Deadly Heat Exposure in an Urbanized World

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Abstract

Climate-change exposes an increasing share of the world population to potentially lethal heat, a threat accentuated by rapid urbanization. Here, we project occurrence of future deadly heat for urban agglomerations around the world until 2080 by using CMIP6 climate model projections of temperature and relative humidity, urbanization prospects and GDP projections from the SSP scenarios. We show that while nearly all regions within latitudes 35°S - 45°N experience an increase in days of deadly heat, Sub-Saharan Africa and Southeastern Asia are particularly exposed, a trend exacerbated by rapid urbanization. By 2080, between 2.3 (59%) (SSP1-2.6) and 3.0 (75%) (SSP5-8.5) billion urban dwellers will experience more than 30 annual days of deadly heat, including 477 (66%) - 546 (77%) million in Sub-Saharan Africa and 988 (93%) - 993 million (94%) in South and South-Eastern Asia. The exposure to heat is highly unequal, with some of the poorest regions affected the most. Our results imply that jointly mitigating climate change, planning for well-ventilated cities, and combating poverty to enable economic access to air conditioning is required to avert a global-scale humanitarian crisis.

1 Introduction

Extreme heat is an increasingly frequent reality for many global populations living in cities[1;2;3;4;5;6]. Very high air temperatures and their lethal combination with high humidity are expected to increasingly surpass limits of human acclimatization necessitating behavioural change[7], leading to migration[8], and may, by 2070, expose up to 3.5 billion people worldwide to temperature regimes that are nowadays only exceeded in uninhabited parts of the planet[9]. Globally, 37% of warm-season heat-related deaths have been attributed to anthropogenic climate change[10]. Individual heat events can be attributed to anthropogenic climate change, such as the Russian 2010 heatwave[11;12;13], the European 2019 heatwave[14] or the unprecedented temperatures in the Pacific North-West during summer 2021[15].

Heat "extremes" are defined in numerous ways, both as a deviation from the climatological mean or in absolute values. Dry-Bulb air temperature is an adequate measure for capturing extreme heat, and has been shown to explain extra-mortality caused by heat in epidemiological studies[16]. It becomes more meaningful to the human ability to cool via respiration when combined with relative humidity RH and further parameters such as wind, or irradiation[17]. The Wet-Bulb Globe Temperature, developed to keep military personnel save during training days in extreme heat[18], is likely one of the better studied indicators for heat impacts on the human body. However its calculation requires in-situ measurements which are not readily available from climate or weather models. For that purpose, manifold heat indices have been developed, and even if they are similar in principle, there is not coherent definition for "extreme" or "deadly" heat[19]. Different indicators have been shown to all increase significantly with average temperature, albeit with a substantial spread[20].

The urban focus matters threefold. First, more than two thirds of humanity is expected to live in cities by 2050, with most urbanization expected to happen in the Global South[21]. Second, the urban heat island effect[22] increases both daytime and nighttime temperatures. Third, local air pollutants, concentrated in metropolitan areas, amplify health impacts from heat[23]. Not even accounting for urban heat islands, 22% of cities worldwide are projected to enter previously uncharted climate territory by 2050[24]. Taking into account urban heat effects, a warming of 4K is projected for cities in several world regions including the United States, the Middle East, inland South America and Africa under a high-emissions scenario, larger than regional warming without urban effects[25]. Individual magnitudes of the urban heat island effect strongly depend on climatic conditions and both urban morphology and local meteorological conditions.

Extreme heat does not impact people equally. Individual risk and vulnerability factors to extreme heat - such as age, pre-existing medical conditions and access to air-conditioning - all matter[26;27;28].

However, despite the apparent impact of heat events on specifically urban areas and poor populations, there is scarce quantitative understanding of which cities and socioeconomic groups will be most impacted by deadly heat, and what their adaptive capacities are. But better understanding of distributional consequences is important to tailor geographically specific adaptation measures.

Here we investigate the impact of extreme heat against the backdrop of rapid urbanization, another major transition of the 21st century. Exposure to extreme heat has been previously assessed in several studies[29;30;31;2;1], each using slightly varying definitions of heat extremes and different methodologies to assess population numbers. We focus our analysis on cities and reflect urban equity considerations as these are known to amplify vulnerability to climate change[32]. In this paper, we aim to determine the dynamics of deadly heat and the exposure of urban populations. For this, we intersect urbanization dynamics and climate projections. We obtain per-capital exposure in "person-days of heat", a metric previously used[30;29;2;1]. We conclude by discussing how coordinated climate change mitigation and adaptation efforts in cities can address this challenge.

2 Methods

Trend estimates for future emissions and urban populations depend on the larger economic and social pathway the world may follow. Future urban population numbers reported here reflect the choices and assumptions made in different scenarios explicated in the Shared Socioeconomic Scenario (SSPs)[33]. We use three of these as part of the Scenario Model Intercomparison Project (ScenarioMIP)[34]: i) strong mitigation in a sustainable world (SSP1-2.6); ii) a baseline scenario (SSP3-7.0); iii) a severe climate change scenario driven by fossil-fuel technology and global inequality (SSP5-8.5). We first develop city-level population estimates for 1860 cities based on Shared Socioeconomic Pathways (SSPs)[33]. For this we use the World Urbanization Prospects[21], the SSP-projections for country-level population numbers from IIASA-WiC POP[35] and the country-level urban population share from the NCAR population prospects on country-level[36]. This includes all urban agglomerations which had a population $> 300,000$ in 2018, and we extrapolate population numbers assuming a constant population rank of cities onward from 2030. We then apply previously published thresholds for temperature-humidity combinations that have been shown to increase mortality[3] to projections of surface air temperature (*tas*) and relative humidity (*hurs*). These are from 10 bias-corrected models in ISIMIP3b[37;38], which are taken from the CMIP6 simulations, and using the SSP1-2.6, SSP3-7.0 and SSP5-8.5 scenarios[34]. A full list of the climate model data used can be found in Appendix 5.1.

3 Results

3.1 Urban population

Urban population numbers in Europe, Northern America and Eastern Asia are expected to peak mid-century and then decline to varying degrees (Fig. 1) throughout all SSP scenarios. Eastern Asia shows a more significant population decline in all scenarios, owing to the consequences of China's population control policies. Population numbers in Africa and Asia are expected to peak towards the end of the century in SSP1 ("Sustainability"), SSP2 ("Middle of the Road") and SSP5 ("Fossil-fueled Development"). In Sub-Saharan Africa, total population and urbanization rates are expected to keep growing beyond 2100, most strongly in SSP4 ("Inequality") and SSP3 ("Regional Rivalry"), slightly weaker in SSP2. The Americas also are projected continued population growth in SSP3 and SSP5 scenarios, albeit at a lower rate than Africa. In Europe, higher urban population numbers are projected under SSP3 and SSP5 than under the other scenarios.

3.2 Trends in urban population exposure to deadly heat

Extreme heat, here expressed in annual number of deadly heat days, is set to be-

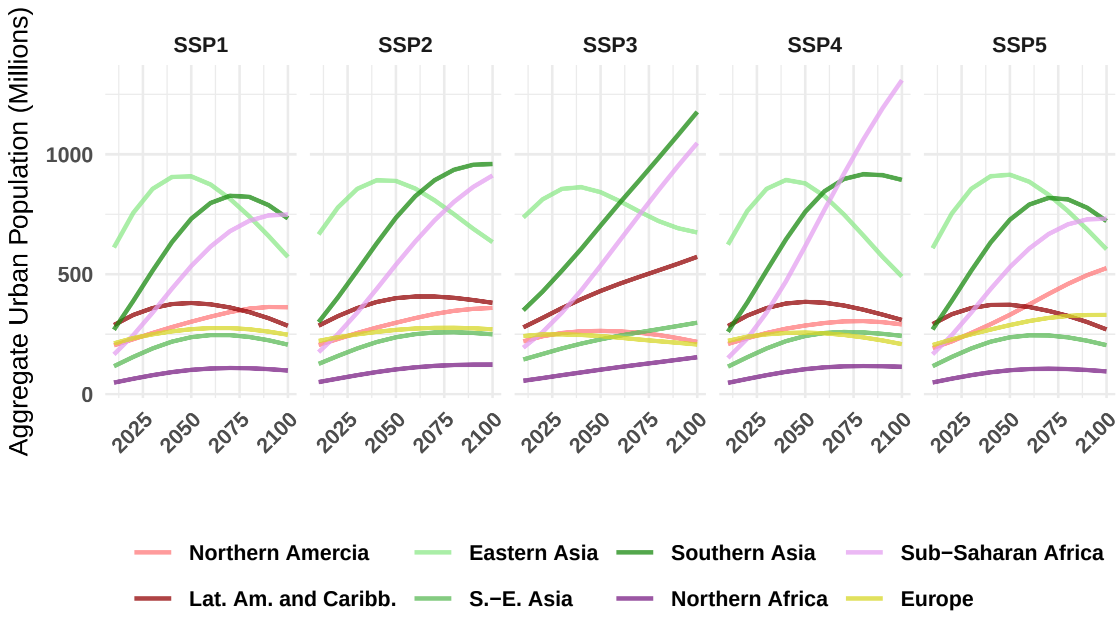

Figure 1: Aggregate urban population projections based on the World Urbanization Prospects and SSP scenarios. These projections include all cities which had a population count $> 300,000$ in 2018.

come more prevalent in all world regions (Fig. 2). Under all climate scenarios, urban dwellers will experience previously unknown numbers of extreme heat days which increasingly often will be deadly. In the low emissions scenario (SSP1-2.6), warming is projected to level off in the second half of the century, but extreme heat events keep increasing in the SSP3-7.0 and SSP5-8.5 scenarios. In Northern America, more than 10 annual deadly heat days were experienced by 48 cities in a year 2000 climate according to our simulations. This will change dramatically in future climates: in a baseline 7.0 emissions scenario, 108 out of 161 cities will experience at least 10 deadly heat days and 34 of them will experience more than 100 days of deadly heat by the end of the century. The hottest cities are located in Florida in this analysis. With strong climate mitigation (SSP1-2.6), 70 of Northern American cities would experience more than 10 annual deadly heat days, and only 24 cities

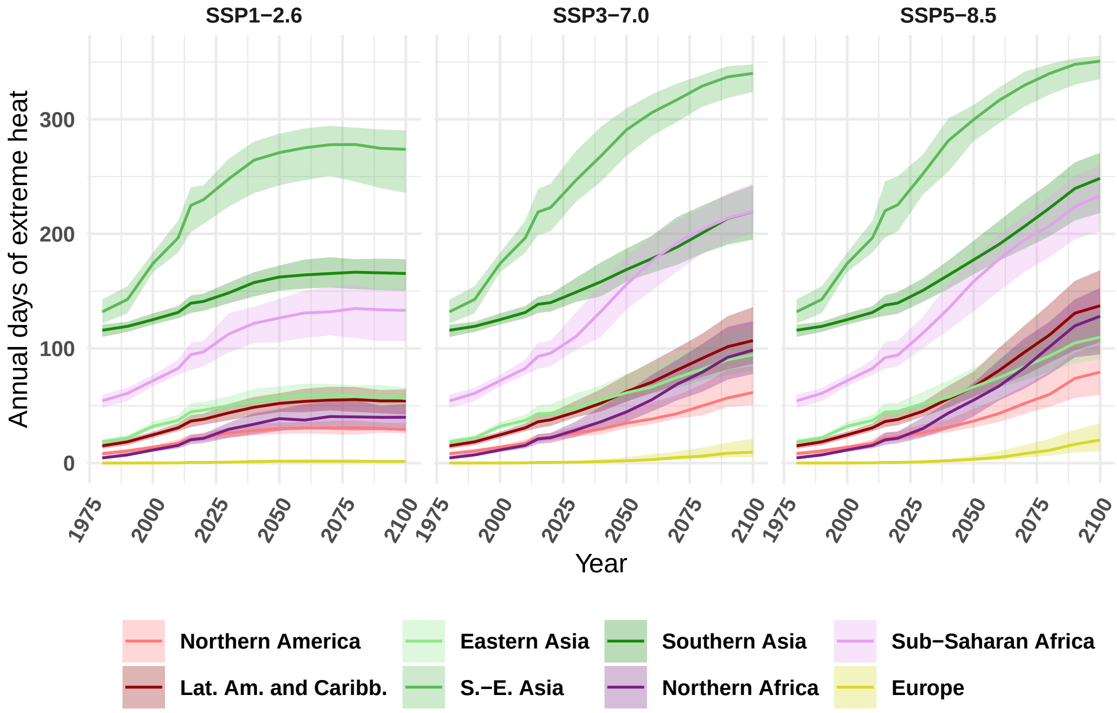

Figure 2: Annual mean days of deadly heat of all cities aggregated by Regions for SSP1-2.6, SSP3-7.0 and SSP5-8.5. Smoothed with a running 10-year average. The line depicts the multi-model median, the shaded areas the 10% and 90% multi-model quantiles. Average values are weighted by population size of the cities.

(instead of 34) would pass the 100-day threshold. Also in Sub-Saharan Africa, the heat threshold will be passed much more frequently in future climates. While in the year-2000 climate, 92 out of 177 cities in Sub-Sahara African experienced more than 30 annual deadly heat days, by 2080 116 cities would pass that threshold in an RCP 7.0 baseline scenario and 108 cities in an RCP 2.6 scenario. In baseline RCP 7.0, 112 cities will have more than 120 annual deadly heat days (91 in SSP1-2.6, 114 in SSP5-8.5)).

Deadly heat conditions have their worst direct impact on human life where they directly intersect with human settlements. The population exposure to heat is thus conflated by both climate and urbanization trends. Some parts of the world experience large urban population

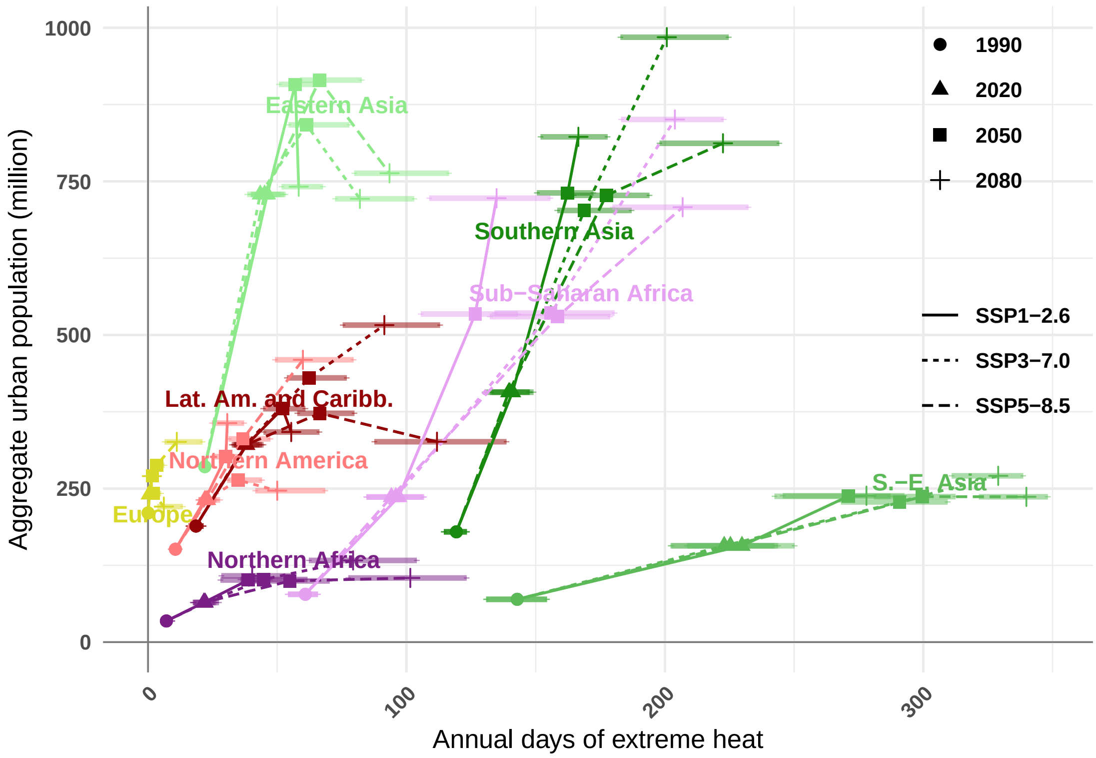

Figure 3: Days of deadly heat and population dynamics as individual change contributors to heat exposure. The x-axis corresponds to days of deadly heat and is influenced by the choice of the emissions scenario, while the y-axis reflects demographic trends that are influenced by the choice of socioeconomic scenarios (SSP). Three scenario combinations are shown: high climate mitigation (SSP1-2.6), medium mitigation (SSP3-7.0) and no climate change mitigation (SSP5-8.5). The lines represent the multi-model median, the horizontal error bars the 10% and 90% multi-model quantiles.

growth, others a strong increase in deadly heat days, and in some areas both come together. In Fig.3, the trends of both deadly heat exposure and urban population trends are depicted, aggregated by world region.

World regions which show predominantly a growth in urban population, are Eastern Asia and Southern Asia. Eastern Asia has seen the bulk of its population growth before the year 2020, and the number of deadly heat days expected will increase from less than 50 to below 100 in all scenarios. Urban Population in

Southern Asia will more than double by the end of the century, and the average days of deadly heat increase from about 140 to 200 in SSP3-7.0.

In South-Eastern Asia and Northern Africa, the warming climate contributes more to total heat exposure than their urban population growth, in the other regions, the effects are more balanced or dominated by population growth.

South-Eastern Asia shows as by far the hottest region under our heat definition: The heat threshold applied here is surpassed on average in already more than 200 days in cities in the region, and will reach 178 even in a high mitigation scenario (2.6) by the end of the century, with climate scenarios 7.0 and 8.5 surpassing the 300 days. Urban population is projected to grow 1.5-1.7 fold from 157 million urban dwellers in 2020 to up to 270 million in SSP3 (236 million and 236 million in SSP1 and SSP5). However, from 2050 to 2080, all growth in exposure to deadly heat is projected to stem from an increase in heat days, as population growth will flatten out.

Eastern Asia is the only region with a noticeable decline in population numbers and thus the potential decreasing in total exposure. However, the annual number deadly heat days will keep increasing in 7.0 and 8.5 scenarios.

Sub-Saharan Africa arguably stands out as the region with the greatest dynamics both in heat as well as in population and is experiencing imminent change. The region would move from a relatively low exposure of 8.1 billion person-days in the year 2000 to 38 billion person-days in 2030 even with high climate mitigation (RCP2.6), a near 5-fold change. The days of deadly heat quickly reach levels experienced by Southern Asia and South-Eastern Asia today. By 2080, the exposure to deadly heat would reach levels only surpassed by Southern Asia. This means that Sub-Saharan until recently has just been short of reaching the applied threshold for deadly heat, but will soon exceeded it very frequently.

The cities with the highest total exposure are mega-cities in hot regions with high population densities. The top ten in

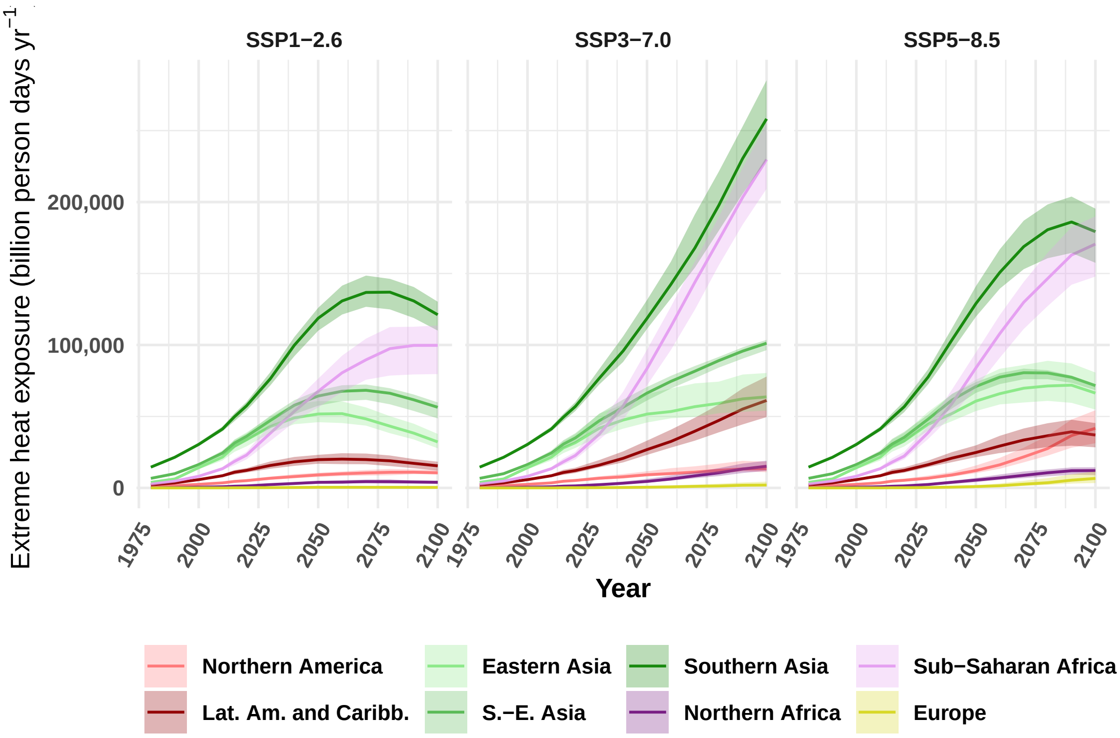

Figure 4: Exposure to deadly heat for 8 sub-regions of the world and three scenario combinations: high climate mitigation (SSP1-2.6), medium mitigation (SSP3-3.7) and no climate change mitigation (SSP5-8.5). A dramatic relative increase of exposure to deadly heat is apparent particularly in Sub-Saharan Africa and Southern Asia. The line depicts the multi-model median, the shaded areas the 10% and 90% multi-model quantiles.

this analysis are Dhaka, Lagos, Mumbai, Delhi, Manila, Jakarta, Kolkata, Karachi, Chennai and Bangkok 1. They are all located in Asia or Africa. Even though some high-GDP cities can be identified in the deadly heat zone, including Houston (USA), Dubai (UAE) or Shanghai (CHN), the majority of the cities that experience days of deadly heat are in countries classified as "developing"[39].

Table 1: Ranking of cities most exposed to deadly heat days. Pop: urban population in million; DDH: Average days of deadly heat; THE: heat exposure in million person days yr^{-1}

Rank		2020 SSP5-8.5			2080 SSP1-2.6			2080 SSP5-8.5		
(2030)	City	Pop.	DDH	THE	Pop.	DDH	THE	Pop.	DDH	THE
1	Dhaka	28	210.00	5915.00	42	225.00	9527.00	40	264.00	10641.00
2	Lagos	21	277.00	5716.00	48	317.00	15173.00	47	362.00	17152.00
3	Mumbai (Bombay)	25	227.00	5580.00	40	245.00	9799.00	40	315.00	12587.00
4	Delhi	39	131.00	5126.00	63	143.00	9090.00	63	183.00	11583.00
5	Manila	17	273.00	4606.00	25	305.00	7663.00	24	356.00	8717.00
6	Jakarta	13	338.00	4297.00	15	355.00	5175.00	14	365.00	5249.00
7	Kolkata (Calcutta)	18	229.00	4043.00	29	240.00	6890.00	29	279.00	7974.00
8	Karachi	20	191.00	3907.00	34	196.00	6766.00	33	225.00	7526.00
9	Chennai (Madras)	14	253.00	3508.00	22	269.00	6049.00	22	346.00	7761.00
10	Krung Thep (Bangkok)	12	285.00	3451.00	14	296.00	4210.00	15	336.00	4972.00
11	Thành Pho Ho Chí Minh (Ho Chi Minh City)	11	302.00	3342.00	15	322.00	4854.00	15	358.00	5287.00
12	Kuala Lumpur	10	277.00	2719.00	12	327.00	3830.00	12	365.00	4309.00
13	Shanghai	33	65.00	2154.00	28	72.00	2056.00	28	107.00	3031.00
14	Singapore	6	338.00	2147.00	6	355.00	2118.00	7	365.00	2400.00
15	Lahore	17	125.00	2110.00	28	134.00	3830.00	28	176.00	4868.00
16	Surat	10	214.00	2081.00	16	225.00	3555.00	16	268.00	4225.00
17	Guangzhou, Guangdong	16	127.00	2049.00	14	146.00	2015.00	14	185.00	2567.00
18	Dar es Salaam	11	184.00	1988.00	27	203.00	5531.00	26	290.00	7575.00
19	Shenzhen	15	133.00	1941.00	13	151.00	1890.00	13	190.00	2387.00
20	Abidjan	7	263.00	1878.00	10	291.00	2956.00	9	363.00	3270.00
60	Houston	7	109.00	791.00	10	120.00	1213.00	13	159.00	2073.00
906	Roma (Rome)	4	5.00	24.00	5	12.00	60.00	6	63.00	377.00
1566	Madrid	7	0.00	0.00	8	0.00	0.00	10	0.00	4.00

4 Discussion

Deadly heat intersects with urban population dynamics and will strongly increase in future climates[3]. Strong increases both in population numbers and deadly heat days appear in Western and Eastern Africa, Southern and South-Eastern Asia and the Caribbean region. In historical climates, large cities that have been affected by deadly heat conditions lie no further north than $\sim 43°$ N, but with climate change, this zone expands to $\sim 48°$ N by 2080. The Southern Hemisphere boundary is located $\sim 35°$ S, owing to the different distribution of land and oceans.

In 2020, 1.2 billion (of 2.6 billion) of the global urban population have been affected by at least 30 deadly heat days each year (46%), a number to rise to 2.2 billion out of 3.6 billion (61%) by 2050 and 3.0 billion out of a total of 4.3 billion people (70%) by 2080 in SSP3-7.0. Taking the other scenarios into consideration, by 2080, between 2.3 (59%) (SSP1-2.6) and 3.0 (75%) (SSP5-8.5) billion urbanites are likely to experience more than

30 annual days of deadly heat worldwide. In Sub-Saharan Africa, 477 (66%) - 546 (77%) million are affected and in South and South-Eastern Asia above 90% of all urban populations experience at least a month of deadly heat in all scenarios by 2080 (ranges are based on SSP1-2.6 and SSP5-8.5 scenarios).

We find the highest relative increases in rapidly urbanizing Sub-Saharan Africa, and the overall highest heat load in South-Eastern Asia. There, extreme heat will soon surpass the deadliness threshold used here. Our results demonstrate that urban deadly heat (at least one day a year) will impact 86% of urbanized humanity by 2080, compared to 66% in 2020. But the urban poor, both within cities, and comparatively between cities, are most affected by heatwaves. While representing about half of the projected urban population, affected urbanites will share only up to a quarter (19%-25%) of global GDP. In Sub-Saharan Africa they will only share 0.2% of global GDP and 1.5% in South and South-Eastern Asia.

The numbers for heat exposure presented in this study lie in the order of magnitude that have been drawn in other studies[3;31;30;2]. Research on cities analogues[24] confirms a latitudinal shift of cities towards hotter regimes, with its rate of change increasing with distance from the equator, but cities close to the equator moving into a subtropical climate. The same research demonstrates that 22% of all global cities (population > 1 million), and 64% of them in the tropics, will experienced globally uncharted climate conditions by 2050. While we here consider "deadly" heat, other research has shown that climatological heat extremes can equally be deadly in particular to older population groups or those with pre-existing conditions.

The numbers reported here are no exact numbers, but shed a light on the magnitude and geographic locations of where the challenge is greatest. Uncertainties exist in both population and climate projections, as well as in the blurry threshold of when heat becomes indeed lethal. The example of the 2021 Canada heatwave[15] has shown that heat extremes may come indeed quicker and in a larger magnitude than suggested by climate models. Further, lethality thresholds for heat are difficult to pin down to exact numbers as they depend too much on the individual risk-factors, exposure and adaptive capacity. The many heat metrics which exist cannot be compared across studies straight-forwardly[40]. Impacts on human well-being and productivity appear already at much lower heat levels, and in cool climate, extra mortality has been observed during heatwaves which are relative climatological extremes but stay below absolute lethality thresholds.

The dramatic relative increase of exposure to deadly heat projected for Sub-Saharan Africa implies a massive adaptation challenge. Large parts of Sub-Saharan Africa lack adaptive capacity, and heat is only one among many challenges for large shares of population groups living below the poverty line and without access to air-conditioning[41]. Uncertainty in both economic and population growth in this part of the world is very high, and rapid urbanization is already happening. It is challenge and opportunity alike to reduce the heat load in yet-to-be-built cities. There are three ways to address the modelled future heat impact: 1) mitigate climate change; 2) reduce poverty and thus increase adaptive capacity; and 3) adapt urban structures. First, reducing GHG emissions globally and thus switching from a 7.0 to a lower-emissions pathway will alleviate the health burden and save lives. Specifically, the population exposed to deadly heat end of the century may be 64% lower in SSP1-2.6 (387 billion person days) compared to SSP3-7.0 (609 billion person days).

Second, deadly heat impact can be avoided locally by sufficiently high quality of shelter, access to cooling, and by the capacity to avoid working outside in extreme heat. Public prevention campaigns, and public health measures also can play a crucial role[42;27;43]. Levels of poverty and inequality, and the capacity of the public health system, are hence a key determinant of future deadly heat impact. Socioeconomic development that focuses on providing the capacity and service-levels for the poor that enables them to handle heat stress is hence key to prevent the worst impact of future deadly heat events. On an individual level, populations with low adaptive capacity will have little to no access to air-conditioning[41;44]. When considering national poverty headcounts at the 5.50 USD (PPP) poverty level, then a total of roughly 500 million urban dwellers live below this upper poverty line among a total urban population of 3 billion people by 2030, and roughly 1 billion people by 2080 if poverty rates stay the same. Third, cities need to urgently stave off additional local warming by reducing their urban heat island effect. Particularly, urban form can be changed to improve thermal comfort[45;46;47]. The possibility of a scaled installation of air-conditioning implies massive challenges to a strongly increased urban heat island effect[48], as well as a dramatic rise in energy demand, further hampering climate mitigation efforts. Thus, a re-thinking of urban design practices towards green infrastructure is the preferred way to go. Traditional architectures point at sustainable solutions[49], and green roofs and urban parks provide cooling.

Competing Interests

The authors declare that there are no competing interests.

Author Contributions

SL and FC conceptualized the study. CM contributed the code for determining deadly heat from climate data and assisted with its implementation as well as interpretation of the results. DR contributed to the discussion on distributional aspects. SL wrote the computer code, carried out the analyses and produced the figures. SL wrote the first draft of the manuscript, which was substantially reviewed and revised by all authors.

Data Availability

The code used for producing the research outcomes and figures in this article can be shared in an GitHub repository upon request. The climate model output used is available via the ISIMIP programme.

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References

[1] Saeed, F., Schleussner, C.-F. & Ashfaq, M. Deadly Heat Stress to Become Commonplace Across South Asia Already at 1.5°C of Global Warming. *Geophys Res Lett* **48**

(2021).

[2] Rohat, G., Flacke, J., Dosio, A., Dao, H. & Maarseveen, M. Projections of Human Exposure to Dangerous Heat in African Cities Under Multiple Socioeconomic and Climate Scenarios. *Earth's Future* 2018EF001020 (2019).

[3] Mora, C. *et al.* Global risk of deadly heat. *Nature Climate Change* **7**, 501–506 (2017).

[4] Gasparrini, A. *et al.* Projections of temperature-related excess mortality under climate change scenarios. *The Lancet Planetary Health* **1**, e360–e367 (2017).

[5] Stocker, T. F. *et al.* Climate change 2013: The physical science basis. *Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change* 14 (2013).

[6] Matthews, T. K. R., Wilby, R. L. & Murphy, C. Communicating the deadly consequences of global warming for human heat stress. *Proc Natl Acad Sci USA* **114**, 3861–3866 (2017).

[7] Hanna, E. & Tait, P. Limitations to Thermoregulation and Acclimatization Challenge Human Adaptation to Global Warming. *International Journal of Environmental Research and Public Health* **12**, 8034–8074 (2015).

[8] Zander, K. K., Richerzhagen, C. & Garnett, S. T. Human mobility intentions in response to heat in urban South East Asia. *Global Environmental Change* **56**, 18–28 (2019).

[9] Xu, C., Kohler, T. A., Lenton, T. M., Svenning, J.-C. & Scheffer, M. Future of the human climate niche. *Proc Natl Acad Sci USA* 201910114 (2020).

[10] Vicedo-Cabrera, A. M. *et al.* The burden of heat-related mortality attributable to recent human-induced climate change. *Nat. Clim. Chang.* **11**, 492–500 (2021).

[11] Rahmstorf, S. & Coumou, D. Increase of extreme events in a warming world. *Proc Natl Acad Sci USA* **108**, 17905 (2011).

[12] Dole, R. *et al.* Was there a basis for anticipating the 2010 Russian heat wave? *Geophysical Research Letters* **38** (2011).

[13] Otto, F. E. L., Massey, N., van Oldenborgh, G. J., Jones, R. G. & Allen, M. R. Reconciling two approaches to attribution of the 2010 Russian heat wave: RUSSIAN HEAT WAVE 2010. *Geophysical Research Letters* **39**, n/a–n/a (2012).

[14] Vautard, R. *et al.* Human contribution to the record-breaking July 2019 heat wave in Western Europe. *Word Weather Attribution* 32 (2019).

[15] Philip, S. Y. *et al.* Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada June 2021. *World Weather Attribution* 37 (2021).

[16] Armstrong, B. *et al.* The Role of Humidity in Associations of High Temperature with Mortality: A Multicountry, Multicity Study. *Environ Health Perspect* **127**, 097007 (2019).

[17] Macpherson, R. K. The Assessment of the Thermal Environment. A Review. *Occupational and Environmental Medicine* **19**, 151–164 (1962).

[18] Yaglou, C. P. & Minard, D. Control of heat casualties at military training centers. *AMA Arch Ind Health* **16**, 302–316 (1957).

[19] Perkins, S. E. A review on the scientific understanding of heatwaves—Their measurement, driving mechanisms, and changes at the global scale. *Atmospheric Research* **164-165**, 242–267 (2015).

[20] Schwingshackl, C., Sillmann, J., Vicedo-Cabrera, A. M., Sandstad, M. & Aunan, K.

Heat Stress Indicators in CMIP6: Estimating Future Trends and Exceedances of Impact-Relevant Thresholds. *Earth's Future* **9** (2021).

[21] United Nations, Department of Economic and Social Affairs, Population Division. World Urbanization Prospects: The 2018 Revision, Online Edition. (2018).

[22] Oke, T. R. City size and the urban heat island. *Atmospheric Environment (1967)* **7**, 769–779 (1973).

[23] Harlan, S. L. & Ruddell, D. M. Climate change and health in cities: Impacts of heat and air pollution and potential co-benefits from mitigation and adaptation. *Current Opinion in Environmental Sustainability* **3**, 126–134 (2011).

[24] Bastin, J.-F. *et al.* Understanding climate change from a global analysis of city analogues. *PLoS ONE* **14**, e0217592 (2019).

[25] Zhao, L. *et al.* Global multi-model projections of local urban climates. *Nat. Clim. Chang.* **11**, 152–157 (2021).

[26] Semenza, J. C. *et al.* Heat-Related Deaths during the July 1995 Heat Wave in Chicago. *N Engl J Med* **335**, 84–90 (1996).

[27] Gasparrini, A. *et al.* Mortality risk attributable to high and low ambient temperature: A multicountry observational study. *The Lancet* **386**, 369–375 (2015).

[28] Guo, Y. *et al.* Heat Wave and Mortality: A Multicountry, Multicommunity Study. *Environmental Health Perspectives* **125** (2017).

[29] Jones, B. *et al.* Future population exposure to US heat extremes. *Nature Climate Change* **5**, 652–655 (2015).

[30] Jones, B., Tebaldi, C., O'Neill, B. C., Oleson, K. & Gao, J. Avoiding population exposure to heat-related extremes: Demographic change vs climate change. *Climatic Change* **146**, 423–437 (2018).

[31] Harrington, L. J. & Otto, F. E. L. Changing population dynamics and uneven temperature emergence combine to exacerbate regional exposure to heat extremes under 1.5 °C and 2 °C of warming. *Environmental Research Letters* **13**, 034011 (2018).

[32] Reckien, D. *et al.* Climate change, equity and the Sustainable Development Goals: An urban perspective. *Environment and urbanization* **29**, 159–182 (2017).

[33] Riahi, K. *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* **42**, 153–168 (2017).

[34] O'Neill, B. C. *et al.* The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci. Model Dev.* **9**, 3461–3482 (2016).

[35] Kc, S. & Lutz, W. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change* **42**, 181–192 (2017).

[36] Jiang, L. & O'Neill, B. C. Global urbanization projections for the Shared Socioeconomic Pathways. *Global Environmental Change* **42**, 193–199 (2017).

[37] Lange, S. Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0). *Geosci. Model Dev.* **12**, 3055–3070 (2019).

[38] Lange, S. ISIMIP3BASD v2.5.0 (2021).

[39] UN-Habitat. UN-Habitat Urban Data. http://urbandata.unhabitat.org (2018).

[40] Perkins-Kirkpatrick, S. E. & Gibson, P. B. Changes in regional heatwave characteristics as a function of increasing global temperature. *Sci Rep* **7**, 12256 (2017).

[41] Mastrucci, A., Byers, E., Pachauri, S. & Rao, N. D. Improving the SDG energy poverty targets: Residential cooling needs in the Global South. *Energy and Buildings* **186**, 405–415 (2019).

[42] Fouillet, A. *et al.* Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. *International Journal of Epidemiology* **37**, 309–317 (2008).

[43] Centre, R. C. C. RCCC Heatwave Guide. http://www.climatecentre.org/downloads/files/IFRCGeneva/RCCC%20Heatwave%20Guide%202019%2 (2019).

[44] Lohrey, S., Chua, M., Gros, C., Faucet, J. & Lee, J. Perceptions of heat-health impacts and the effects of knowledge and preventive actions by outdoor workers in Hanoi, Vietnam. *Science of The Total Environment* **794**, 148260 (2021).

[45] Masson, V., Bonhomme, M., Salagnac, J.-L., Briottet, X. & Lemonsu, A. Solar panels reduce both global warming and urban heat island. *Frontiers in Environmental Science* **2**, 14 (2014).

[46] Fernandez Milan, B. & Creutzig, F. Reducing urban heat wave risk in the 21st century. *Current Opinion in Environmental Sustainability* **14**, 221–231 (2015).

[47] Zhou, B., Rybski, D. & Kropp, J. P. The role of city size and urban form in the surface urban heat island. *Scientific Reports* **7** (2017).

[48] Lemonsu, A., Viguié, V., Daniel, M. & Masson, V. Vulnerability to heat waves: Impact of urban expansion scenarios on urban heat island and heat stress in Paris (France). *Urban Climate* **14**, 586–605 (2015).

[49] Johansson, E. Influence of urban geometry on outdoor thermal comfort in a hot dry climate: A study in Fez, Morocco. *Building and Environment* **41**, 1326–1338 (2006).

[50] Lange, S. ISIMIP3b bias adjustment fact sheet (2021).

[51] Hoornweg, D. & Pope, K. Population predictions for the world's largest cities in the 21st century. *Environment and Urbanization* **29**, 195–216 (2017).

[52] Jones, B. & O'Neill, B. C. Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. *Environ. Res. Lett.* **11**, 084003 (2016).

5 Supporting Information

5.1 Climate data processing

We use the variables surface relative humidity *hurs* and surface temperature *tas* in daily resolution from the CMIP6 climate models listed in Tab. 2. We did not use the CMIP6 output directly, but relied on the model data prepared for the ISIMIP3b, which is bias-corrected and harmonized in its resolution[37;38]. We use a total of 10 ISIMIP3b models, of which four are included in the Primary ISIMIP3b input data, and six in the Secondary input data.

Model	Variables	Ensemble
ISIMIP3b Primary		
GFDL-ESM4	*tas*; *hurs*	r1p1f1
MPI-ESM1-2-HR	*tas*; *hurs*	r1i1p1f
MRI-ESM2-0	*tas*; *hurs*	r1i1p1f
UKESM1-0-LL	*tas*; *hurs*	r1i1p1f2
ISIMIP3b Secondary		
IPSL-CM6A-LR	*tas*; *hurs*	r1i1p1f2
CNRM-CM6-1	*tas*; *hurs*	r1i1p1f2
CNRM-ESM1-2	*tas*; *hurs*	r1i1p1f2
CANESM5	*tas*; *hurs*	r1i1p1f1
EC-EARTH3	*tas*; *hurs*	r1i1p1f1
MIROC6	*tas*; *hurs*	r1i1p1f1

Table 2: Primary and Secondary models from ISIMIP3b used in this study. All model data comes from CMIP6 output[50].

We use a support vector model on *tas* and *hurs* for determining heat anomalies as presented in[3]. We use a 95% margin for the SVM to select the heat anomaly as lethal. For each city, number of deadly days are summarized per year, and the outputs reported in this paper are the 10-year rolling mean of deadly days.

We use the IPCC AR6 language for depicting multi-model uncertainty: *very likely* (90% – 100%) and *likely* (66% – 100%) for the multi-model central range. These are applied to the rolling 10-year mean number of deadly days.

5.2 Population Predictions

Population predictions for individual cities over several decades are to be taken with a grain of salt. Reasons are the uncertainty in growth rates, owing to both their economic and social drivers, and possible inhibitors such as climate change, lack of land mass or other local resource constraints. We here (Tab. 3) compare our results for urban population numbers with the outcome of a more refined analysis which population size for the 100 largest cities under different assumptions for urban growth rate[51]. The projections are largely in the same order of magnitude, even though some exceptions exist (Table 3) which are a result of the different methodologies: While we here assume a constant distribution among cities in one country, we do not use the urban growth rate of individual cities as done in[51], which leads to an overestimation of the growth of large cities in our methodology.

5.3 Caveats

Further methodological challenges include the challenge to forecast individual city growth and the large, but difficult to model, contribution of the urban heat island effect on temperature.A practical solution to account for the urban heat island effect direct in climate models has recently been presented using an urban climate emulator that has originalle been included in the CESM2 climate model[25].

The urban population projections presented here do not account for differential growth rates of different cities, which exist without doubt. Different assumptions for how the observed urban growth may continue in future has been investigated[51], and a further way to include precise population numbers could be through the use of spatially explicit population forecasts[52].

Scenario	City	Pop. this study (rank) 2100 (million)	Pop. in[51] (rank) 2100 (million)
SSP1	Delhi	55.8 (1)	44.3 (5)
	Lagos	51.9 (2)	61.3 (1)
	Kinshasa	50.7 (3)	48.8 (3)
	Dhaka	37.3 (4)	40.2 (7)
	Cairo	35.6 (5)	
SSP2	Delhi	73.0 (1)	48.9 (6)
	Lagos	62.1 (2)	79.8 (1)
	Kinshasa	59.2 (3)	60.3 (3)
	Mumbai	46.1 (4)	57.6 (4)
	Dhaka	45.3 (5)	42.3 (9)
SSP3	Delhi	88.1 (1)	44.6 (9)
	Lagos	76.1 (2)	100.1 (1)
	Kinshasa	60.6 (3)	50.8 (6)
	Dhaka	57.4 (4)	45.5 (8)
	Karachi	56.5 (5)	52.8 (4)
WUP	Lagos	NA	88.5 (1)
	Kinshasa	NA	88.3 (2)
	Dar es Salaam	NA	73.7 (3)
	Mumbai	NA	67.2 (4)
	Delhi	NA	57.3 (5)

Table 3: Population estimates for the five largest cities in 2100 under different scenarios and methods (WUP), first with the method used in this study and second a previously published analysis[51]. The WUP population numbers are dveloped in that study using the urban growth rates from WUP, and there is no direct analogue in this study.

5.4 Number of people affected

Table 4 lists the number of people affected by number of deadly heat days for two different thresholds.

Sub-region	Pop. Scen.	Clim. Scen.	Year Year	Pop Total	Pop. affected ≥1 DDH	Pop. affected ≥ 30 DDH
Austr. and N.Z.	WUP	SSP1-2.6	2020	20.69	2.75	0.00
Austr. and N.Z.	WUP	SSP3-7.0	2020	20.69	2.75	0.00
Austr. and N.Z.	WUP	SSP5-8.5	2020	20.69	2.75	0.00
Central Asia	WUP	SSP1-2.6	2020	13.61	0.00	0.00
Central Asia	WUP	SSP3-7.0	2020	13.61	0.00	0.00
Central Asia	WUP	SSP5-8.5	2020	13.61	0.00	0.00
Eastern Asia	WUP	SSP1-2.6	2020	728.76	638.48	447.85
Eastern Asia	WUP	SSP3-7.0	2020	728.76	625.60	406.23
Eastern Asia	WUP	SSP5-8.5	2020	728.76	656.76	420.76
Eastern Europe	WUP	SSP1-2.6	2020	90.09	2.19	0.00
Eastern Europe	WUP	SSP3-7.0	2020	90.09	1.58	0.00
Eastern Europe	WUP	SSP5-8.5	2020	90.09	2.19	0.00
Lat. Am. and Caribb.	WUP	SSP1-2.6	2020	321.20	125.14	69.73
Lat. Am. and Caribb.	WUP	SSP3-7.0	2020	321.20	140.69	69.73
Lat. Am. and Caribb.	WUP	SSP5-8.5	2020	321.20	120.89	72.28
Melanesia	WUP	SSP1-2.6	2020	0.38	0.38	0.38
Melanesia	WUP	SSP3-7.0	2020	0.38	0.38	0.38
Melanesia	WUP	SSP5-8.5	2020	0.38	0.38	0.38
Northern Africa	WUP	SSP1-2.6	2020	64.46	48.85	15.80
Northern Africa	WUP	SSP3-7.0	2020	64.46	48.52	15.80
Northern Africa	WUP	SSP5-8.5	2020	64.46	48.52	15.80
Northern America	WUP	SSP1-2.6	2020	231.42	146.19	46.44
Northern America	WUP	SSP3-7.0	2020	231.42	146.74	46.44
Northern America	WUP	SSP5-8.5	2020	231.42	144.69	46.96
Northern Europe	WUP	SSP1-2.6	2020	39.60	0.00	0.00
Northern Europe	WUP	SSP3-7.0	2020	39.60	0.00	0.00
Northern Europe	WUP	SSP5-8.5	2020	39.60	0.00	0.00
South-eastern Asia	WUP	SSP1-2.6	2020	156.79	151.72	144.15
South-eastern Asia	WUP	SSP3-7.0	2020	156.79	151.72	144.15
South-eastern Asia	WUP	SSP5-8.5	2020	156.79	151.72	141.20
Southern Asia	WUP	SSP1-2.6	2020	406.85	368.17	350.79
Southern Asia	WUP	SSP3-7.0	2020	406.85	368.17	349.19
Southern Asia	WUP	SSP5-8.5	2020	406.85	368.17	350.79
Southern Europe	WUP	SSP1-2.6	2020	55.90	17.73	0.00
Southern Europe	WUP	SSP3-7.0	2020	55.90	18.58	0.00
Southern Europe	WUP	SSP5-8.5	2020	55.90	18.74	0.00

Sub-Saharan Africa	WUP	SSP1-2.6	2020	236.21	161.83	149.33
Sub-Saharan Africa	WUP	SSP3-7.0	2020	236.21	160.37	149.33
Sub-Saharan Africa	WUP	SSP5-8.5	2020	236.21	156.38	149.33
Western Asia	WUP	SSP1-2.6	2020	134.14	50.61	29.11
Western Asia	WUP	SSP3-7.0	2020	134.14	51.84	28.49
Western Asia	WUP	SSP5-8.5	2020	134.14	51.84	29.11
Western Europe	WUP	SSP1-2.6	2020	54.98	0.94	0.00
Western Europe	WUP	SSP3-7.0	2020	54.98	0.94	0.00
Western Europe	WUP	SSP5-8.5	2020	54.98	0.94	0.00
Austr. and N.Z.	SSP1	SSP1-2.6	2050	29.23	4.57	0.00
Austr. and N.Z.	SSP1	SSP1-2.6	2080	34.88	6.04	0.00
Austr. and N.Z.	SSP3	SSP3-7.0	2050	25.26	5.20	0.00
Austr. and N.Z.	SSP3	SSP3-7.0	2080	24.02	20.97	0.42
Austr. and N.Z.	SSP5	SSP5-8.5	2050	32.39	7.18	0.00
Austr. and N.Z.	SSP5	SSP5-8.5	2080	45.55	40.09	6.20
Central Asia	SSP1	SSP1-2.6	2050	19.56	0.00	0.00
Central Asia	SSP1	SSP1-2.6	2080	19.70	0.51	0.00
Central Asia	SSP3	SSP3-7.0	2050	19.48	3.99	0.00
Central Asia	SSP3	SSP3-7.0	2080	23.72	10.05	0.00
Central Asia	SSP5	SSP5-8.5	2050	18.89	3.91	0.00
Central Asia	SSP5	SSP5-8.5	2080	18.08	9.13	3.25
Eastern Asia	SSP1	SSP1-2.6	2050	907.89	828.22	655.76
Eastern Asia	SSP1	SSP1-2.6	2080	741.35	677.26	516.88
Eastern Asia	SSP3	SSP3-7.0	2050	842.05	772.02	632.42
Eastern Asia	SSP3	SSP3-7.0	2080	721.58	682.96	603.63
Eastern Asia	SSP5	SSP5-8.5	2050	914.78	850.40	698.10
Eastern Asia	SSP5	SSP5-8.5	2080	763.22	738.54	676.48
Eastern Europe	SSP1	SSP1-2.6	2050	91.59	7.23	0.00
Eastern Europe	SSP1	SSP1-2.6	2080	81.28	6.80	0.53
Eastern Europe	SSP3	SSP3-7.0	2050	88.81	15.87	0.60
Eastern Europe	SSP3	SSP3-7.0	2080	90.69	63.49	1.17
Eastern Europe	SSP5	SSP5-8.5	2050	94.69	29.37	0.63
Eastern Europe	SSP5	SSP5-8.5	2080	88.05	82.36	3.79
Lat. Am. and Caribb.	SSP1	SSP1-2.6	2050	380.04	208.31	117.84
Lat. Am. and Caribb.	SSP1	SSP1-2.6	2080	341.99	182.38	108.54
Lat. Am. and Caribb.	SSP3	SSP3-7.0	2050	430.08	243.23	150.11
Lat. Am. and Caribb.	SSP3	SSP3-7.0	2080	516.02	354.32	220.97
Lat. Am. and Caribb.	SSP5	SSP5-8.5	2050	372.50	224.42	139.88
Lat. Am. and Caribb.	SSP5	SSP5-8.5	2080	326.17	240.27	179.52
Melanesia	SSP1	SSP1-2.6	2050	0.99	0.99	0.99
Melanesia	SSP1	SSP1-2.6	2080	1.51	1.51	1.51
Melanesia	SSP3	SSP3-7.0	2050	0.76	0.76	0.76
Melanesia	SSP3	SSP3-7.0	2080	1.00	1.00	1.00

Melanesia	SSP5	SSP5-8.5	2050	0.99	0.99	0.99
Melanesia	SSP5	SSP5-8.5	2080	1.51	1.51	1.51
Northern Africa	SSP1	SSP1-2.6	2050	101.04	88.98	36.99
Northern Africa	SSP1	SSP1-2.6	2080	107.87	94.91	40.98
Northern Africa	SSP3	SSP3-7.0	2050	101.91	94.76	37.29
Northern Africa	SSP3	SSP3-7.0	2080	132.97	128.24	106.19
Northern Africa	SSP5	SSP5-8.5	2050	99.57	94.22	74.49
Northern Africa	SSP5	SSP5-8.5	2080	104.41	102.20	94.28
Northern America	SSP1	SSP1-2.6	2050	301.86	219.16	93.29
Northern America	SSP1	SSP1-2.6	2080	356.48	243.00	112.78
Northern America	SSP3	SSP3-7.0	2050	263.65	194.05	86.16
Northern America	SSP3	SSP3-7.0	2080	246.49	216.12	124.28
Northern America	SSP5	SSP5-8.5	2050	330.78	245.95	108.09
Northern America	SSP5	SSP5-8.5	2080	459.52	410.89	267.98
Northern Europe	SSP1	SSP1-2.6	2050	50.36	0.00	0.00
Northern Europe	SSP1	SSP1-2.6	2080	57.09	0.00	0.00
Northern Europe	SSP3	SSP3-7.0	2050	43.81	0.00	0.00
Northern Europe	SSP3	SSP3-7.0	2080	40.64	0.00	0.00
Northern Europe	SSP5	SSP5-8.5	2050	54.71	0.00	0.00
Northern Europe	SSP5	SSP5-8.5	2080	72.73	0.38	0.00
South-eastern Asia	SSP1	SSP1-2.6	2050	237.34	229.92	229.39
South-eastern Asia	SSP1	SSP1-2.6	2080	238.24	232.09	230.71
South-eastern Asia	SSP3	SSP3-7.0	2050	228.17	227.33	220.80
South-eastern Asia	SSP3	SSP3-7.0	2080	270.66	270.66	269.58
South-eastern Asia	SSP5	SSP5-8.5	2050	236.83	236.04	229.46
South-eastern Asia	SSP5	SSP5-8.5	2080	236.54	236.54	236.54
Southern Asia	SSP1	SSP1-2.6	2050	731.20	674.80	670.09
Southern Asia	SSP1	SSP1-2.6	2080	822.47	762.71	757.76
Southern Asia	SSP3	SSP3-7.0	2050	702.64	647.39	640.28
Southern Asia	SSP3	SSP3-7.0	2080	984.63	916.52	907.59
Southern Asia	SSP5	SSP5-8.5	2050	727.21	674.64	667.45
Southern Asia	SSP5	SSP5-8.5	2080	811.98	763.34	756.61
Southern Europe	SSP1	SSP1-2.6	2050	64.47	33.09	1.08
Southern Europe	SSP1	SSP1-2.6	2080	64.04	29.25	0.51
Southern Europe	SSP3	SSP3-7.0	2050	53.88	31.85	2.10
Southern Europe	SSP3	SSP3-7.0	2080	42.37	31.37	12.69
Southern Europe	SSP5	SSP5-8.5	2050	69.16	47.38	6.84
Southern Europe	SSP5	SSP5-8.5	2080	79.61	61.71	31.87
Sub-Saharan Africa	SSP1	SSP1-2.6	2050	534.03	377.19	352.21
Sub-Saharan Africa	SSP1	SSP1-2.6	2080	722.58	507.47	476.72
Sub-Saharan Africa	SSP3	SSP3-7.0	2050	535.61	388.91	366.93
Sub-Saharan Africa	SSP3	SSP3-7.0	2080	850.76	708.15	623.02
Sub-Saharan Africa	SSP5	SSP5-8.5	2050	529.77	394.67	366.23

Sub-Saharan Africa	SSP5	SSP5-8.5	2080	707.90	592.27	546.42
Western Asia	SSP1	SSP1-2.6	2050	203.47	99.35	49.68
Western Asia	SSP1	SSP1-2.6	2080	220.04	109.30	52.60
Western Asia	SSP3	SSP3-7.0	2050	218.10	152.15	62.39
Western Asia	SSP3	SSP3-7.0	2080	301.72	249.24	122.14
Western Asia	SSP5	SSP5-8.5	2050	206.19	145.15	72.67
Western Asia	SSP5	SSP5-8.5	2080	226.47	192.69	157.94
Western Europe	SSP1	SSP1-2.6	2050	64.15	2.97	0.00
Western Europe	SSP1	SSP1-2.6	2080	67.86	4.07	0.00
Western Europe	SSP3	SSP3-7.0	2050	55.54	3.76	0.00
Western Europe	SSP3	SSP3-7.0	2080	46.84	22.37	0.00
Western Europe	SSP5	SSP5-8.5	2050	69.24	21.06	0.00
Western Europe	SSP5	SSP5-8.5	2080	85.52	75.23	2.37

Table 4: Number of people affected by deadly heat days in billion and per Sub-Region. Pop. Scen. is the population scenario used, Clim. Scen. the climate scneario used, total population the total urban population in cities contained in the WUP 300.000, pop. affected ≥ 1 DDH means number of urban population affected by at least one annual day of deadly heat, pop. affected ≥ 30 DDH means number of urban population affected by at least 30 annual day of deadly heat.