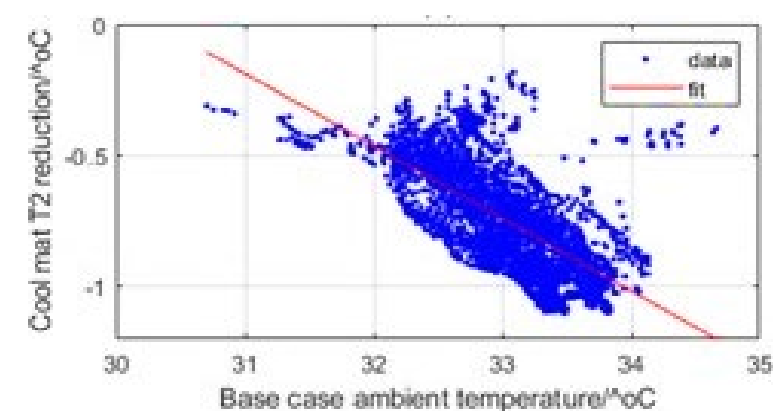


Figure S21B. Association between the background ambient temperature and the temperature drop during the nighttime for the scenario of Very Reflective Riyadh

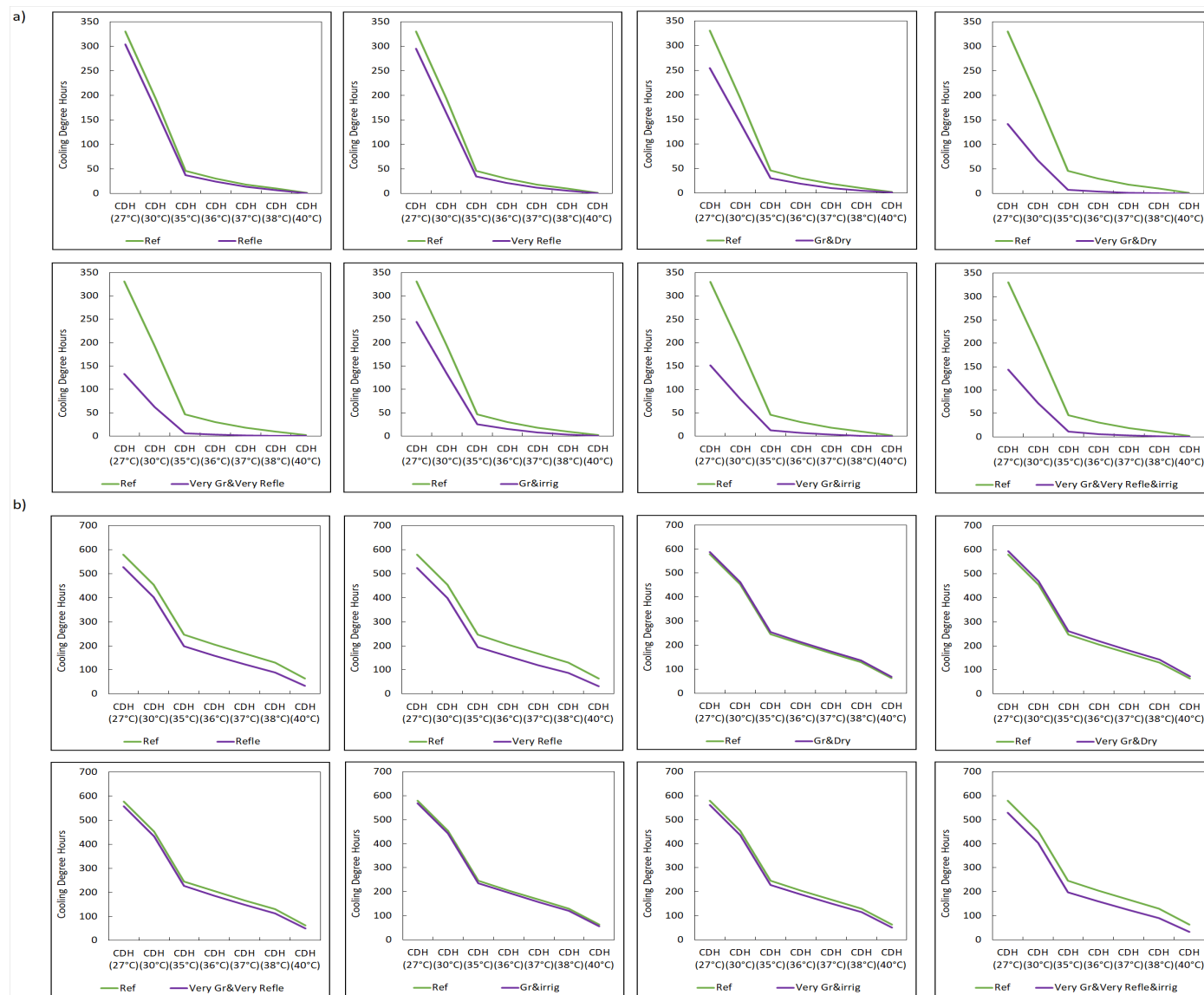


Figure S22 Night-time (a) and daytime (b) Cooling Degree Hours for all the considered mitigation scenarios.

Table S5. Reduction of the cooling load of buildings with one to four stories under the Reflective and Very Reflective Riyadh scenarios.

	One Storey	Two Storey	Three Storey	Four Storey	Average All Buildings
Scenario Reflective Riyadh					
Reduction of the Cooling Load – Indirect Impact (%)	6.2	4.1	3.6	3.4	4.4
Reduction of the Cooling Load – Combined Impact (%)	7.8	5.4	5.3	5.3	5.6
Scenario Very Reflective Riyadh					
Reduction of the Cooling Load – Indirect Impact (%)	8.2	5.3	4.5	4.2	5.2
Reduction of the Cooling Load – Combined Impact (%)	9.6	6.7	6.4	6.3	6.9

Note: Indirect impact considers the cooling load modification because of the ambient temperature reduction. Combined impact considers both the cooling load modification because of the ambient temperature reduction plus the decrease of the absorbed solar radiation by the roof of the building because of the increased albedo.

Table S6. Characteristics of the building retrofit scenarios used in CityBES simulations

Retrofit option	Description
Retrofit roof*	- Add insulation layer: reroof and roof with insulation R24.83 (R-value of 4.37 m² K/W) - Apply Cool Roof Coating with Reflectivity of 0.75 to all buildings (office and residential)

Retrofit external wall*	• Add insulation layer: apply wall insulation of R21 (R-value of 2.04 m² K/W)
Infiltration	• Add air sealing to seal leaks (reduction by 50% compared to the base case)
Retrofit windows	• Replace fixed windows to achieve a U-value of 1.6 W/m²K and SHGC of 0.2 • Use window shades/blinds in all building types

**Note: The R21 for walls is cavity insulation, while that R24.83 for roof is continuous insulation. The R-value noted above is for the insulation layer within the construction of roof or exterior wall. The wall external insulation was increased from 0.92 and 1.074 m² K/W (in the baseline residential and office building respectively) to 2.04 m² K/W in the retrofit scenario. The roof insulation was increased from 1.947 and 2.197 m² K/W (in the baseline residential and office building respectively) to 4.37 m² K/W in the retrofit scenario.*

Impact of Temperature on Evapotranspiration of Greenery and Environmental Impact

Excessive temperatures usually combined with drought, result in the closure of the plant stomates, senescence and increase of the leaves temperature above the ambient one and disruptions to the plants nutrient system, (24). The increase of the surface temperature of the plants increases the release of sensible heat and may result in heating of the ambient air. Several mechanisms are used by plants to ameliorate part of the thermal damage like the increase of the reflectance of the leaves to decrease the absorption of solar radiation and the production of heat shock proteins [25].

Trees, contribute to decreasing the concentration of harmful pollutants like ground-level ozone and Particulate Matter [50]. Trees can remove between 2-7% of the locally emitted PM₁₀ [26], while can reduce the 8-hour average peak concentration of PM₁₀ by 1-2% [27]. However, trees emit BVOCs, which are about 2-3 times more reactive than the average emissions of oil combustion [28]. The majority of BVOCs are isoprenoids, monoterpenes and sesquiterpenes, which result in a considerable increase in the concentration of tropospheric ozone and the production of airborne particles during periods of high temperature [29].

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