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The future urban heat-wave challenge in Africa

Exploratory analysis

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5
6 *The future urban heat-wave challenge in Africa: Exploratory analysis*

7
8 Peter J. Marcotullio, Carsten Keßler, Balázs M. Fekete

9
10 **Abstract**

11 Urbanization and climate change are among the most important global trends affecting human
12 well-being during the twenty-first century. One region expected to undergo enormous
13 urbanization and be significantly affected by climate change is Africa. Studies already find
14 increases in temperature and high temperature events for the region. How many people will
15 be exposed to heat events in the future remains unclear. This paper attempts to provide a first
16 estimate of the number of African urban residents exposed to very warm 15-day heat events
17 (>42°C). Using the Shared Socio-economic Pathways and Representative Concentration
18 Pathways framework we estimate the numbers of exposed, sensitive (those younger than 5 and
19 older than 64 years), and those in low-income nations, with gross national products of \$4000
20 (\$2005, purchasing power parity), from 2010 to 2100. We examine heat events both with and
21 without urban heat island estimates. Our results suggest that at the low end of the range,
22 under pathways defined as sustainable (SSP 1) and low relative levels of climate change (RCP
23 2.6) without including the urban heat island effect there will be large populations (>300 million)
24 exposed to very warm heat wave by 2100. Alternatively, by 2100, the high end exposure level
25 is approximately 2.0 billion for SSP 4 under RCP 4.5 where the urban heat island effect is
26 included.

27
28 **Keywords:** Urban, Heat wave, Climate Change, Africa, vulnerability, scenarios

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30

31 **I.0 Introduction**

32

33 During the first decades of the twenty-first century, urban scholars have focused attention on
34 developing-world cities. This is understandable considering the enormous economic and population
35 growth that these parts of the world have recently experienced and the future anticipation of billions of
36 residents and further economic activity. Indeed, according to the UN (2018), after around 2025 all
37 global population growth will be in the world's cities and over 95% will be in the developing world.

38

39 Much previous interest has been on Asia, as the region has experienced the world's largest and most
40 intense changes. Towards the middle of this century, however, conditions are expected to shift, as
41 Africa is projected to undergo enormous population growth and urbanization. While Africa has
42 experienced the world's highest regional population growth rate since the 1970s, total population has
43 remained much lower than that of Asia. By 2010, the population of Africa was about a quarter of that of
44 Asia, as the region held approximately 10% of the world's population. By the end of the twenty-first
45 century, however, the region's total population is projected to be over 90% of Asia's (approximately 40%
46 of the world's total population), exceeding 4.4 billion (UN, 2017). Urbanization across the continent is
47 also projected to increase dramatically (Güneralp et al., 2018; UN, 2018). Despite these population and
48 urbanization forecasts, however, whether economic activity will increase remains uncertain.

49 Urbanization in African nations has not always brought economic growth as experienced by other
50 regions. Currently, more than half of the global extremely poor (those that live on less than US\$1.90 a
51 day) live in sub-Saharan Africa. The World Bank projects that if trends continue, by 2030, 9 out of 10
52 extremely poor will live in the region (World Bank, 2018).

53

54 Simultaneously, climate analysts project enhanced climate change, driven by anthropogenic influence.
55 Even if countries meet the Paris Agreement Nationally Determined Contributions, the world will warm
56 by more than 1.5°C by 2050 (Obersteiner et al., 2018, Rogelj et al., 2016, Rogelj et al., 2015), bringing
57 climate risks to urban centers around the world (Eakin and Lynd Luers, 2006, IPCC, 2018, Revi et al.,
58 2014). Among a variety of threats, one particularly important climate risk for urban residents is high
59 temperature events. Future projections suggest high-temperature events affecting large portions of
60 Earth (Mora et al., 2017, Seneviratne et al., 2012, Meehl and Tebaldi, 2004, Russo et al., 2014).
61 Generally, climate change-related induced heat events include increases in maximum extreme
62 temperatures, heat waves of greater intensity and duration than currently experienced and increasingly
63 warm summers (Dosio et al., 2018, Seneviratne et al., 2016, Fischer and Schär, 2009, King et al., 2018).
64 Recent studies suggest the number of high temperature events have already increased (Christidis et al.,
65 2015, Rahmstorf and Coumou, 2011, Sun et al., 2014), including in urban areas (Matthews et al., 2017,
66 Mishra et al., 2015). In Africa, heat waves are increasing in intensity and frequency (Ceccherini et al.,
67 2017) and with increasing climate change, this region is also projected to experience significant
68 increases in future extreme heat events (Harrington et al., 2016, Nikulin et al., 2018, Russo et al., 2019,
69 Russo et al., 2016).

70

71 While research has projected increases in frequency and intensity of heat waves, there remains much
72 we do not know about the scale of the potential impacts, particularly for African cities. For example,
73 there are limited studies that examine the extent of urban heat wave vulnerability in Africa (Carter,
74 2018). There also remain very basic unanswered questions. How many urban Africans might be

75 exposed to these heat waves? Where might the largest exposed populations be located within the
76 continent? Of those urban populations exposed, how many might be sensitive to heat events and how
77 many might be living in countries with low incomes, with limited resources to provide relief? The
78 objective of this research is to generate ranges of estimates to help answer these questions. We
79 attempt this through an exploratory scenarios study that provides ranges of urban population and
80 identification of the general location (to the sub-regional level) exposed to 15-day heat events of
81 different magnitudes across three 30-year periods, from 2010 to 2100. Our study suggests a range of
82 futures for urban heat exposure in Africa, although one common element across projections is the large
83 and growing numbers of residents that may be exposed to very warm (42°C and higher) 15-day heat
84 waves.

85
86 In the next section, we describe the background to this research. This includes sections on scenario
87 frameworks, urban land cover simulations, heat waves and the urban heat island effect. The section
88 ends with a discussion of the relationship of the project's results to urban climate vulnerability research.
89 The third section presents the research methods for identification of heat waves, urban land cover
90 growth modeling, identification of urban heat islands and how these data are combined in the scenarios.
91 The fourth section provides the results of the analysis including ranges of population exposure to
92 different intensity heat waves of 15-day duration and the share of heat-sensitive and low-income
93 persons in these populations. In the fifth section we discuss the implications of the findings and
94 conclude with a summary and an agenda for future work.

95 96 **2.0 Background**

97 98 *2.1 Scenarios*

99
100 Scholars argue that scenarios are good tools to analyze future trends while addressing uncertainties
101 (Peterson et al., 2003, Schoemaker, 1991, van Vliet and Kok, 2015, van't Klooster and van Asselt, 2011).
102 Several different approaches to scenario development exist (Borjeson et al., 2006, van Notten et al.,
103 2003). While there is no universal scenario typology, literature reviews often include three distinct
104 types: predictive, exploratory, and backcasting (Borjeson et al., 2006). Predictive scenarios forecast how
105 the future will unfold, based on preconceived development patterns. Exploratory scenarios sketch
106 plausible futures, showing the implications of change in external drivers. Though not necessarily for
107 prediction, they focus on what *may* happen, ultimately exploring uncertainty in outcomes and driving
108 forces (Shearer, 2005, van der Heijden, 2000). Typically, exploratory projects include a set of scenarios
109 constructed to span a wide scope of plausible developments over a very long-time span. The third
110 scenario type includes normative, transformation studies. These scenarios start with the end state and
111 work backwards, hence the name "backcasting" (Quist, 2007, Lovins, 1977, Robinson, 1982).

112
113 We use exploratory scenarios to address the questions of what may happen over the course of the
114 century. There is already a developed framework for exploratory climate change and socio-economic
115 development scenarios (Moss et al., 2008). This framework deploys, at least, two sets of data. The first
116 set is defined by representative concentration pathways (RCPs), which embody climate changes through
117 projecting different levels of greenhouse gas (GHG) concentrations in the atmosphere to 2100. The
118 RCPs represent trajectories for emissions that subsequently affect the radiative forcing of the climate

119 system (van Vuuren et al., 2014). This study uses RCPs 2.6, 4.5, 6.0 and 8.5. The RCP numbers describe
120 energy intensity (watts per m²) above the 1750 level by the end of the current century and are meant to
121 reflect different emission scenarios (Wayne, 2013). The corresponding greenhouse gas concentrations
122 for the emissions scenarios vary for individual global circulation models (GCMs) as a function of their
123 climate sensitivity. RCP 8.5 is the reference scenario and results in the highest GHG concentrations and
124 temperatures among all RCPs by the end of the century. Any deviation from this pathway (including
125 the other RCPs) is arguably because of actions to reduce emissions (i.e., mitigation efforts).

126
127 The second set of data in the framework is the shared socioeconomic pathways (SSPs), which describe
128 development trends and conditions. The SSPs offer plausible alternative tendencies in the evolution of
129 society and natural systems and include narrative descriptions and quantifications of selected
130 socioeconomic variables at the national, regional and global scales. SSP categorization is through the
131 individual pathway's global challenges to mitigation and to adaptation (Riahi et al., 2017). That is, in
132 each SSP, the level of energy usage, the increases in GDP, trade, population and urbanization growth
133 and the scale of international coordination, among other aspects, provide for either benefits or
134 challenges to climate mitigation or adaptation (O'Neill et al., 2017). This SSP is the most sustainable
135 development pathway with low mitigation and adaptation challenges. SSP 2 results in both slightly
136 higher mitigation and adaptation challenges than SSP 1. SSP 3 defines a pathway where the world faces
137 the highest mitigation and adaptation challenges among all SSPs. SSP 4 describes a world with
138 increasing inequality where mitigation challenges are low, but adaptation challenges are high. Finally,
139 SSP 5 – the high fossil fuel use pathway – includes development patterns such that adaptation
140 challenges are low, but mitigation challenges are high. All SSPs are "reference" pathways and assume
141 no climate change or climate impacts, and no new climate policies (Kriegler et al., 2014).

142
143 Together the set of RCPs and SSPs provide tools to explore a wide range of outcomes given socio-
144 economic development and GHG emission concentrations. Mapping an SSP across different RCPs can
145 reveal the relationship between changing climate policies and climate impacts for a particular socio-
146 economic development pathway. Conversely, mapping an RCP across different SSPs can reveal how a
147 specific climate change trend impacts different socio-economic development pathways. There are
148 constraints to combining RCPs and SSPs, however. For example, given the socio-economic conditions in
149 SSP 3, it is not possible to achieve RCP 2.6 (the lowest GHG emissions levels trajectory in our study).
150 Likewise, the GHG levels of RCP 8.5 can only be reached with SSP 5.

151 152 *2.2 Urban land cover growth simulations*

153
154 Cities have taken on a multitude of urban forms since their emergence (Kostof, 1991, Morris, 1994).
155 Over the past 200 years, urban growth patterns have differed across cultural regions (Brunn et al., 2016)
156 and across time with technological development, particularly mobility (Newman and Kenworthy, 1999).
157 Some argue that during the era of globalization urban growth patterns in developed and rapidly
158 developing world cities are converging in urban form (Dick and Rimmer, 1998) although others debate
159 this claim (Marcotullio, 2003).

160

161 Understanding the drivers and patterns of urban land cover growth is critical to projecting future spatial
162 urbanization patterns. As mentioned, population growth estimates suggest that the world will be
163 increasingly urban. After around 2030, almost all population growth will occur in the world's cities, as
164 the global rural population is anticipated to decline. While there are population projections for national
165 urban population shares, however, there are a limited number of spatially disaggregated projections.
166 An analysis that examines the exposure of urban populations to heat waves, necessitates spatially
167 disaggregating these national population estimates to local areas (cities, towns, villages).

168
169 The few models that exist attempt to use drivers of urbanization to project urban growth. For example,
170 Seto et al. (2012) and Güneralp et al. (2017) use an analysis of satellite imagery combined with an urban
171 growth modeling to develop probabilities of future urban land cover growth and urban population
172 densities to 2030 and 2050. Angel et al. (2005) also use satellite imagery to define urban extents and
173 then bases growth on projected future changes in urban densities. This group projects urban land cover
174 change to 2100. Jones and O'Neill (2016) use a gravity model to spatially project urban and rural
175 populations, to identify the urban demographic change. All of these simulations project urbanization
176 based upon an understanding of previous patterns, drivers, or urban forms. There is, however, no one
177 best simulation, as all face similar challenges including the lack of historical spatial data on which to base
178 future urban growth, the uncertainty of future technologies, governance and cultural factors that affect
179 urban growth, and difficulties of modeling the details of urban land cover growth at regional and global
180 scales.

181
182 An alternative technique to project urban land cover growth is to address uncertainty using multiple
183 models that provide a range in growth outcomes. That is, rather than attempting to define urban land
184 growth as a specific pattern, using one model, it is feasible to use different models to develop a range
185 that defines extremes in future outcomes. Arguably, the true future outcome would fall between these
186 extremes. This study uses this assumption to present differences between so-called sprawled and
187 compacted urban development as distinct urban land cover growth patterns. While these ideal
188 categories are notional, scholars suggest that a sprawled development pattern is evident in the US and
189 Australia and that compacted urban development can be found in parts of Europe and Asia (Newman
190 and Kenworthy, 1999). These terms also carry more than just an indication of difference in urban area.
191 Compact urban development for example, can include integrated land cover zoning, transit-oriented
192 development, walkable neighborhoods, traffic calming, eco-city orientation and a host of other
193 elements (Kenworthy, 2006). Sprawled development, alternatively, is often associated with rising
194 incomes, supporting government land use and tax policies or lack of land use regulations and increase
195 use of personal vehicles, among other elements (Nechyba and Walsh, 2004, Sudhira et al., 2004). There
196 are also variants within each type of land cover pattern, as there are different urban forms that provide
197 similar types of densities (Seto et al., 2014). We do not include these differences in policies, governance
198 and social conditions in our definitions. And we do not promote one form as normatively preferred over
199 the other. Furthermore, we do not attempt to assess the plausible responses to heatwaves under
200 different growth pattern (i.e., are heat waves hotter in compact versus sprawled settings), as we do not
201 have the detailed data at the urban scale with regional coverage to perform such an analysis. Rather we
202 use these terms to describe urban land cover patterns that signify the difference in both population
203 densities and urban area at the extremes. The goal is to define a range of the extent of urban land cover
204 with increasing population that might affect exposure to heat events.

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2.3 Heat waves

There is no standardized definition or measure of a heat wave (Horton et al., 2016, Perkins, 2015, Dosio et al., 2018). Heat wave characteristics (e.g., intensity and duration) vary over different regions (Perkins et al., 2012) making a universal definition for these phenomena difficult. The most agreed upon definition is that heat waves are observed high temperature extremes over consecutive days at the global, regional or local scales (Alexander et al., 2006, Della-Marta et al., 2007). Some researchers have attempted to define heat waves empirically. One example is an event of at least three days in duration during which the daily maximum temperature starts above the 97.5th percentile of temperature distribution and remains above the 81st percentile of temperature thereafter (Meehl and Tebaldi, 2004).

High temperatures alone, however, make up only a part of what might be considered heat waves. Another component is humidity. Together these weather aspects define how ambient conditions “feel” and arguably provide a better indicator of human comfort than either one alone (Epstein and Moran, 2006). Combining these two factors creates a heat index. The most common technique used in heat index research today is a variant originally proposed by Steadman (1979a; 1979b) and has subsequently been refined (Anderson et al., 2013). National weather bureaus often define heat waves with a heat index. For example, the US National Oceanographic and Atmospheric Administration (NOAA) National Weather Service’s heat index is called the “Likelihood of Heat Disorder with Prolonged Exposure or Strenuous Activity” index¹ and includes categories with accompanying thresholds; Caution ~ >30°C, Extreme Caution ~ >35°C, Danger ~ >42°C and Extreme Danger ~ >50°C.

Observers argue that heat waves can be experienced differently by cultures and societies across climate zones (Patz et al., 2005). In a recent global review of heat mortality, however, researchers have defined a threshold level for temperature and humidity at which excess in mortality is experienced across all cultures and climates (Mora et al., 2017). This is not surprising, as there are upper physiological limits for all humans’ and mammals’ exposure to heat (Sherwood et al., 2010).

2.4 Urban heat island effect

For cities, climate related heat concern is exacerbated by the higher temperatures in the urban core as compared to surrounding areas. This is called the urban heat island (UHI) and it provides a clear example of anthropogenic impacts on climate. UHI has been known for some time, as it was identified 200 years ago by Howard (1818) and has subsequently been found in cities around the world (Kataoka et al., 2009). Analysts consider UHI one of the major environmental problems of the twenty-first century (McKendry, 2003, Rizwan et al., 2008, Arnfield, 2003)

In recent years, four different types of UHI have been defined, including subsurface UHI, surface UHI, canopy layer UHI and boundary layer UHI. All these different UHIs relate to differences between the urban and rural temperatures, but each is measured at different altitudes and with different techniques. The canopy UHI is measured between the surface and the tree canopy or below the average building height of the city with stationary sensors or those mounted on vehicles. For this study we are interested

¹ See <https://www.weather.gov/safety/heat-index>.

248 in the canopy UHI, because compared to the other types it has the best correspondence with climate
249 model air temperatures, it is taken at the most appropriate geographic scale and is the most relevant
250 temperature experienced by people. Henceforth, referenced UHI in this research refers to canopy UHI.

251

252 In general, UHIs are typically around 3–4° C (Oke, 1997, Voogt, 2002), but can vary between 0.4-12°C
253 (Santamouris, 2015) and reach 17°C in inner-city hot spots (Makrogiannis et al., 1998). In many cases,
254 the highest UHI occurs during the summer or warmer seasons (Erell and Williamson, 2007, Makrogiannis
255 et al., 1998, Wang and Hu, 2006), although there are studies that find it is highest during the winter or
256 cooler months (Hinkel et al., 2003, Salvati et al., 2017). Maximum UHI intensities are typically
257 experienced during the evenings (Arnfield, 2003), but in some cases, the maximum UHI occurs during
258 the afternoons (Oguntoyinbo, 1984).

259

260 The set of driving factors for UHI include local climatology, street geometry, building fabric and
261 anthropogenic activities. Given the importance of urban form and human activities, UHI intensities for
262 individual cities change as they grow. In the UHI literature, one important indicator for the level of UHI
263 is city size, measured by population, city area or diameter (Oke et al., 2017). Several studies have
264 identified the positive relationship between the urban population and UHI, although the slope of the
265 increase and intercept vary by geographical region (Oke, 1973, Roth, 2007, Jauregui, 1997, Santamouris,
266 2015).

267 Exactly how global climate change will affect UHI is a current topic of research, but much remains
268 unknown (Huebler et al., 2007, Roy et al., 2011). A recent study suggests that UHI will increase across all
269 SSPs for RCP 4.5 due to urban expansion (Huang et al, 2019). Others find that both climate change and
270 future urban population size and other factors will determine UHI (Shastri et al., 2017, Tran et al., 2006,
271 US EPA, 2018, Manoli, et al 2019). While difficult to project, a study of future urbanization and heat
272 waves is incomplete without the inclusion of UHI. Rather than forecasting a particular UHI value for a
273 city, this study provides a range of UHI values for cities of different sizes.

274 *2.5 Vulnerability, heat wave sensitivity and the low-income status of those exposed*

275

276 The evaluation of the full impact of heat waves is a complex task and is approached with different
277 framings and methods (O'Brien, et al, 2009). Scientific framings define vulnerability as a function of the
278 intensity of the shock, the exposure of the population or infrastructure, the sensitivity of the population
279 or infrastructure to that shock and the adaptive capacity of the system to avoid or ameliorate the shock
280 (IPCC, 2014). Alternatively, contextual framings of vulnerability are based on multidimensional views of
281 climate-society interactions. These studies focus on the political, institutional, economic and social
282 structures, their interactions and how they condition the context for exposure, sensitivity and capacity
283 to address climate events (O'Brien, et al 2009; Adger and Kelly, 2000). These different approaches
284 prioritize different types of knowledge, can lead to different types of responses and therefore require
285 explicit recognition.

286

287 This study uses a scientific framing of vulnerability. However, it is further limited by data availability.
288 Scientific studies of vulnerability often estimate the potential monetary cost, morbidity or mortality
289 associated with heat waves, and assess the potential ability of societies to cope with or adapt to these
290 events. Therefore, they require detailed local knowledge and information, which is not available for
291 global or even regional projections. Rather than focus on vulnerability, this provides more basic,

292 components of vulnerability. We focus on total exposure and the heat sensitive and low-income
293 population shares of those exposed.

294
295 Data available to identify this scientific framing of sensitivity is available through projected population
296 structures (Samir and Lutz, 2017) for the shares of the population younger than 5 or older than 64 to
297 define the heat wave sensitive population (Kovats and Hajat, 2008, Sheridan and Allen, 2018), as a
298 partial indicator of heat wave sensitivity. We also use national income per capita, as incomplete
299 measure of adaptive capacity. Of the exposed population, we identify those living in nations with GDP
300 per capita levels lower than \$4,000 across all decades. For the GDP data we use values at purchasing
301 power parity (PPP) at constant US\$2005. We use the \$4,000 threshold, based upon World Bank
302 definition of the boundary between middle class and above and lower-income and below countries.²
303 Certainly, adaptation will necessitate financial resources to mobilize public efforts (cool and green roofs,
304 increased open space and vegetation, increased outdoor watering in parks, provision of cooling stations,
305 etc.) (Gill et al., 2007, Harlan and Ruddell, 2011, Hewitt et al., 2014), as well as private efforts (increased
306 air conditioning, social networking during heat events, etc.). Vulnerability assessments typically
307 aggregate indices and almost all include economic indicators (Brooks et al., 2005, Cinner et al., 2018),
308 but adaptive capacity also includes a host of other conditions such as the level of management
309 (particularly governance and strength of institutional responses), access to resources and demonstrated
310 successful historical coping experiences (Smit et al., 2001, Yohe and Tol, 2002). Furthermore, low-
311 income status only partially estimates the impact of low per capita income, as it does not identify the
312 distribution of incomes within nations. There is evidence that, even within wealthy nations, there are
313 significant disparities of urban household incomes (Gornig and Goebel, 2016, Timberlake et al., 2012).
314 By this proxy, therefore we can obtain a sense of the numbers living in conditions with tight
315 governmental and private resources, but we do not claim to identify the population's adaptive capacity
316 to urban heat wave events. Given the coarse indicators used, the project makes no claim to identify
317 urban vulnerability to heat waves.

318 319 **3.0 Methods**

320 321 *3.1 Generation of spatialized heat waves data*

322
323 We used an established technique to create a heat index (Rothfus, 1990) by combining mean daily
324 temperature and relative humidity (Anderson et al., 2013) from the outputs of climate models.³ We
325 group the strength of the heat waves into the following categories, <30°C, 30-36°C, 36-42°C, 42-46°C,
326 46-50°C, >50°C, based upon NOAA's National Weather Service Heat Index Likelihood of Heat Disorder
327 with Prolonged Exposure or Strenuous Activity and the results of a recent global study on mortality
328 under heat waves (Mora et al., 2017). The threshold of approximately 30°C, signals conditions that
329 above which result in excess mortality due to heat in some cities. The threshold, at >42°C, signals where
330 there will be excess mortality due to heat in all cities. These thresholds bookend approximations of
331 conditions from a recent study that reviewed over 780 cases of excess mortality associated with heat
332 from 164 cities in 36 countries (Mora et al., 2017). In the Mora et al (2017) study, a moving index

² World Bank list of economies database under the World Bank Country and Lending Groups,
<https://datahelpdesk.worldbank.org/knowledgebase/articles/906519>

³ See https://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml

333 defined by temperature and humidity defined a “deadly threshold” under which excess mortality during
334 heat waves emerged. From these data, we estimated that the lowest heat index conditions under which
335 excess heat-related mortality emerged was approximately 30°C. The highest heat index was
336 approximately 42°C. We use the upper threshold as an indicator of when all societies will experience
337 some excess heat-related mortality during this level heat wave. Finally, rather than defining the
338 duration of a heat event differently depending upon climate, we set a 15-day period to demonstrate the
339 potential for prolonged intense high temperature events.

340

341 We based our temperature and humidity values for the heat index calculations on Coupled Model
342 Intercomparison Project Phase 5 (CMIP5) historical and climate projections from the Inter-Sectorial
343 Impact Model Intercomparison Project (ISIMIP) comprehensive compilation of five Global Circulation
344 Model (GCM) outputs from Earth System models (Warszawski et al., 2014). The ISIMIP five cover 1950-
345 2005 (historical period) and future projections up to 2099. The outputs included daily time series for all
346 meteorological variables consistently bias corrected (Hempel et al., 2013) so the spatialized model
347 results from different contributing groups yielded comparable annual baselines for the contemporary
348 period and only deviated in their future projections. We used mean daily temperatures and relative
349 humidity for the calculations. For the heat indices, we computed 15-day running means and tested
350 when the running mean was above our thresholds. The running mean acts as a low-pass filter that
351 attenuated the temperature signal, captured the low frequency variations and therefore expressed the
352 prolonged conditions over the 15-day period of time. From the running means, we identified the
353 warmest 15-day heat indices for each cell for 30-year periods from 1950-2009 (current climate), 2010-
354 2039 (near future), 2040-2069 (mid-future) and 2070-2099 (far future).

355

356 Using the mean temperatures and not the maximum daily temperatures provides conservative
357 estimates of heat waves. We also believed that these values were more meaningful when adding urban
358 heat island intensities. According to UHI research, urban and rural temperatures were approximately
359 equal during mid-day to early afternoon, which was approximately when urban ambient temperatures
360 were highest. That means that UHI values should not affect maximum temperatures. UHI intensities,
361 however, affected minimum and mean daily temperature and arguably, the UHI intensities can be added
362 to these means to achieve a heat index that roughly approximates the UHI impact. Given that the
363 identified temperature values for the chosen 15-days are the highest temperatures over 30 years, we
364 call them heat waves. Henceforth, we refer to heat waves that exceed the 42°C threshold as “very
365 warm.”

366

367 *3.2 Generation of urban land cover simulations*

368

369 Our urban growth simulations were based on urban population increases and urban densities. The
370 urban populations were taken from the SSPs at the country level. We adopted an approach to urban
371 simulations that considered concentrated (compacted) and dispersed (sprawled) urban growth. The
372 simulation for the sprawled scenario started with the urban extents layer from the Global Rural-Urban
373 Mapping Project (GRUMP) datasets (Balk, 2009), which was a gridded binary classification between
374 urban and rural areas with 30 arc-second resolution (~1 km at the equator). GRUMP defined urban
375 extents as derived from population counts, settlement points and nighttime lights. We used the
376 European Space Agency’s Global Land Cover Map (GlobCover) (Bontemps et al., 2011) for the start of

377 the compacted urban growth simulation. GlobCover, based on data from the MERIS sensor on board
378 the ENVISAT satellite mission, was then classified into 24 land cover classes. From those, we used cells
379 classified as artificial surfaces and associated urban areas. In addition to these two starting layers, we
380 used a national grid that identified the cells in each country using ISO/UN numeric identifier codes, as
381 well as a layer storing the area for each grid cell. This last layer is used to calculate population densities,
382 as cells decreased in size with increasing latitude. All layers were scaled to 30 arc-second
383 resolution. GlobCover was initially of higher resolution, but subsequently scaled to the same resolution
384 as GRUMP. We used these two different starting layers because they were at opposing extremes of
385 urban land cover estimations, with urban land cover area in GRUMP approximately 10 times larger than
386 that of GlobCover (Schneider et al., 2009). These two extremes were chosen to identify the range within
387 urban growth is most likely to stay until the end of the century.

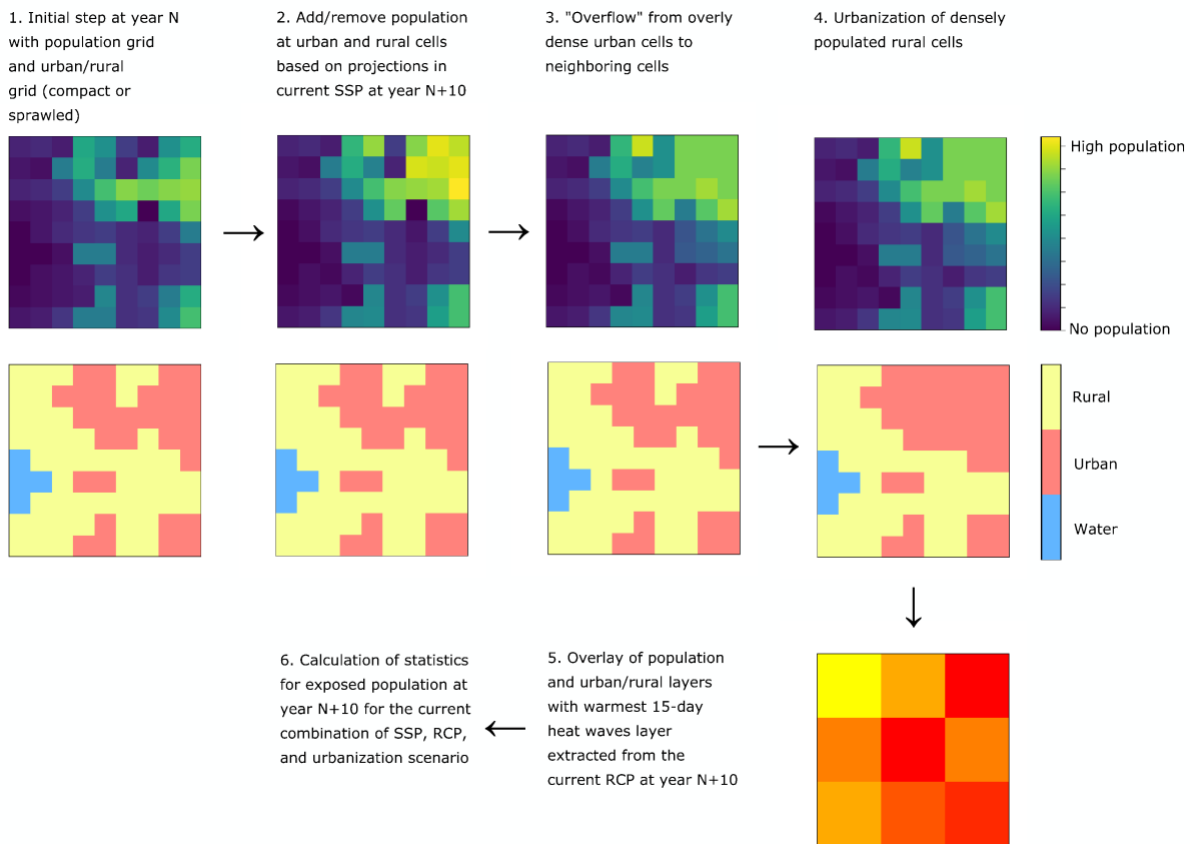
388
389 The SSPs included total population and urban share by decade to 2100 for 167 nations (Samir and Lutz,
390 2017, Jiang and O'Neill, 2017). Each urban growth simulation was performed independently in 10-year
391 steps for each of the 167 nations, starting with the current state in 2010, and running until
392 2100. National total population changes were calculated by urban and rural distinctions and the results
393 were distributed or removed from cells within each country for each step. For example, for the change
394 in urban population, as each simulation moved 10 years forward (e.g., from 2040 to 2050), the urban
395 extents layer and population layer of the previous step (2040 in this example) were compared to the
396 numbers projected for the following year (2050) in terms of total urban population per country. The
397 numbers in the layers were then adjusted to match the projections from the SSP under consideration,
398 such that population is added to the urban cells (or added or removed from non-urban cells) of each
399 country. Population was added randomly in the urban cells (and added or removed randomly from rural
400 cells), such that the urban and non-urban totals matched the following SSP year (2050) projections at
401 the national level. For both urban and non-urban cells, however, the current population in the cell was
402 used as a weight for the random assignment of new population, so that densely populated cells are
403 more likely to attract additional population than less dense (or completely uninhabited) cells. The
404 random factor was still used as a way to account for potential future development within cells which
405 cannot be accounted for decades in advance, at continental scale.

406
407 During the process, a control mechanism was implemented to make sure that population density in a
408 cell did not exceed a realistic limit. Without this control, populations could exceed millions per cell (i.e.,
409 millions per square kilometer at the equator). To identify a realistic limit, we used the current urban
410 population densities as defined by the initial maps (GRUMP and Globcover) and set a limit based upon
411 the mean of the 50 highest-density urban cells in the considered country. We argued that these 50 cells
412 are enough to represent the high-end of the density distribution for each country. We then set the limit
413 of 95% of this density for the next step. Thus, the threshold and the decreasing trend depended upon
414 the urban density distribution within each nation. We lowered densities in conformance to research
415 findings of this worldwide trend (Jiang and O'Neill, 2009, Angel et al., 2010, Guneralp, et al, 2020).

416
417 A rural cell was urbanized if it ended the step with a population density equal to or greater than the
418 national mean for urban cells. Inside urban areas, we re-examined urban cells to determine if they have
419 a density higher than maximum threshold identified in the previous step. If so, population in the cell
420 was automatically set to the threshold value, and the excess population is pushed to neighboring

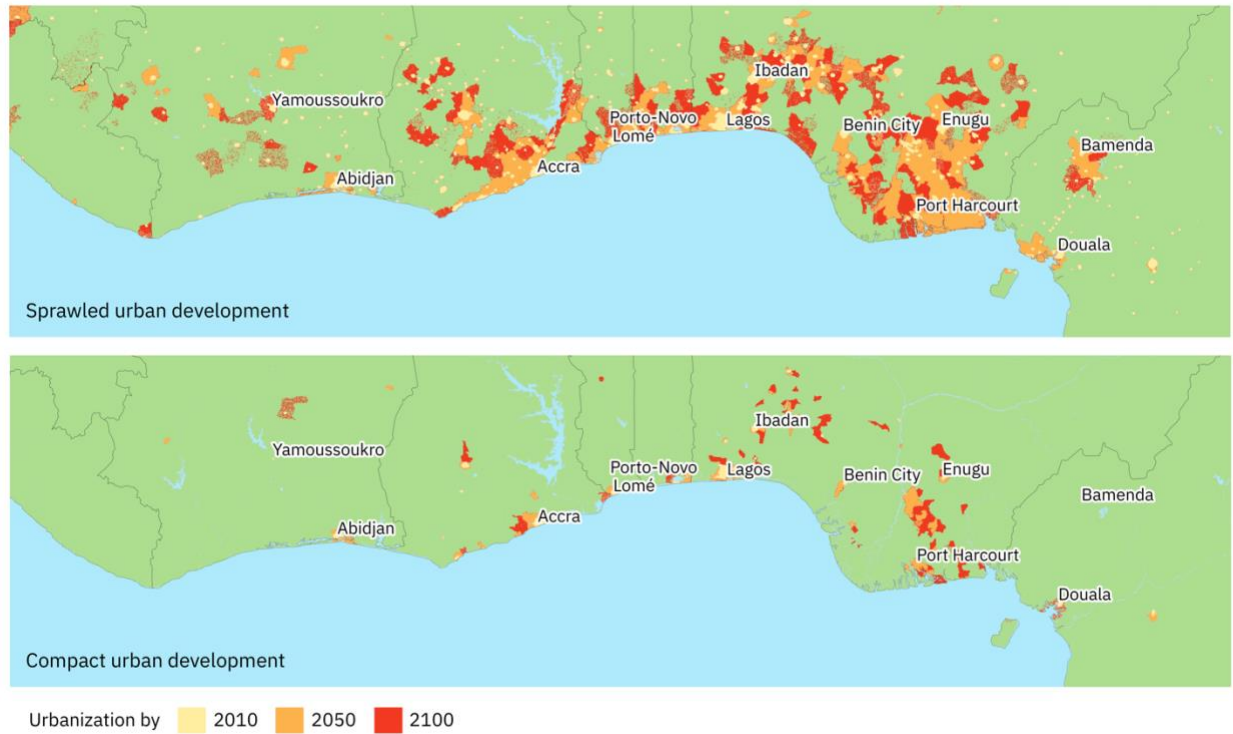
421 cells. With these steps, urban expansion was simulated by *urbanizing* cells, i.e., turning them from rural
 422 to urban in the urban extents layer. This process was iteratively repeated until no cells exceed the
 423 threshold. There were constraints to placing population in cells including no population in water bodies
 424 and pre-identified desert and mountain areas.

425
 426 **Figure 1** illustrates one step in the simulation and analysis process for a given combination of SSP, RCP
 427 and urbanization scenario. The population grid and urban/rural grid for the current time step (1) was
 428 compared to the urban and rural population from the given SSP at the following time step, moving 10
 429 years forward. The population grid was then adjusted to match the SSP number by adding or removing
 430 population from the urban and rural areas (2). For unrealistically densely populated cells, population
 431 was then moved to neighboring cells (3), followed by an urbanization step where densely populated
 432 rural cells were turned urban in the urban/rural grid (4). This population and urban/rural grid at time
 433 step N+10 were then overlaid with the temperature grid indicating the warmest 15-day heat waves for
 434 the given year, extracted from the current RCP (5), allowing us to calculate the exposed urban and total
 435 population (6). **Figure 2** presents an example of the results of our two urban land use simulations.
 436



437
 438 *Figure 1: Overview of one step in the simulation and calculation of exposed population for a given combination of*
 439 *SSP, RCP, and urbanization scenario. The output population and urban/rural grids will be the starting point for the*
 440 *following simulation step going to N+10.*

441
 442



443
 444 *Figure 2: Example of the difference between in results between the sprawled urban land cover model outcomes and*
 445 *the compact urban land cover model outcomes for parts of West Africa.*

446
 447 **3.3 Urban Heat island analysis**

448
 449 We obtained UHI intensities from a review of 131 studies for 135 cities around the world. We identified
 450 these studies through a 3-step process. First, we identified UHI research reviews from 1979 to 2018
 451 through a search of ISI Web of Science using the phrase “urban heat island”. From the approximately
 452 178 review results we examined 30 reviews that had some part related to canopy UHI measurements.
 453 From these reviews, we identified highly regarded case studies (those included in more than two
 454 different reviews) with UHI results. In the second step we examined these highly regarded studies for
 455 results. Finally, we used the snowball method, in the third step, to identify references used in the highly
 456 regarded studies for further UHI data. In total, over 200 studies were examined. The results for several
 457 studies were incomplete and therefore not included in the analysis.

458
 Table 1: Urban Heat Island sample statistics

City size name	Population Size range	Mean population of category	Sample Size (n)	UHI	
				Mean	sd
Very small	<=50,000	19,191	18	3.9	1.98
Small	>50,000 & <=250,000	125,587	18	5.1	2.29
Medium	>250,000 & <=500,000	369,154	13	5.1	1.82
Large	>500,000 & <=1,000,000	780,067	15	5.7	3.04
Very Large	>1,000,000 & <=10,000,000	3,801,921	45	5.3	3.07
Mega city	>10,000,000	16,375,000	4	7.6	2.85

460
 461 We used the UHI and city size data reported in the final 135 case studies and combined these data with
 462 Koppen-Geiger climate zone classification and population estimates for each city. We added the climate
 463 zone classifications because of the small number (eight) of published results identified for African cities.
 464 To get a representative sample of UHI intensities, therefore, we used results from cities located in
 465 similar climate zones found in Africa for our UHI analysis. This resulted in over 110 UHI values. We
 466 further divided the cities by size and obtained the mean and standard deviation UHI (**Table 1**) (see also
 467 Manoli et al., 2019). In our final results we presented both heat indices with and without the addition of
 468 UHI to get a range of outcomes.

469
 470
 471 *3.4 Low-income national status and sensitive populations*
 472

473 Data for national GDP per capita was available by SSP from the results of the IIASA GDP model (PPP at
 474 US\$2005).⁴ To identify the nations which might have resources for mitigation, we used the World
 475 Bank’s 2010 threshold for low-middle income of approximately US\$4,000 GDP per capita.⁵ This cutoff,
 476 applied to the GDP per capita data from the SSPs for 2010, identified approximately the same share of
 477 countries as did the World Bank during that year (World Bank’s share was around 37% of 218 nations
 478 and ours was about 41% of 167 nations) (World Bank, 2019). We applied a similar allocation of low-
 479 income status share to urban and rural populations. We then used this threshold across time,
 480 suggesting that this low-income indicator did not change, although some studies suggest that poverty
 481 levels shift upward over time (Hoy, 2016).
 482

Table 2: Low income African countries, total and urban population				Percent of total Africa			
		2010	2050	2100	2010	2050	2100
SSP 1	Countries	40	10	0	80.0	20.0	0.0
	Total pop	810	325	0	79.3	18.4	0.0
	Urban pop	290	193	0	71.1	15.4	0.0
SSP 2	Countries	40	28	0	80.0	56.0	0.0
	Total pop	810	898	0	79.3	44.6	0.0
	Urban pop	290	433	0	71.1	36.9	0.0
SSP 3	Countries	40	35	32	80.0	70.0	64.0
	Total pop	810	1,497	2,162	79.3	64.2	54.8
	Urban pop	290	555	920	71.1	52.6	45.9
SSP 4	Countries	40	34	17	80.0	68.0	34.0
	Total pop	810	1,383	1,314	79.3	61.4	36.3
	Urban pop	290	891	1,157	71.1	56.5	35.3
SSP 5	Countries	40	4	0	80.0	8.0	0.0
	Total pop	810	67	0	79.3	3.9	0.0
	Urban pop	290	45	0	71.1	3.6	0.0

483 Data are for number of countries and total and urban population in millions

484
 485 Of the 52 African countries in the IIASA GDP database, 50 had data on GDP per capita. Of these,
 486 approximately 80% were below \$4000 per capita in 2010 and these nations held over 810 million total

⁴ Data was obtained from SSP Database (Shared Socioeconomic Pathways) – Version 1.1 from:
<https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about>

⁵ See the World Bank GNI per capita Operational Guidelines & Analytical Classification database under “How does the World Bank classify countries?” <https://datahelpdesk.worldbank.org/knowledgebase/articles/378834-how-does-the-world-bank-classify-countries>.

487 and 290 million urban low-income populations (**Table 2**). The SSP 1 and 5 defined rapid decreases in the
 488 number of low-income nations and total and urban populations. SSP 2 outlined a similar trend, but in
 489 slower fashion. SSPs 3 and 4 defined increases in low-income total and urban populations over time.
 490 These trends were commensurate with the descriptions of the SSPs above. Using the (2005) \$4,000
 491 threshold, by 2100, low-income nations no longer exist in SSPs 1, 2 and 5. That is, in these development
 492 pathways all nations on the continent have GDP per capita levels above \$4000 by 2100.

493
 494 The sensitive population was identified as the share of population in each country of a certain age (< 5
 495 and > 64). Given that the population age structure was available for each SSP by gender for each 10-
 496 year step, we calculated the numbers of people in this category for each nation. We then applied the
 497 share of sensitive population uniformly across urban and non-urban cells. The sensitive population
 498 made up about 19% of the African population in 2010, which translated into 191 million total and 76
 499 million urban persons. The shares of these populations changed with the different SSPs, increasing
 500 dramatically in SSPs 1 and 5 and remaining fairly flat in SSPs 3 and 4 (**Table 3**).

501

Table 3: African sensitive population by SSP

	2010	2030	2070	2100
Share of population (%)				
SSP 1	18.7	15.1	23.3	39.8
SSP 2	18.7	16.8	18.1	24.1
SSP 3	18.7	18.7	17.1	18.4
SSP 4	18.7	18.5	17.5	19.0
SSP 5	18.7	15.1	23.4	39.8
Total sensitive population (millions)				
SSP 1	191.1	217.2	448.2	742.6
SSP 2	191.1	255.0	429.0	633.0
SSP 3	191.1	301.4	519.4	727.4
SSP 4	191.1	294.2	502.6	686.8
SSP 5	191.1	216.3	439.0	719.6
Urban sensitive population (millions)				
SSP 1	76.3	122.5	367.5	683.2
SSP 2	76.3	127.5	282.8	469.8
SSP 3	76.3	129.0	249.7	375.8
SSP 4	76.3	165.2	412.3	638.5
SSP 5	76.3	122.0	360.0	662.1

502

503 3.5 Application of the framework

504

505 After spatially allocating urban population derived from the SSPs, we overlaid the heat indices derived
 506 from the 5 GCMs in ISIMIP for each RCP, to identify the location of urban areas and residents projected
 507 to be exposed to the heat waves of different intensities for the different urban simulations (compacted
 508 and sprawled). We compared results along RCPs for the different appropriate SSPs to show how climate
 509 change impacts played out under different socio-economic futures (Ebi et al., 2014). We presented the
 510 most likely estimates (means), high and low for each analysis. Because SSP 1 is considered the
 511 sustainable pathway, we reported figures for this SSP across appropriate RCPs and compared them with
 512 other pathways.

513

514 3.6 Sources of uncertainty

515

516 The numerous data sources and assumptions made in the different analyses introduced uncertainties in
517 our outcomes. The sources of these uncertainties are found in the four major tasks of the research
518 including the: 1) quantitative socio-economic projections; 2) heat wave estimates; 3) urban land cover
519 expansion and urban population projections; and 4) UHI estimates. Within each SSP, there is
520 uncertainty in the quantitative projections from the interpretation of the SSP narratives, as well as from
521 the models that have generated the quantitative projections (Riahia et al., 2017). Moreover, our
522 choices of indicators for sensitive and low-income populations (only using age, for example) introduced
523 uncertainty in the results.

524
525 The use of an ensemble of GCMs was an attempt to capture uncertainty. In this case, we attempted to
526 quantify the resultant uncertainty by presenting the most likely estimate (mean) and the entire range
527 found within the ensemble of model outputs (using the symbol “±” for heat indices and reporting the
528 max and min values for exposure estimates). Our categorization of heat wave intensities (> 42 C) and
529 choice of heat wave duration (15-days) inevitably lead to conservative numbers of exposed populations.
530 For both the RCPs and SSPs the combination of all the different pathways attempted to account for a
531 wide variety of possibilities. No one pathway was prioritized, and the entire framework helped to
532 identify the range of possible futures.

533
534 Uncertainty was also introduced in the urban land use expansion models. These were particularly
535 difficult to address, as we were unsure of how future technologies, policies and behaviors could change
536 urban patterns. Furthermore, the identification of what was urban was challenging. We attempted to
537 address this through the use of two different urban extent simulations (compact and sprawled), which
538 provided a range of outcomes. Our modeling approach for both urban land cover growth depended on
539 a binary distinction between urban and non-urban areas (instead of a graded measure of level of
540 urbanization per unit) missing much of the detail of urbanism. We also assumed urban expansion
541 follows urban population growth rates. There are several sources of uncertainty in this assumption,
542 most notably the reduction of urbanization to population density, as well as the limited resolution of 30
543 arc-second grid cells, which demanded a significant simplification of the urban structure within each cell.
544 Finally, we randomly distributed urban population rather than privileging specific cities. Identifying
545 where economic activity will blossom was inherently difficult. Ultimately, we presented and compared
546 the highest and lowest heat indices in both the sprawled and compacted models to find a range of
547 exposure values and averaged the results from the two models to get a most likely outcome.

548
549 In terms of our UHI estimates, it is known that while there is abundant research on UHI, the methods
550 used in studies may not be similar (Stewart, 2010). As such, our grouping of canopy level estimates
551 introduced uncertainty. At the same time, we followed UHI experts’ examples by categorizing cities by
552 population to predict UHI intensities (Oke, 1973, Roth, 2007, Jauregui, 1997, Santamouris, 2015). To
553 address uncertainties in UHI, we estimated heat indices both with and without UHI values.

554

555 **4.0 Results**

556

557 *4.1 Urban land cover simulations for Africa*

558

559 Empirically, the SSPs define three general population patterns for African urbanization through the
 560 twenty-first century (**Table 4**). The first pattern is presented in SSPs 1 and 5, where urban growth
 561 proceeds rapidly during the first half of the century, tripling the total urban population. Then, during
 562 the second half of the century, total urban population growth decreases dramatically, resulting in a
 563 regional urban population of approximately 1.7 billion (91% of total population) by 2100. The second
 564 pattern, exemplified by SSPs 3 and 4, includes rapid urban growth during the first part of the century,
 565 and continued growth but at slower but steady growth rates during the second half of the century, at
 566 which time urban populations reach 2.0 and 3.3, respectively. Due to high total population growth in
 567 SSP3, by 2100, the urban share is only 51% of total population. In SSP 4, by 2100, the urban share is
 568 similar to SSPs 1 and 5 at 91% of total population. The third pattern, demonstrated in SSP 2, is mid-way
 569 between these SSP 1 and SSP 4 and includes steady urban growth throughout the first half of the
 570 century. During the second half of the century the growth rate drops by more than half resulting in
 571 approximately 1.9 billion urban dwellers making up 73% of the total population in the region in 2100.
 572

Table 4: Projections for African urban population and urbanization levels by SSP, 2010-2100

	2010	2050	2100	Projected annual average growth (%)	
				2010-2050	2050-2100
SSP 1					
Urban population (millions)	410	1,250	1,700	2.83	0.62
Urbanization (%)	40	71	91		
SSP 2					
Urban population (millions)	410	1,180	1,930	2.68	0.99
Urbanization (%)	40	59	73		
SSP 3					
Urban population (millions)	410	1,060	2,000	2.40	1.28
Urbanization (%)	40	44	51		
SSP 4					
Urban population (millions)	410	1,580	3,280	3.43	1.47
Urbanization (%)	40	63	91		
SSP 5					
Urban population (millions)	410	1,230	1,640	2.78	0.58
Urbanization (%)	40	64	91		

573
 574 Growth patterns for the two urban land cover simulations result in different numbers of cities, total
 575 urban area and mean densities (**Table 5**). Total urban area in the sprawled model is an order of
 576 magnitude larger than in the compact model, therefore the urban densities in the compact model are
 577 typically higher than those using the sprawled model. The number of urban areas grows more rapidly in
 578 the sprawled model than the compact model due to the algorithm specifications. Urban area growth
 579 also varies across SSPs, but not as starkly as population. This is due to the fact that in our simulations,
 580 while population can decrease, urban area does not.
 581

Table 5: Simulated African urban area expansion (Km²), increase in number of urban extents and change in mean densities by urban land use model and SSP

	URBAN AREA (1000 KM ²)					GloboCover (compacted urban use)					MEAN DENSITY (1000 PERSONS/KM ²)				
	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5	URBAN EXTENTS (1000s)					SSP 1	SSP 2	SSP 3	SSP 4	SSP 5
	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5
2010	29	29	29	29	29	3.8	3.8	3.8	3.8	3.8	14.2	14.2	14.2	14.2	14.2
2030	51	48	43	54	51	5.6	5.3	5.1	5.5	5.7	16.0	15.9	15.9	16.5	16.0
2070	84	83	77	115	82	7.9	7.7	6.6	8.3	7.9	18.7	18.8	18.7	20.2	18.6
2100	91	98	103	156	89	8.7	8.6	8.4	10.3	8.7	18.7	19.7	19.9	21.0	18.5
	URBAN AREA (1000 KM ²)					GRUMP (sprawled urban land use)					MEAN DENSITY (1000 PERSONS/KM ²)				
	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5	URBAN EXTENTS (1000s)					SSP 1	SSP 2	SSP 3	SSP 4	SSP 5
	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5
2010	253	253	253	253	253	3.3	3.3	3.3	3.3	3.3	1.6	1.6	1.6	1.6	1.6
2030	453	425	386	480	451	16.9	16.3	13.8	16.0	17.0	1.8	1.8	1.8	1.9	1.8
2070	772	760	703	1,044	759	28.4	28.0	36.3	41.5	28.4	2.0	2.0	2.1	2.2	2.0
2100	838	904	935	1,410	821	31.8	32.9	45.3	63.0	31.5	2.0	2.1	2.2	2.3	2.0

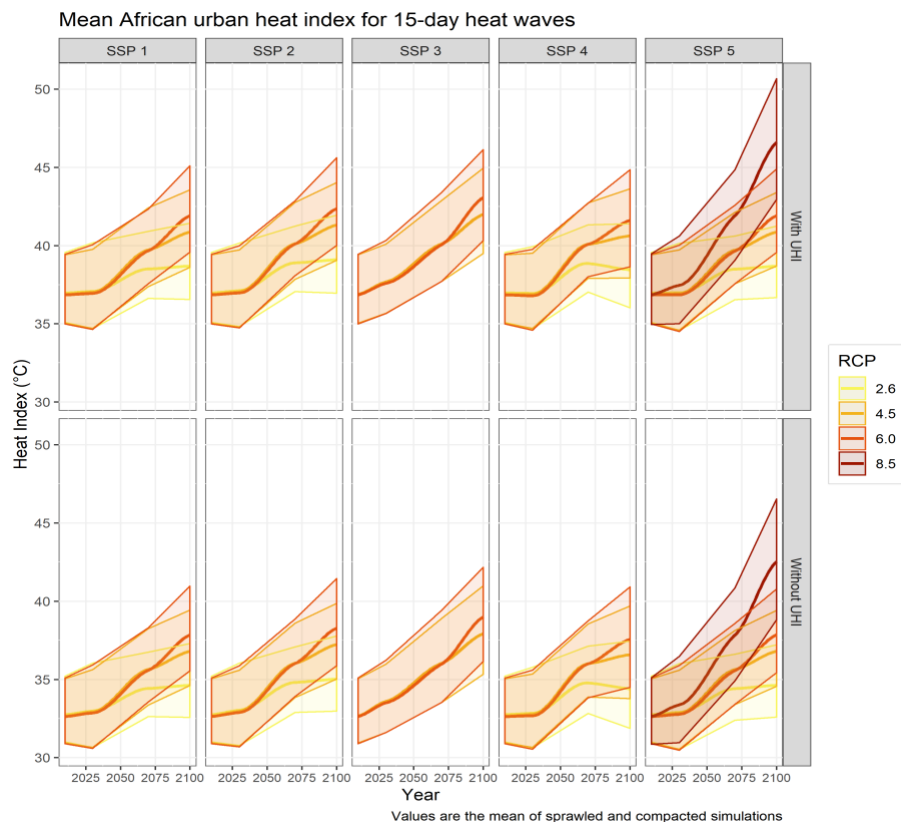
582 The urban land cover simulations result in two patterns across SSPs. On the one hand, urban area
583 growth continues throughout the century resulting in similar amounts of urban land cover for SSPs 1, 2,
584 3 and 5. In these cases, urban land cover varies between 840 and 935 thousand km² (sprawled) and 91
585 to 103 thousand km² (compact). On the other hand, in SSP 4 urban area growth is the greatest leading
586 to over 1.4 million km² in the sprawled model and 156 thousand km² in the compact model. By 2100,
587 the number of urban areas also is largest in SSP 4 for the sprawled model (over 63 thousand) and is
588 similar across SSPs 1,2 and 5 (around 31 – 32 thousand). SSP 3 had the intermediate number of urban
589 areas (approximately 45 thousand). The same relative pattern, with smaller numbers of urban areas
590 was exhibited in the compact simulation.
591

592
593 As a result of the different size of urban areas, the urban densities vary between the different
594 simulations. By 2100, in SSPs 1, 2 3 and 5, the compacted urban growth model densities are
595 approximately 3.8 – 4.5 times that of the sprawled model. In SSP 4, the compacted simulations result in
596 average regional densities that are almost 6 times as dense as the sprawled simulations.
597

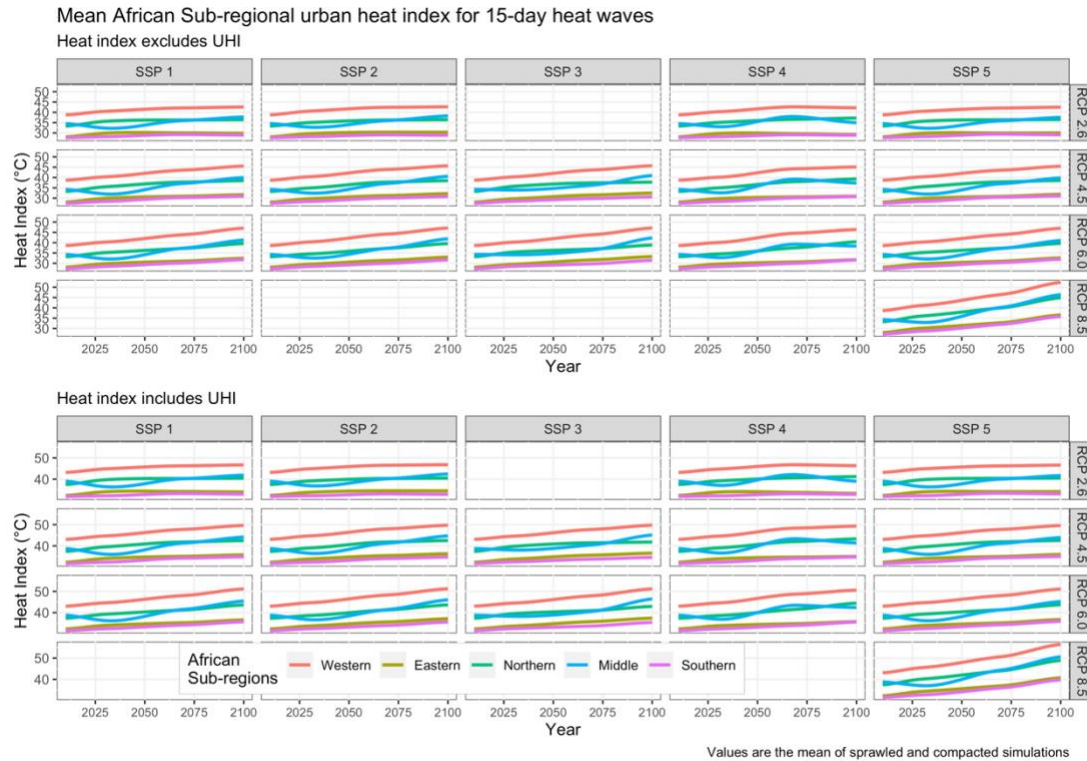
598 4.2 Future heat waves

599
600 Over the course of the century, the average regional 15-day urban heat wave index climbs for all RCPs,
601 although for RCP 2.6 heat indices level off between 2030 and 2070 for the rest of the century (**Figure 3**).
602 The greatest increases are seen in the higher RCPs. There are also large differences in heat indices
603 depending upon whether UHI is included or not. For example, during the current period, the estimates
604 suggest that the mean warmest 15-day heat wave is approximately 32.7°C (± 2.1°C) without UHI and
605 with UHI is approximately 36.9 °C (±2.2°C). By the end of the century, in RCP 2.6 and the sustainable
606 development pathway (SSP 1) the mean 15-day heat waves are estimated to increase to 34.6°C (± 2.4°C)
607 without UHI and 38.7°C (± 2.4°C). At the high end, for the high fossil fuel use development pathway (SSP
608 5) and RCP 8.5, the mean 15-day heat wave is projected to increase to 42.5°C (± 3.9°C) without UHI and
609 46.6°C (± 3.9°C) when UHI is included. For SSPs 2-4 for RCPs 4.5 and 6.0, by the end of the century, the
610 mean 15-day heat wave index is projected to rise to intermediate levels. Estimates for without UHI

611 suggest levels of between 36.8°C and 42.2°C, while with UHI projections reach between 40.6°C and
 612 43.1°C (**Table 6, supplement**). Across RCPs, the African sub-region with the warmest 15-day heat indices
 613 is Western Africa, where the heat index rises higher than projected for the Northern and Middle sub-
 614 regions (**Figure 4**).
 615



616
 617 *Figure 3: Average heat index for 15-day heat waves in cities of Africa by SSP, RCP and with and without UHI values*
 618 *added.*
 619
 620

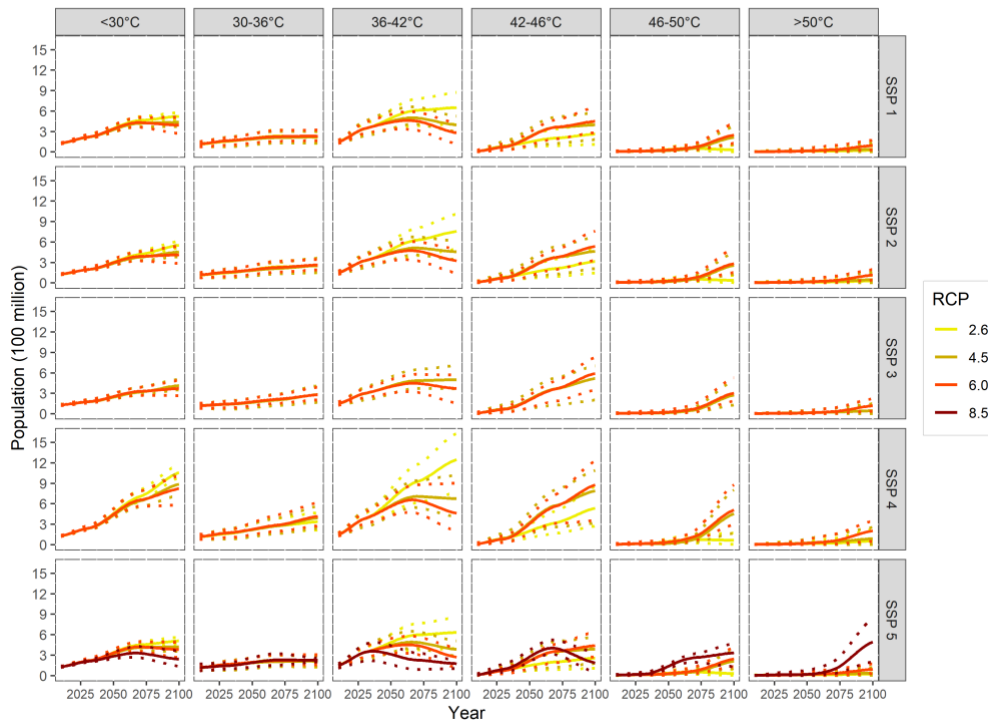


621
622 *Figure 4: Mean heat indices for cities in Africa by sub-region, SSP, RCP and with UHI and without UHI values. The*
623 *red colored curves are for Western Africa.*

624
625 **4.3 Future exposure**

626
627 The findings suggest large differences in African population exposure levels to very warm heat waves
628 between simulations with and without the additional UHI effect (**Figure 5**). For example, projections
629 without the UHI effect suggest that in SSP 1 and RCP 2.6, the numbers projected to experience very
630 warm conditions will increase from approximately 18 million (range: 3.0 to 47 million) in 2010 to 313
631 million (range: 111 – 608 million). With added UHI, the numbers exposed start and end much higher:
632 from 136 million (range: 87 to 191 million) in 2010 to 947 million (range: 542-1367 million) in 2100
633 (**Table 7 supplement**). The numbers exposed to these warm conditions increase with RCP. In RCP 4.6,
634 for example, exposure exceeds 600 million for SSPs 1,2 & 5 by 2100, and exceeds 1 billion for SSP 4,
635 even for heat indices without the UHI effect. With the UHI effect exposure levels reach or exceed 1
636 billion for all SSPs for all RCPs.
637

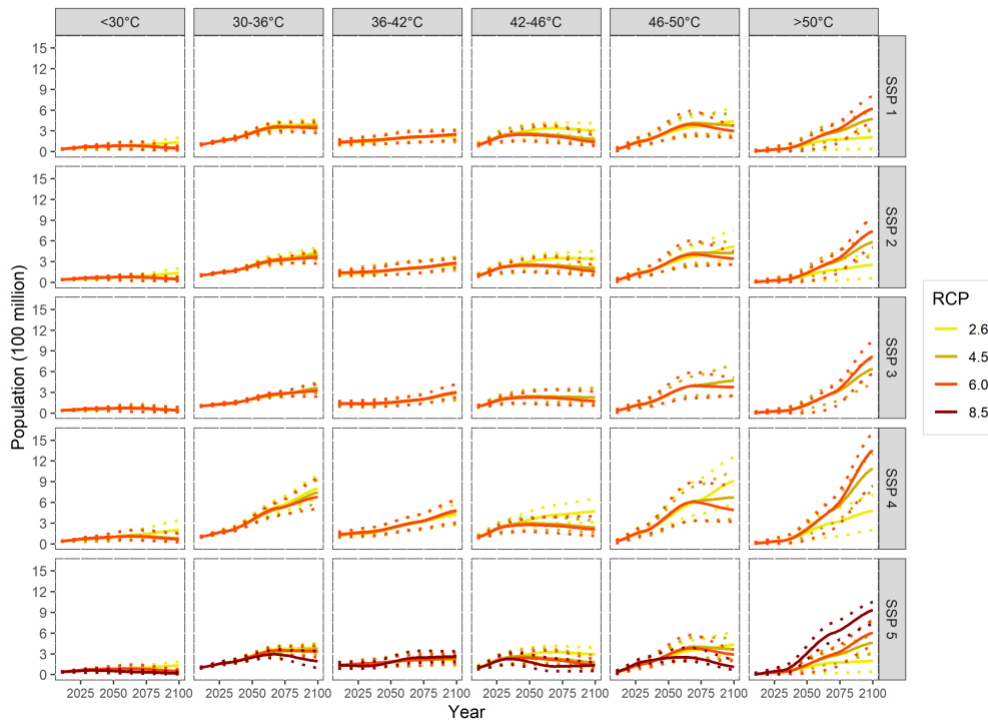
African urban population exposure estimates for 15-day heat waves of varied intensity
Heat index excludes UHI



Dotted lines represent the full range of estimates for each RCP

638

African urban population exposure estimates for 15-day heat waves of varied intensity
Heat index includes UHI



Dotted lines represent the full range of estimates for each RCP

639

640

641

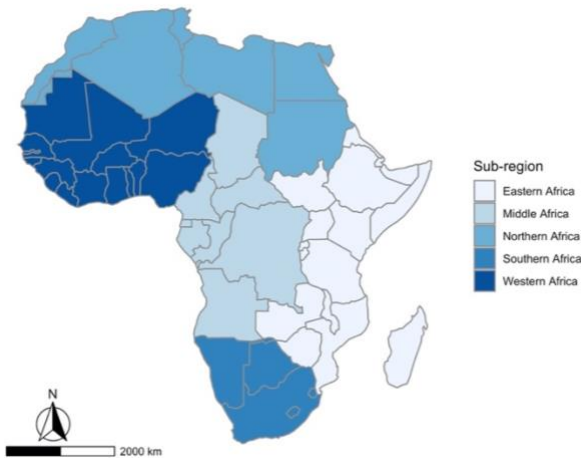
642

Figure 5: African urban population exposed to various levels of 15-day heat intensity by SSP, RCP and with and without UHI values.

643 The figures of exposure to high index heat waves absorb a large share of the African urban population.
 644 In SSP 1 - RCP 2.6, the percent of the African urban population exposed to very warm heat waves rises
 645 from 4% in 2010 to over 18% of the total urban population when UHI is excluded from the analysis.
 646 Including UHI in the heat index, the share rises from 36% in 2010 to over 55% in 2100. In other
 647 scenarios that include UHI, the share of the urban African population that experiences very warm heat
 648 waves typically exceed 50% of the population by 2100. Furthermore, much of the increase in numbers
 649 in this category is due to increases in exposure to the *extremely warm* heat waves (>50°C). When UHI is
 650 included in the heat index, the share of those exposed to heat waves of >50°C rises from very low levels
 651 (around <2%) in 2010 to, in some cases, over 40% of the urban population. For SSP 5 and RCP 8.5, this
 652 share exceeds 56% and includes over 490 million people (or more than the total urban African
 653 population in 2010).

654
 655 In each projection, while the numbers exposed to the milder level heat waves (<30°C) increases across
 656 the century, the shares of this population decrease. For example, in SSP 1, RCP 2.6 including UHI, the
 657 numbers exposed to <30°C heat waves increase from 38.2 million in 2010 to approximately 133 million,
 658 but these values translate to approximately 9.3% of the total African urban population in 2010, and 7.8%
 659 of the total African urban population in 2100. These increases in populations and declines in share are
 660 projected across all SSPs and RCPs and suggest population growth is projected to occur in areas prone to
 661 warmer heat events.
 662

African sub-regions



663
 664 *Figure 6: Sub-region in Africa, as defined by the UN*
 665 We use the UN sub-regional distinctions (**Figure 6**). At the sub-regional level those in Western Africa
 666 have the highest numbers of exposed populations to very warm heat waves. In this analysis we
 667 compare SSP 1 and SSP 4 results across heat wave categories, RCPs and with and without the addition of
 668 UHI. **Figure 7** demonstrates that in both pathways and across RCPs, Western African urban populations
 669 make up the lion’s share of those projected to experience the higher intensity heat waves compared to
 670 residents in other parts of the continent. Those in Eastern Africa, alternatively will have the largest
 671 populations exposed to heat waves of <30°C and 30-36°C. As can be seen by the charts, SSPs 4 present
 672 cases of highest exposure levels to extremely warm 15-day heat waves of >50°C. For SSP 4 and RCPs 4.5
 673 and 6.0, projections, which include UHI, results project that the total number of urban Africans exposed

674 to these intensities by 2100 may exceed 1 billion and most of these populations may be located in
 675 Western Africa.

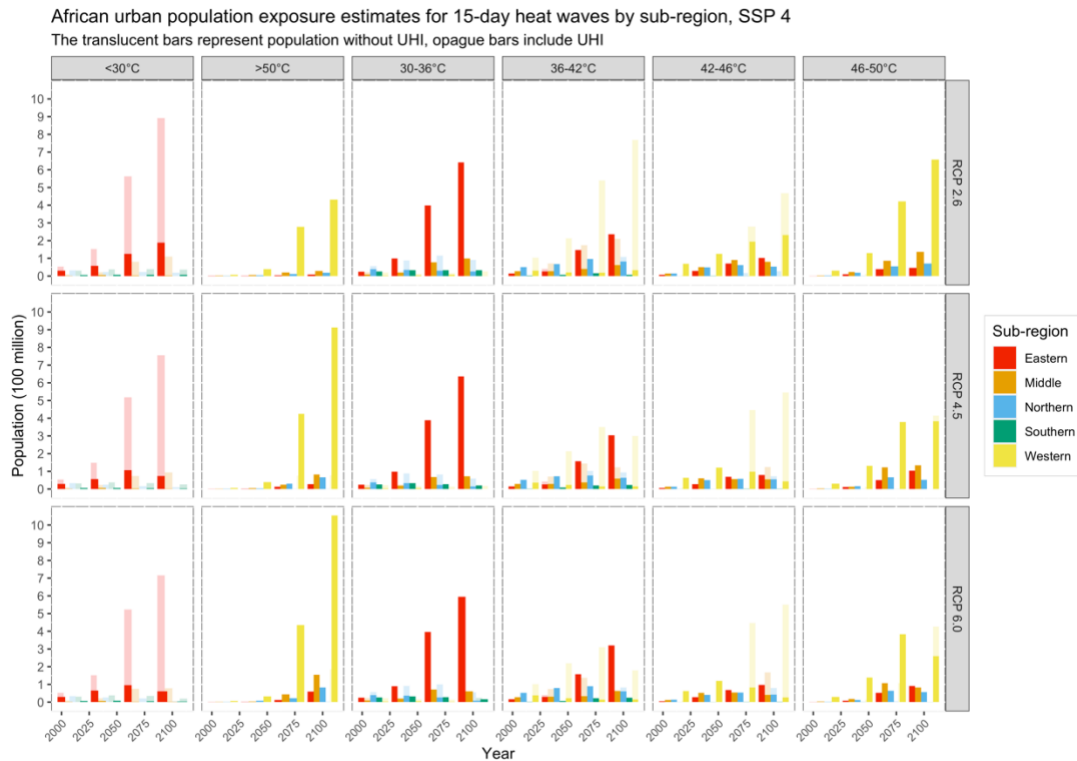


Figure 7: Bar charts demonstrating the difference in exposure to very warm heat waves by sub-region in Africa for SSPs 1 and 4 by RCP. The translucent bars are for exposure without UHI and the opaque are for exposure with UHI

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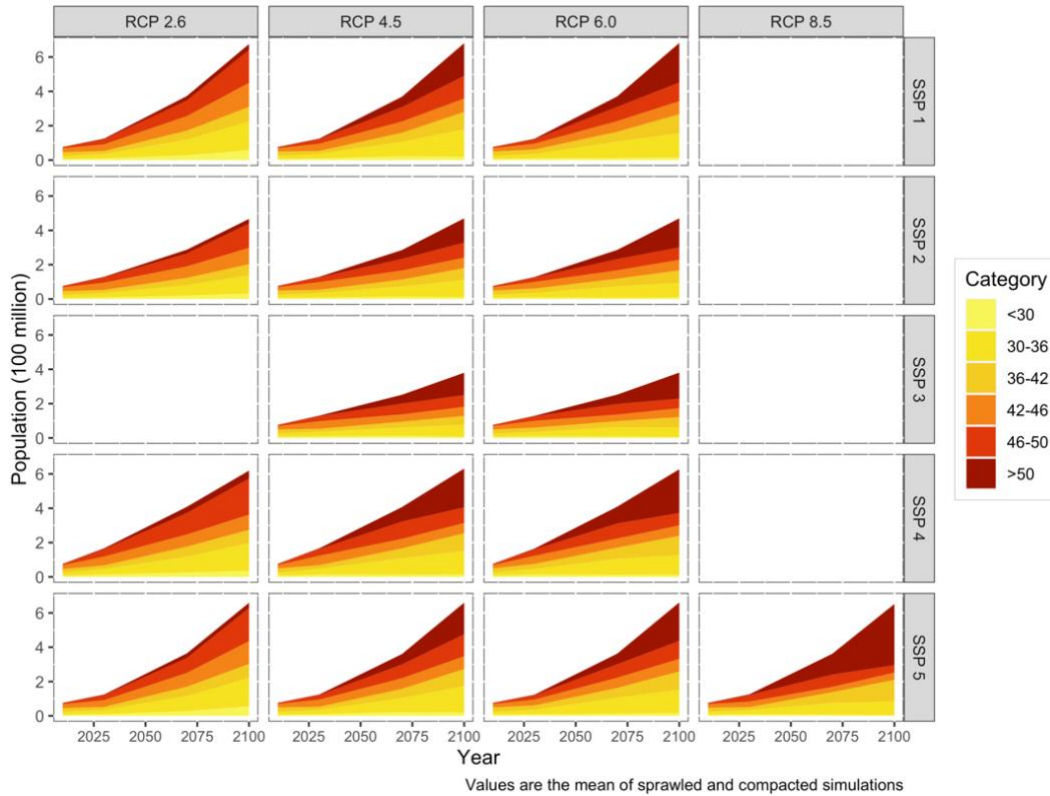
4.4 Future heat sensitivity and low-income populations

The African share of the elderly and very young population exposed to very warm heat waves varies across SSPs and RCPs (**Figure 8**). From 2010 to 2100, in RCP 2.6 and SSP 1, without accounting for UHI, the number of sensitive populations in African cities exposed to very warm heat waves increases more than 40-fold, from around 2 million to 87 million (**Table 8 supplement**). If UHI is included in the heat indices, the figures are more dramatic, suggesting an increase from 27 million in 2010 to over 360 million (or approximately 54% of the regional sensitive population) by 2100. By 2100, the highest shares of sensitive populations exposed to very warm heat waves are projected for the SSP 5 pathway, across all RCPs. For RCP 8.5 and SSP 5, by 2100, the numbers of sensitive population exposed to very warm heat waves climbs to over 380 million (range: 241 – 471 million) for the simulations without UHI and to over 440 million (range; 331-560 million) when UHI is included in the projections.

The population living in the lower income nations changes during the twenty-first century, due to projected economic growth that increases economic production faster than population growth (**Figure 9**). These conditions are seen in SSPs 1 and 5, where by the end of the century, there are low numbers of countries with GDP per capita at or below \$4,000. Even in SSP 2, projections suggest that the number of low-income Africans decreases over time. At present, approximately 8 million low-income African urban residents are exposed to very warm heat waves, if UHI is not included in the analysis. If the UHI effect is included, the numbers of low-income residents exposed to very warm heat waves almost equals the total African urban population exposed to these events. That is, with UHI added, most of those exposed to very warm heat waves during the current period are living in low-income countries (**Table 9 supplement**).

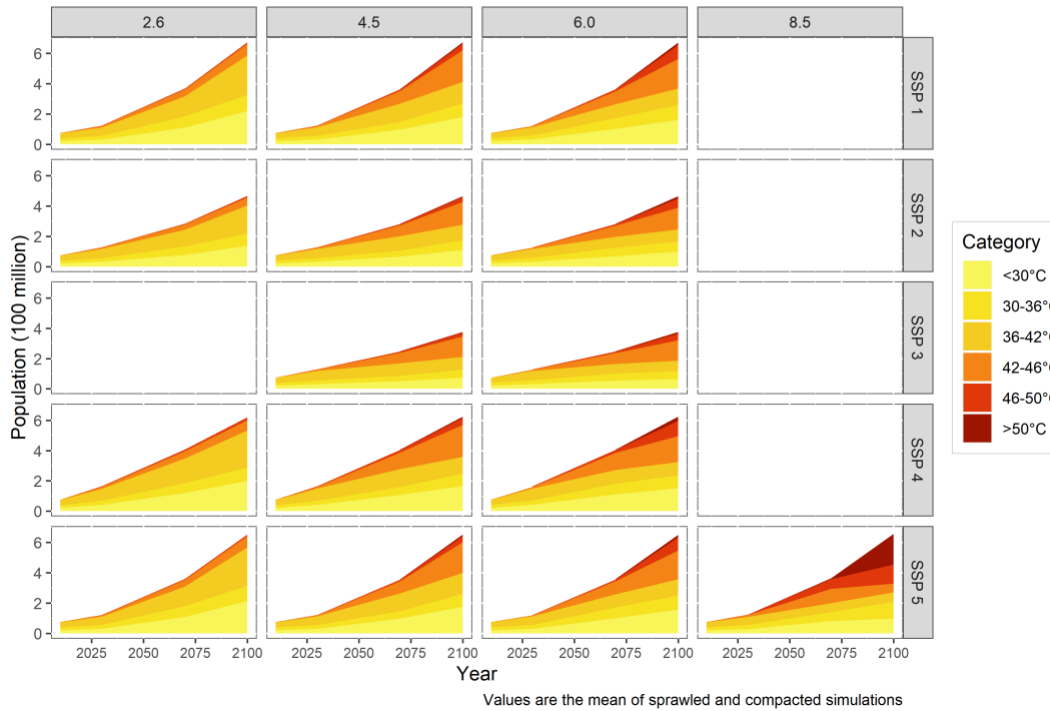
Alternatively, for SSP 3 and 4 economic growth is slower than population growth inducing an increase in low-income populations. As such, the low-income population climbs throughout the century in these pathways and with it the numbers of those exposed to very warm heat waves (**Figure 7**). This suggests that changing development strategies will have an enormous effect on exposure and adaptation potential. While the numbers of low income exposed to very warm heat waves decline to 0 by the end of the century in SSP 1, 2 and 5, they increase in SSP 3 and 4.

African urban sensitive population exposure estimates for 15-day heat waves
Heat Index excludes UHI



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African urban sensitive population exposure estimates for 15-day heat waves
Heat Index excludes UHI



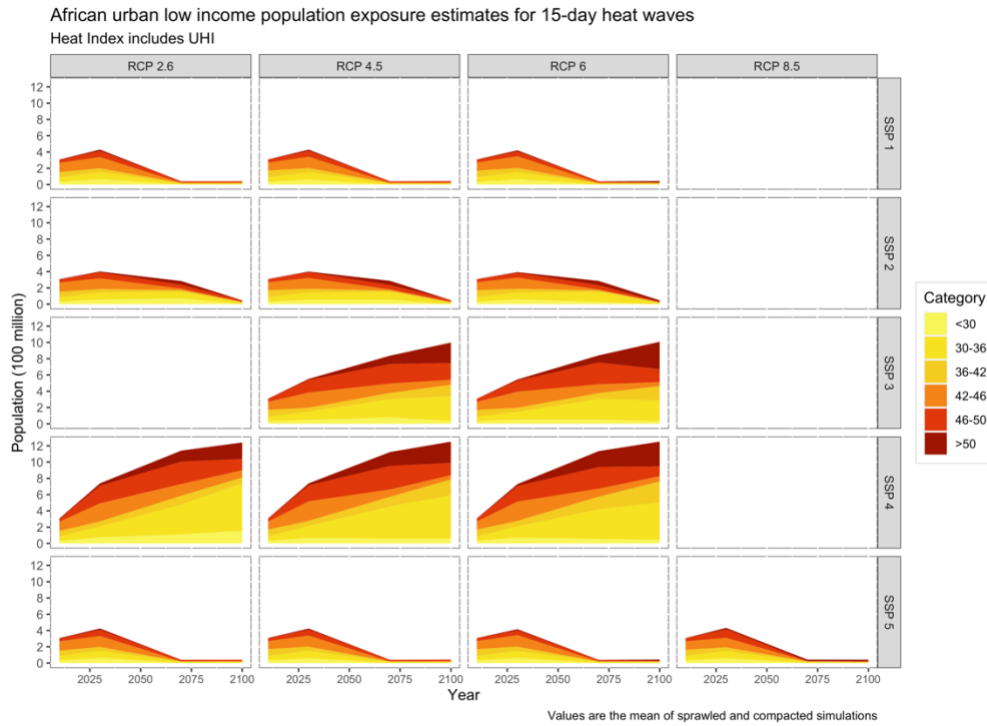
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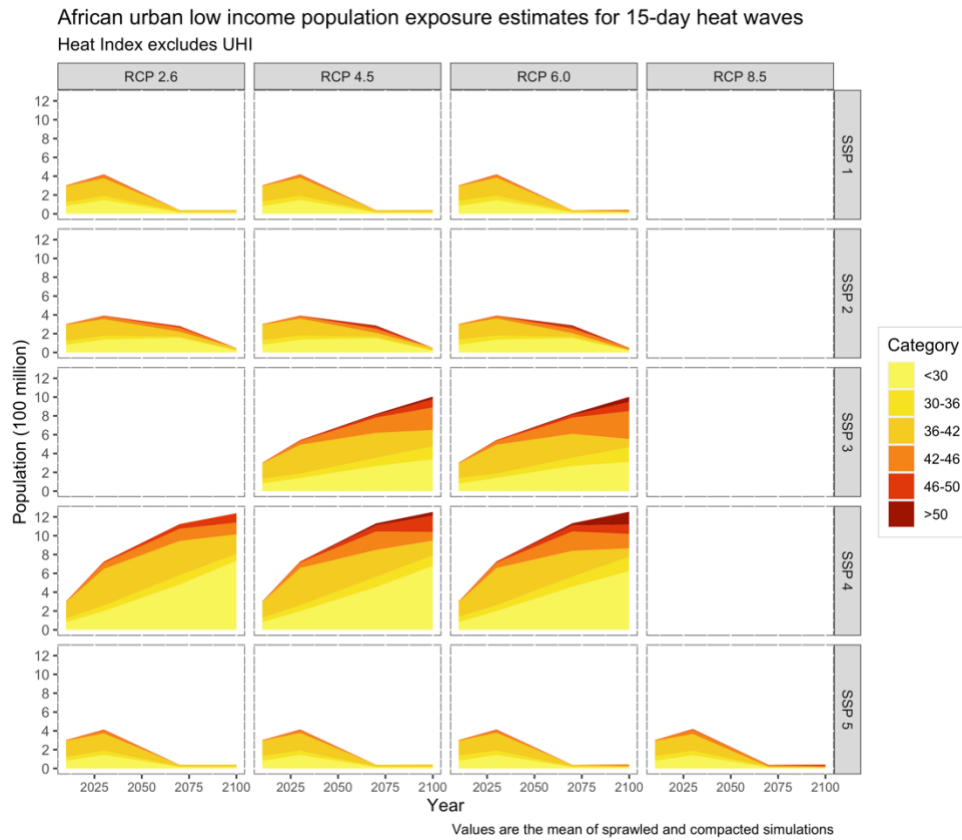
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Figure 8: Sensitive population exposed population to very warm 15-day heat waves by heat wave intensity, SSP and RCP and with and without UHI

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Figure 9: Low-income population exposed population to very warm 15-day heat waves by heat wave intensity, SSP and RCP and with and without UHI

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723

724 **5.0 Discussion**

725

726 *5.1 Projected African urban land use*

727

728 The goal of using a sprawled and a compacted scenario for simulating urban land use growth was to
729 delineate the range of possible futures for urban area expansion. There are three published urban land
730 use projections for the globe that include Africa, which can test whether our models achieve the
731 objective of providing the outside range of estimates. The first published future estimate for Africa
732 starts with 41,450 km² urban areas in 2000 and projects a 5.9-fold increase by 2030 to 244,000 km²
733 (Güneralp et al., 2017; Seto, Güneralp, & Hutya, 2012). This model starts with the global urban extent
734 circa 2000 from National Aeronautics and Space Administration's Moderate Resolution Imaging
735 Spectroradiometer (Schneider, Friedl, & Potere, 2009). After modeling population densities, the
736 research utilizes a spatial urban growth model, based upon the densities and surface slope, distance to
737 roads and land cover as the primary drivers of land change. The second future urban land cover
738 estimate for Africa starts with approximately 53,000 km². This model has three scenarios based upon
739 proposed decreases in density of over time (0%, 1% and 2% annually). By 2030, this second model
740 projects between 96,000 (low) and 175,000 (high) km² of urban areas and by 2050 projects between
741 154,000 (low) and 418,000 (high) km² of urban area on the continent (Angel, 2012; Angel, Parent, Civco,
742 Blei, & Potere, 2010). In a recent set of urban land use projections that explicitly use the SSP framework
743 Chen et al. (2020) present the scenario projections of global urban land expansion at a fine spatial
744 resolution of 1 km. This research starts at 2015 with urban land estimates provided by the Global
745 Human Settlement Layer (GHSL) dataset. Future urban land use growth to 2100 is estimated by a
746 regression model with factors of population, urbanization rate (percentage of urban population to total
747 population) and gross domestic product (GDP). The project provides data by 10-year steps for public
748 analysis (Chen et al., 2019).

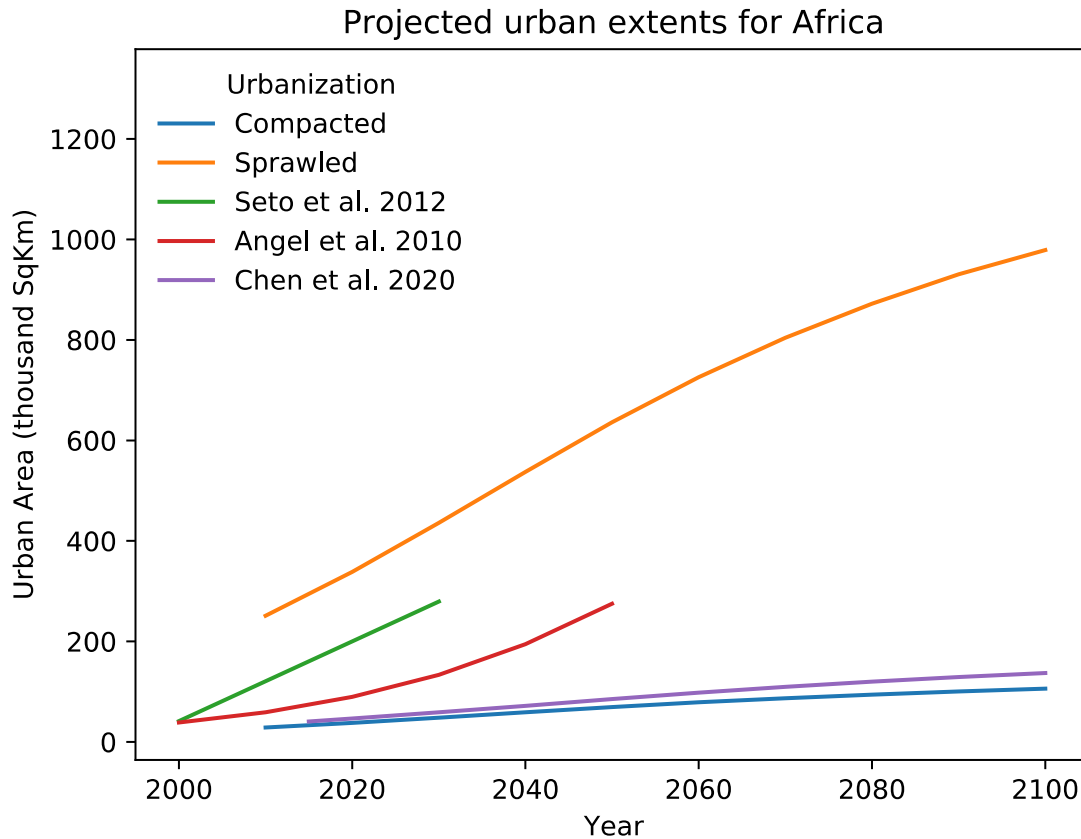
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750 While the first two models span a considerable range of urban expansion scenarios depending on the
751 corresponding model assumptions, the Chen et al (2019, 2020) analysis produces a very tight range of
752 possible urban expansion values for the African continent. Notably, the results are very close to, yet
753 slightly above, our compacted scenarios. **Figure 10** shows how the different model outputs for Africa
754 relate to each other and to our estimates. Given these comparisons, the intended results of the
755 simulations, to capture plausible urban land use growth between sprawled and compacted simulations,
756 given current estimations has been successful.

757

758 We further examine a fourth model by Jones and O'Neill (2016), which has become widely used in
759 studies involving future urban populations. Their approach, however, focuses on urban and rural
760 populations on a grid distributed by a gravity-based downscaling model. As such, their model does not
761 rely on clearly delineated (and potentially expanding) urban extents but allows for urban and rural
762 populations to co-exist in the same grid cells. There is no indication of the size of urban land use or
763 boundaries of urban areas in this study. This makes comparison with our outputs difficult. Finally, a
764 recent study of urban land use and heat exposure for Africa used a combination of the above scenarios
765 Rohat, Flacke, Dosio, Dao, and van Maarseveen (2020) delineated future cities' boundaries based on

766 declines in urban density were informed by historical trends (Angel et al., 2016), existing scenarios of
 767 urban densities in Africa (Angel et al., 2010; Güneralp et al., 2017) and assumptions of spatial patterns of
 768 urban development under the SSPs (Jiang & O’Neill, 2017; Jones & O’Neill, 2016). The land use change
 769 models, however differed by SSP in terms of rates of population density change. To get population
 770 sizes, these land use maps were then combined with spatially explicitly projections of urban population
 771 for the different SSPs (Jones & O’Neill, 2016).



772
 773 *Figure 10: Comparison of our compacted and sprawled scenario with the projections by Seto et al. (2012), Angel et*
 774 *al. (2010), and Chen et al. (2020). The ranges derive from the five SSPs (for our projections and Chen et al. 2020),*
 775 *quartiles of urbanization probabilities >25% (Seto et al. 2012) and three different assumptions for the decrease in*
 776 *urban density 0%, 1% and 2% (Angel et al., 2010). The projections by Seto et al. (2012) and Angel et al. (2010) are*
 777 *only available up to 2030 and 2050, respectively.*

778
 779 **5.2 Projected urban heat in Africa**
 780

781 It is more difficult to compare our future projections of heat waves with other models due to the
 782 different methods to compute heat waves and the techniques to present the data. General trends
 783 across studies, however, are consistent with our results. Research demonstrates that in a future
 784 warmer climate, African heat waves will not only become more frequent but also increase in duration
 785 and intensity (Ceccherini, Russo, Amezttoy, Marchese, & Carmona-Moreno, 2017; IPCC, 2012; Nangombe
 786 et al., 2018). (Dosio, 2017) employing the HWMId index (Russo et al., 2014; Russo, Sillmann, & Fischer,
 787 2015) presents projections of temperature and the frequency and intensity of extreme warm events for

788 Africa based on the results of a large ensemble of the World Climate Research Programme COordinated
789 Regional climate Downscaling Experiment (CORDEX) Regional Circulation Models. He finds that by
790 between 2071 and 2100, under RCP8.5, warming for Africa can reach 5-6°C and that the gulf of Guinea,
791 the Horn of Africa, the Arabian peninsula, Angola and the Democratic Republic of Congo are expected to
792 face, every 2 years, heat waves (defined by the model) of length between 60 and 120 days. This study
793 also projects for these areas that by the end decades of the twenty-first century, the total length of heat
794 spells projected to occur normally (i.e. once every 2 years) under RCP8.5 may be longer than those
795 occurring once every 30 years under the lower emission scenarios.

796

797 Rohat et al. (2020) project that the annual number of days when the heat index (including temperature
798 and humidity) exceeds 40.6°C (what they term is “dangerous heat”), averaged across 150 African cities,
799 increases under all RCPs until the 2060s and then stabilizes for RCP 2.6 and RCP 4.5, but at different
800 levels. The number of days in exceedance of this heat index continues to rise under RCP8.5 through to
801 the end of the century. By the 2090s, the number of days in exceedance of 40.6°C could reach 59, 82,
802 and 123 annually for RCPs 2.6, 4.5 and 8.5, respectively. These patterns in intensity and trends among
803 different RCPs are similar to what is found in this study. The Rohat et al. (2020) study also find, similar
804 to this study, that the cities of Western Africa are by far the most severely affected by, what they call,
805 dangerous heat.

806

807 *5.3 Projected urban heat exposure in Africa*

808

809 There are fewer studies that have identified population exposure, in terms of total urban population to
810 future heat. A recent global study identified the land area that will be above a ‘deadly threshold’,
811 identified with temperature and humidity levels, at the global scale (Mora et al., 2017). Based upon the
812 estimated land area affected, they report that while around 30% of the world’s population is currently
813 exposed to their “deadly” threshold for at least 20 days a year, by 2100, this percentage may increase to
814 ~48% under a RCP 2.6 scenario, and ~74% under a RCP 8.5 scenario. They also point out that that
815 exposure to these levels of heat is concentrated in tropical areas, and that most of the land area in this
816 climatic zone will be over the threshold every day of the year by 2100.

817

818 Rohat et al (2020) in their study of 173 large African cities find exposure to “dangerous heat” (exceeding
819 40.6°C) will increase by a multiple of 20-52-fold, depending upon the SSP. By the 2090, their results
820 suggest a range of 86-217 billion person-days per year. They also demonstrate the concentration of
821 exposure in cities of Western Africa. Importantly, however, this study did not include UHI in their final
822 estimates and as the authors suggest, the final results are therefore conservative. Nevertheless, both of
823 these studies point to the potential high exposure levels in Western Africa and the high potential
824 population exposure levels.

825

826 *5.4 Projected UHI in African cities*

827

828 Recent research has simulated future urban growth to project UHI increases across arid, cold, tropical
829 and temperature climate zones for RCP 4.5 to 2050 (Huang, Li, Liu, & Seto, 2019). In this study, the
830 intensity of UHI for summer daytime and nighttime warming increased on average between 0.5-0.7°C,
831 but could reach ~3°C in some locations. By 2050, UHI related warming is on average about half, and
832 sometimes up to two times, as strong as that caused by greenhouse gas (GHG) emissions for the RCP.
833 The extra urban expansion-induced warming increases extreme heat risks for about half of the future
834 urban population, primarily in the tropical Global South. As S. Chapman, Watson, Salazar, Thatcher, and

835 McAlpine (2017) explain, however, UHI responds differentially to cloud cover, wind speed,
836 evapotranspiration and anthropogenic heat release and therefore can certainly increase with climate
837 change, but may also decrease, as rural areas warm more than urban areas (see also, Oleson, 2012;
838 Oleson, Bonan, Feddema, & Jackson, 2011).

839
840 In another recent analysis, UHI is associated with population size (a proxy for infrastructure) and mean
841 annual precipitation (Manoli et al., 2019). This study analyzed surface land temperatures in 30,000 cities
842 globally, in an attempt to identify a scaling law for UHI in cities. The model is based upon the argument
843 that, as a city grows, its structure and function are predictably modified (Bettencourt, Lobo, Helbing,
844 Kühnert, & West, 2007). As with Huang, et al (2019), the study suggests that as UHI will continue to
845 increase as urban population increases. The Manoli et al. (2019) study further adds precipitation
846 patterns into the equation.

847
848 Our results do not consider a change in UHI with urban land use change and increased climate warming.
849 Nevertheless, our study points to the significant addition of UHI effect for exposure to heat waves. For
850 example, in SSP 1, RCP 2.6 without the UHI values, the projections suggest that by the end of the
851 century approximately 18.4% of the total urban population in Africa will be exposed to very warm heat
852 waves, but with UHI, the share increases to 66%. In terms of population number, the addition of UHI
853 triples the number of urban residents exposed (from 313 to 947 million). The additional heat from
854 urban heat islands is a significant factor in increasing the number of residents exposed to these intense
855 heat waves. It is also interesting to note, however, that for larger changes in climate (RCPs 4.5, 6.0 and
856 8.5) the differences in share and total population exposed to very warm heat waves with and without
857 UHI decreases. For example, by 2100 in SSP 5, RCP 8.5, the total numbers of African urban residents
858 exposed to very warm heat waves reaches about 1 billion without adding the UHI factors, and
859 approximately 1.17 billion with UHI and the percent share increases from 61% to 71%, respectively. This
860 is probably due to high numbers of residents already in the very warm category even without UHI.

861
862 *5.5 Projected urban heat sensitivity and the impact of lower resources*

863
864 Urban Africa is highly vulnerable to climate change (Kareem et al., 2020). Recent reviews of the impact
865 of climate change on health in Africa find that heat waves will result in increased vulnerability (Asefi-
866 Najafabady, Vandecar, Seimon, Lawrence, & Lawrence, 2018; Chersich et al., 2018; Pasquini, van
867 Aardenne, Godsmark, Lee, & Jack, 2020), especially among children, elderly, patients taking anti-
868 cholinergic medications and patients with disorders of cornification (Uejio et al., 2011; Zhang et al.,
869 2017). These climate change vulnerabilities for African populations are compounded by poverty (Simon,
870 2010).

871
872 Unfortunately, there is less quantitative research findings on the number of future climate sensitive
873 populations in the region, particularly in cities (Simon & Leck, 2015). One global study that examined
874 the difference in impact of 1.5° and 2.0°C climate change highlighted the potential multiple impacts of
875 climate change on vulnerable populations in the region (Byers et al., 2018). This study found that for
876 populations vulnerable to poverty, climate exposure is an order of magnitude greater (8–32x) in the high
877 poverty and inequality scenarios (SSP3) compared to sustainable socioeconomic development (SSP1).
878 Their findings suggest that while 85%–95% of global exposure falls to Asian and African regions,
879 populations in these continents have 91%–98% of the exposed and vulnerable population. In their

880 study, higher warming scenarios, result in Africa's growing share of the global exposed and vulnerable
881 populations, ranging from 7%–17% at 1.5°C, doubling to 14%–30% at 2°C and again to 27%–51% at 3°C.

882

883 Here our estimates are crude, but comparable to these estimates. By 2100, at the low end,
884 approximately 87 (range: 19-262 million) are projected to be sensitive to heat and none will be living in
885 low income nations. At the high end, approximately 377 million (range: 247 – 460 million) of these
886 residents are projected to be sensitive and 464 million (range: 326-634 million), 23% of the exposed
887 population, may be living in low-income nations.

888

889 *5.6 Summary and implications*

890

891 Our most likely estimates for exposure to very warm heat waves by 2100, vary with the level of climate
892 change, development pathway, the inclusion of UHI and the urban land cover growth patterns,
893 suggesting a final range of between 310 million (range: 111 – 608 million) for SSP 1, RCP 2.6 with heat
894 indices excluding UHI and 2.0 billion (range: 1,277 – 2,679 million) SSP 4, RCP 4.5 with heat indices
895 including UHI. The large ranges suggest significant uncertainty, but there is no doubt that large
896 populations will be exposed in the future. Even in the most sustainable development pathway and
897 lowest climate change levels, both the numbers of urban residents exposed and the numbers of
898 sensitive in the population are projected to climb compared to the current period. This result is
899 probably due to both population growth and climate change. That is, the projections suggest African
900 population growth in already very warm places.

901

902 In our study the differences in mean and range of total, sensitive and low-income exposed vary slightly
903 between our sprawled and compacted urban models. This could be because of the resolution of the
904 climate model outputs, which is not fine enough to identify the difference in urban land cover. Heat
905 waves are typically events affecting larger scales than cities, suggesting that the sprawled aspect of
906 urbanization may not affect the total numbers of those exposed. Alternatively, there are studies that
907 suggest that more compact urban landforms that do not have vegetation and other urban form cooling
908 zones, may be warmer than less dense areas (Bechtel et al., 2019). The Bechtel, et al (2019) study used
909 a dataset of 50 cities to examine differences in surface urban heat islands within different local climate
910 zones (LCZ). They compared urban signal across different type (from the rural to high density compact)
911 to find higher land surface temperatures or the compact and commercial/industrial LCZ types than for
912 the more rural and higher vegetated areas. This study is suggestive that more compact cities may be
913 warmer than sprawled cities, but more research in this area is necessary to assess the impact of urban
914 form on heat and heat exposure.

915

916 The results of our study call attention to not only the critical importance of curbing climate change, but
917 to enhancing growth and well-being in Africa, and particularly for residents of its cities. Changing SSP
918 pathways makes a large difference in the numbers of those projected to be exposed to very warm heat
919 waves, even within the same RCP. The difference in numbers exposed to very warm heat waves can
920 double between the SSP 1 pathway (sustainable development) and the SSP 3 and 4 pathways.

921

922 Changing climate warming trends is important not only to reduce heat exposure and result human
923 health impacts, but also because of potential indirect and synergetic effects. High heat can reduce crop
924 yields (Siebert & Ewert, 2014), potentially forcing people from rural areas into cities (Kanta et al., 2018).
925 Increased heat can also affect the delivery of electricity, if air and water can no longer cool thermal

926 power plants, potentially reducing energy provision for air conditioning-based cooling (Schaeffer et al.,
927 2012). Also among a number of effects, scholars have identified high temperature impacts on
928 biodiversity (marine heat waves) potentially reducing potential protein sources (Smale et al., 2019),
929 wildfire risk (Parente, Pereira, Amraoui, & Fischer, 2018), electricity demand (Miller, Hayhoe, Jin, &
930 Auffhammer, 2008), water supply (Zampieri et al., 2016), economic productivity (Dunne, Stouffer, &
931 John, 2013) and urban infrastructure (L. Chapman, Azevedo, & Prieto-Lopez, 2013). As such, the results
932 of this study provide a critical, but partial, picture of climate-related heat impacts on cities that could be
933 useful for decision makers.

934

935 **6.0 Conclusions**

936

937 This project finds that heat waves of increasing intensity will be part of the future for large numbers of
938 African urban residents. The results from using different socioeconomic and climate pathways suggest,
939 however, a variety of plausible futures. Some scenarios suggest growing numbers of exposed to very
940 warm conditions, high numbers of sensitive urban residents exposed to such conditions and low
941 resources to provide coping solutions. Other pathways suggest less dire overall conditions. The
942 element that is common across all scenarios in the ensemble is the increase in numbers exposed to very
943 warm heat waves. This will be the future for urban Africa unless the world embraces more dramatic
944 changes to climate forcing activities than presented our scenarios.

945

946 These results, as per the title, are exploratory and while they present a vivid picture, they are only a
947 partial glimpse of what can happen. There is a large number of other impacts from heat waves that are
948 unexplored in this study. We also do not evaluate the full extent of vulnerability and potential
949 adaptation options. We base our work upon a scientific framing of climate change vulnerability. To
950 generate a more holistic understanding of heat vulnerability, it critical to engage in contextual framings
951 that examine the socio-economic and political complexities of vulnerability in this region. A variety of
952 different research projections, including different framings, are required to unpack the drivers and
953 policies for remediation. This project suggests the demand for this work is urgent.

954

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956

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Supplement

Table 6: African regional average urban heat index for warmest 15-day heat wave in period (degrees C)

	Heat Index (without UHI)				Heat Index (with UHI)			
	2010	2030	2070	2100	2010	2030	2070	2100
RCP 2.6								
SSP 1	32.7 (± 2.1)	33.0 (± 2.7)	34.4 (± 2.0)	34.6 (± 2.4)	36.9 (± 2.2)	37.0 (± 2.8)	38.5 (± 2.1)	38.9 (± 2.4)
SSP 2	32.7 (± 2.1)	33.0 (± 2.6)	34.8 (± 2.0)	35.0 (± 2.4)	36.9 (± 2.2)	37.1 (± 2.7)	38.9 (± 2.1)	39.1 (± 2.5)
SSP 4	32.7 (± 2.1)	32.8 (± 2.6)	34.8 (± 2.2)	34.4 (± 2.8)	36.9 (± 2.2)	37.0 (± 2.6)	38.9 (± 2.2)	38.5 (± 2.7)
SSP 5	32.7 (± 2.1)	32.9 (± 2.8)	34.4 (± 2.1)	34.6 (± 2.3)	36.9 (± 2.2)	38.5 (± 2.8)	38.5 (± 2.0)	38.7 (± 2.3)
RCP 4.5								
SSP 1	32.7 (± 2.1)	32.9 (± 2.5)	35.6 (± 2.4)	36.8 (± 2.4)	36.9 (± 2.2)	37.1 (± 2.5)	39.7 (± 2.5)	40.9 (± 2.5)
SSP 2	32.7 (± 2.1)	33.0 (± 2.4)	36.0 (± 2.4)	37.2 (± 2.4)	36.9 (± 2.2)	37.1 (± 2.5)	40.1 (± 2.5)	41.3 (± 2.5)
SSP 3	32.7 (± 2.1)	33.6 (± 2.2)	36.0 (± 2.7)	37.9 (± 2.8)	36.9 (± 2.2)	37.7 (± 2.2)	40.1 (± 2.6)	42.0 (± 2.7)
SSP 4	32.7 (± 2.1)	32.8 (± 2.4)	36.0 (± 2.3)	36.6 (± 3.0)	36.9 (± 2.2)	36.9 (± 2.4)	40.1 (± 2.4)	40.6 (± 2.9)
SSP 5	32.7 (± 2.1)	32.8 (± 2.5)	35.6 (± 2.4)	36.8 (± 2.4)	36.9 (± 2.2)	36.9 (± 2.6)	39.7 (± 2.3)	40.9 (± 2.4)
RCP 6.0								
SSP 1	32.7 (± 2.1)	32.8 (± 2.7)	35.6 (± 2.4)	37.9 (± 2.7)	36.9 (± 2.2)	36.9 (± 2.7)	39.7 (± 2.4)	41.9 (± 2.8)
SSP 2	32.7 (± 2.1)	32.9 (± 2.6)	36.0 (± 2.5)	38.2 (± 2.8)	36.9 (± 2.2)	37.0 (± 2.6)	40.1 (± 2.4)	42.4 (± 2.8)
SSP 3	32.7 (± 2.1)	33.5 (± 2.3)	36.0 (± 3.0)	39.0 (± 3.0)	36.9 (± 2.2)	37.6 (± 2.3)	40.1 (± 2.8)	43.1 (± 2.9)
SSP 4	32.7 (± 2.1)	32.7 (± 2.5)	36.0 (± 2.5)	37.6 (± 3.2)	36.9 (± 2.2)	36.8 (± 2.6)	40.1 (± 2.4)	41.6 (± 3.1)
SSP 5	32.7 (± 2.1)	32.8 (± 2.7)	35.6 (± 2.6)	37.9 (± 2.8)	36.9 (± 2.2)	36.9 (± 2.8)	39.6 (± 2.5)	41.9 (± 2.7)
RCP 8.5								
SSP 5	32.7 (± 2.1)	33.4 (± 2.8)	37.8 (± 3.0)	42.5 (± 3.9)	36.9 (± 2.2)	37.6 (± 2.3)	41.9 (± 2.9)	46.6 (± 3.9)

Table 7

African urban population exposed to very warm (>42° C) 15-day heat waves

RCP-SSP	Estimate	Heat Index excluding UHI				Heat Index including UHI			
		Urban Population Exposed (Millions)				Urban Population Exposed (Millions)			
		2010	2030	2070	2100	2010	2030	2070	2100
RCP 2.6									
SSP 1	Mean	18	105	266	313	136	434	872	947
	Range	3-47	42-186	110-484	111-608	87-191	246-639	499-1243	542-1367
SSP 2	Mean	18	100	276	375	136	413	902	1115
	Range	3-47	39-176	112-502	147-719	87-191	243-598	519-1283	651-1608
SSP 4	Mean	18	116	417	648	136	483	1325	1859
	Range	3-47	47-209	187-724	274-1237	87-191	281-694	812-1959	1074-2613
SSP 5	Mean	18	105	260	304	136	432	848	916
	Range	3-47	42-185	107-475	107-587	87-191	244-636	461-1218	521-1313
RCP 4.5									
SSP 1	Mean	18	98	439	647	136	427	926	1029
	Range	3-47	42-206	147-694	289-1069	87-191	220-601	587-1335	649-1406
SSP 2	Mean	18	93	454	764	136	400	956	1211
	Range	3-47	38-195	151-715	331-1267	87-191	203-555	610-1363	784-1629
SSP 3	Mean	18	98	439	647	136	427	926	1029
	Range	3-47	34-180	148-706	327-1328	87-191	189-1305	570-2449	816-3047
SSP 4	Mean	18	111	698	1326	136	475	1393	1992
	Range	3-47	48-232	293-1090	481-2139	87-191	249-643	837-1868	1277-2679
SSP 5	Mean	18	98	428	630	136	425	901	997
	Range	3-47	42-205	143-674	282-1036	87-191	219-598	564-1291	630-1368
RCP 6.0									
SSP 1	Mean	18	88	466	791	136	412	909	1058
	Range	3-47	25-175	225-691	439-1239	87-191	256-567	450-1334	709-1413
SSP 2	Mean	18	83	480	930	136	392	940	1242
	Range	3-47	23-165	231-717	520-1456	87-191	250-532	466-1362	863-1630
SSP 3	Mean	18	88	466	791	136	412	909	1058
	Range	3-47	20-153	215-710	569-1572	87-191	226-495	414-1317	924-1864
SSP 4	Mean	18	100	738	1583	136	460	1378	2050
	Range	3-47	29-198	373-1093	690-2446	87-191	294-635	700-1943	1272-2845
SSP 5	Mean	18	88	456	771	136	410	884	1027
	Range	3-47	25-175	220-674	434-1212	87-191	255-564	430-1290	690-1368
RCP 8.5									
SSP 5	Mean	18	122	747	1009	136	457	959	1174
	Range	3-47	49-258	528-1040	385-1636	87-191	289-646	707-1366	850-1444

Exposed (mean) share of total African urban population (%)

RCP-SSP	Estimate	Heat Index excluding UHI				Heat Index including UHI			
		Urban Population Exposed (Millions)				Urban Population Exposed (Millions)			
		2010	2030	2070	2100	2010	2030	2070	2100
RCP 2.6									
SSP 1	% of total urban	4.3	12.9	17.0	18.4	35.9	53.6	55.8	55.9
SSP 2	% of total urban	4.3	13.2	17.7	19.4	35.9	54.4	58.2	57.9
SSP 4	% of total urban	4.3	13.1	18.0	19.7	35.9	54.4	57.1	56.7
SSP 5	% of total urban	4.3	12.9	17.0	18.5	35.9	53.6	55.5	55.7
RCP 4.5									
SSP 1	% of total urban	4.3	12.1	28.0	38.2	35.9	52.6	59.2	60.7
SSP 2	% of total urban	4.3	12.2	29.3	39.7	35.9	52.7	61.7	62.9
SSP 3	% of total urban	4.3	12.4	30.7	41.1	35.9	53.8	63.7	65.9
SSP 4	% of total urban	4.3	12.4	30.1	40.5	35.9	53.5	60.0	60.8
SSP 5	% of total urban	4.3	12.1	28.0	38.3	35.9	52.7	59.0	60.7
RCP 6.0									
SSP 1	% of total urban	4.3	10.9	29.7	46.7	35.9	50.8	58.1	62.4
SSP 2	% of total urban	4.3	11.0	30.8	48.3	35.9	51.6	60.6	64.5
SSP 3	% of total urban	4.3	11.1	32.2	49.9	35.9	51.9	62.8	67.3
SSP 4	% of total urban	4.3	11.2	31.7	48.3	35.9	51.8	59.4	62.6
SSP 5	% of total urban	4.3	10.9	29.7	46.9	35.9	50.8	57.9	62.4
RCP 8.5									
SSP 5	% of total urban	4.3	15.0	49.0	61.4	35.9	56.7	62.8	71.4

Table 8

Projected sensitive urban population exposed to very warm 15-day heat waves in Africa

		Heat Index excluding UHI				Heat Index including UHI			
		Urban Population Exposed (Millions)				Urban Population Exposed (Millions)			
		2010	2030	2070	2100	2010	2030	2070	2100
RCP 2.6									
SSP 1	Mean	2	11	50	87	27	72	202	366
	Range	0-12	2-42	8-137	19-262	12-48	38-99	113-272	224-486
SSP 2	Mean	2	11	42	62	27	76	164	263
	Range	0-12	2-45	8-116	16-190	12-48	44-104	89-223	167-345
SSP 4	Mean	2	15	59	86	27	99	232	345
	Range	0-12	3-60	15-186	28-278	12-48	53-134	134-309	230-449
SSP 5	Mean	2	11	52	85	27	72	194	356
	Range	0-12	2-42	8-135	19-253	12-48	38-99	110-266	218-473
RCP 4.5									
SSP 1	Mean	2	10	96	261	27	71	210	401
	Range	0-12	2-43	15-190	65-389	12-48	37-91	137-274	255-494
SSP 2	Mean	2	10	82	188	27	75	172	290
	Range	0-12	2-45	12-156	47-281	12-48	42-96	113-225	194-361
SSP 3	Mean	2	10	80	165	27	77	157	252
	Range	0-12	2-47	12-146	40-241	12-48	43-98	110-200	167-314
SSP 4	Mean	2	14	129	266	27	98	241	377
	Range	0-12	2-61	24-234	70-402	12-48	50-124	165-318	247-460
SSP 5	Mean	2	10	94	253	27	71	203	387
	Range	0-12	2-61	14-234	63-402	12-48	37-91	133-265	245-475
RCP 6.0									
SSP 1	Mean	2	9	102	304	27	63	206	415
	Range	0-12	2-40	21-200	123-451	12-48	39-94	137-269	249-530
SSP 2	Mean	2	10	86	220	27	67	168	303
	Range	0-12	2-42	17-166	90-323	12-48	42-97	114-220	187-380
SSP 3	Mean	2	10	85	190	27	69	154	259
	Range	0-12	2-44	16-160	80-274	12-48	44-98	118-197	168-318
SSP 4	Mean	2	14	135	299	27	89	239	388
	Range	0-12	3-57	31-252	112-435	12-48	49-128	170-307	245-500
SSP 5	Mean	2	9	100	294	27	63	199	402
	Range	0-12	2-40	21-196	125-430	12-48	38-93	132-263	244-514
RCP 8.5									
SSP 5	Mean	2	15	164	387	27	74	223	442
	Range	0-12	2-49	92-250	241-471	12-48	41-95	144-277	331-562

Projected share of sensitive population exposed to very warm 15-day heat waves
Share of total sensitive and share of exposed urban population

		Heat Index excluding UHI				Heat Index including UHI			
		Urban Population Exposed (Millions)				Urban Population Exposed (Millions)			
		2010	2030	2070	2100	2010	2030	2070	2100
RCP 2.6									
SSP 1	% of sensitive urban pop	2.4	8.6	13.6	12.9	40.5	57.9	54.1	54.2
	% of exposed urban pop	9.0	10.1	18.8	27.9	20.1	16.7	23.1	38.7
SSP 2	% of sensitive urban pop	2.4	8.7	14.7	13.3	40.5	59.1	57.1	56.4
	% of exposed urban pop	9.0	11.0	15.2	16.6	20.1	18.5	18.2	23.6
SSP 4	% of sensitive urban pop	2.4	9.4	14.5	13.8	40.5	59.7	56.8	55.7
	% of exposed urban pop	9.0	13.3	14.1	13.3	20.1	20.6	17.5	18.6
SSP 5	% of sensitive urban pop	2.4	8.6	14.3	12.9	40.5	57.9	53.3	54.0
	% of exposed urban pop	9.0	10.1	19.8	27.8	20.1	16.7	22.9	38.9
RCP 4.5									
SSP 1	% of sensitive urban pop	2.4	7.8	26.3	38.7	35.8	57.3	56.9	58.9
	% of exposed urban pop	9.0	9.7	22.0	40.4	20.1	16.7	22.7	39.0
SSP 2	% of sensitive urban pop	2.4	7.8	28.8	40.3	35.8	58.4	60.2	61.7
	% of exposed urban pop	9.0	10.7	17.9	24.6	20.1	18.8	18.0	23.9
SSP 3	% of sensitive urban pop	2.4	7.9	32.1	43.7	35.8	59.1	62.4	66.2
	% of exposed urban pop	9.0	10.3	18.3	25.5	20.1	18.0	17.0	24.5
SSP 4	% of sensitive urban pop	2.4	8.5	31.6	42.6	35.8	59.0	59.1	59.7
	% of exposed urban pop	9.0	12.6	18.4	20.0	20.1	20.7	17.3	18.9
SSP 5	% of sensitive urban pop	2.4	7.7	26.3	38.7	35.8	57.3	56.3	58.6
	% of exposed urban pop	9.0	9.7	22.0	40.2	20.1	16.8	22.5	38.8
RCP 6.0									
SSP 1	% of sensitive urban pop	2.4	7.7	27.9	45.1	35.7	50.8	55.5	60.9
	% of exposed urban pop	9.0	10.7	22.0	38.4	20.1	15.2	22.6	39.3
SSP 2	% of sensitive urban pop	2.4	7.7	30.4	47.3	35.7	52.2	58.6	64.4
	% of exposed urban pop	9.0	11.8	18.0	23.7	20.1	17.0	17.8	24.4
SSP 3	% of sensitive urban pop	2.4	7.8	34.1	50.5	35.7	53.4	61.1	68.1
	% of exposed urban pop	9.0	11.3	18.3	24.1	20.1	16.7	17.0	24.5
SSP 4	% of sensitive urban pop	2.4	8.4	33.2	47.9	35.7	54.0	58.3	61.8
	% of exposed urban pop	9.0	13.8	18.3	18.9	20.1	19.3	17.3	18.9
SSP 5	% of sensitive urban pop	2.4	7.7	27.9	45.1	35.7	50.8	54.9	60.8
	% of exposed urban pop	9.0	10.7	22.0	38.1	20.1	15.3	22.5	39.2
RCP 8.5									
SSP 5	% of sensitive urban pop	2.4	11.9	44.9	58.8	37.9	59.3	61.8	67.8
	% of exposed urban pop	9.0	12.0	21.9	38.4	20.1	16.3	23.3	37.6

Table 9

Projected low-income urban population exposed to very warm 15- day heat waves in Africa

		Heat Index excluding UHI				Heat Index including UHI			
		Urban Population Exposed (Millions)				Urban Population Exposed (Millions)			
		2010	2030	2070	2100	2010	2030	2070	2100
RCP 2.6									
SSP 1	Mean	7.9	40.7	0.0	0.0	135.6	229.9	0.0	0.0
	Range	0-59	8-131	0-0	0-0	61-224	103-326	0.0	0.0
SSP 2	Mean	7.9	36.4	60.7	0.0	135.6	215.2	113.5	0.0
	Range	0-59	7-121	31-121	0-0	61-224	105-308	71-142	0.0
SSP 4	Mean	7.9	78	180	225	135.6	467.9	554.6	429.6
	Range	0-59	16-308	68-457	138-356	61-224	265-603	337-702	315-544
SSP 5	Mean	7.9	40.3	0.0	0.0	135.6	226.4	20.5	20.7
	Range	0-59	8-129	0-0	0-0	61-224	100-322	13-29	13-30
RCP 4.5									
SSP 1	Mean	7.9	36.0	0.0	0.0	135.6	226.5	0.0	0.0
	Range	0-59	5-133	0-0	0.0	61-224	110-303	0.0	0.0
SSP 2	Mean	7.9	31.9	77.2	0.0	137.8	211.9	120.0	0.0
	Range	0-59	5-122	32-131	0.0	61-224	112-285	79-139	0.0
SSP 3	Mean	7.9	50.9	202.3	354.7	137.8	353.8	457.7	518.7
	Range	0-59	11-224	51-472	180-664	61-224	220-443	306-618	389-634
SSP 4	Mean	7.9	70.1	282.7	305.3	137.8	461.6	549.7	464.1
	Range	0-59	12-313	95-616	219-504	61-224	256-571	400-729	326-584
SSP 5	Mean	7.9	35.7	0.0	0.0	137.8	223.0	20.8	24.2
	Range	0-59	5-313	0-616	0.0	61-224	109-299	13-29	13-35
RCP 6.0									
SSP 1	Mean	7.9	34.8	0.0	0.0	135.6	218.0	0.0	0.0
	Range	0-59	6-121	0.0	0.0	61-224	101-305	0.0	0.0
SSP 2	Mean	7.9	31.0	82.8	0.0	135.6	204.3	116.8	0.0
	Range	0-59	6-111	31-105	0.0	61-224	104-287	91-145	0.0
SSP 3	Mean	7.9	50.6	214.8	448.4	135.6	347.8	463.6	544.8
	Range	0-59	9-239	38-501	103-597	61-224	221-440	354-606	352-664
SSP 4	Mean	7.9	70	294	389	135.6	451.7	559.7	489.6
	Range	0-59	14-294	121-562	226-576	61-224	251-592	391-684	343-705
SSP 5	Mean	7.9	34.4	0.0	0.0	135.6	214.4	21.0	0.0
	Range	0-59	6-118	0-1	0.0	61-224	99-301	13-33	0.0
RCP 8.5									
SSP 5	Mean	7.9	53.3	20.5	0.0	135.6	238.4	24.0	0.0
	Range	0-59	8-137	0-29	0.0	61-224	113-299	13-34	0.0

Projected share of low-income population exposed to very warm 15-day heat waves

Share of total low-income and share of exposed urban population

		Heat Index excluding UHI				Heat Index including UHI			
		Urban Population Exposed (Millions)				Urban Population Exposed (Millions)			
		2010	2030	2070	2100	2010	2030	2070	2100
RCP 2.6									
SSP 1	% of low-income pop	2.9	9.7	0.0	0.0	44.6	53.4	0.0	0.0
	% of exposed urban pop	44.3	38.8	0.0	0.0	99.4	53.0	0.0	0.0
SSP 2	% of low-income pop	2.9	9.3	21.6	0.0	44.6	53.5	39.9	0.0
	% of exposed urban pop	44.3	36.4	22.0	0.0	99.4	52.1	12.6	0.0
SSP 4	% of low-income pop	2.9	10.8	16.0	18.1	44.6	63.3	48.6	34.6
	% of exposed urban pop	44.3	67.3	43.1	34.7	99.4	96.9	41.8	23.1
SSP 5	% of low-income pop	2.9	9.8	0.0	0.0	44.6	53.2	51.2	0.0
	% of exposed urban pop	44.3	38.6	0.0	0.0	99.4	52.4	2.4	0.0
RCP 4.5									
SSP 1	% of low-income pop	2.9	8.6	0.0	1.0	44.6	52.7	0.0	0.0
	% of exposed urban pop	44.3	36.7	0.0	0.0	99.4	53.1	0.0	0.0
SSP 2	% of low-income pop	2.9	8.1	27.0	0.9	44.6	52.8	41.8	0.0
	% of exposed urban pop	44.2	34.3	17.0	0.0	99.4	52.9	12.5	0.0
SSP 3	% of low-income pop	2.9	9.4	24.6	35.3	44.6	64.1	54.6	51.9
	% of exposed urban pop	44.2	51.8	46.1	54.9	99.4	82.9	49.5	50.4
SSP 4	% of low-income pop	2.9	9.6	25.0	24.4	44.6	62.5	48.9	37.1
	% of exposed urban pop	44.3	63.3	40.5	23.0	99.4	97.2	39.5	23.3
SSP 5	% of low-income pop	2.9	8.6	0.0	1.0	44.6	52.5	52.1	0.0
	% of exposed urban pop	44.2	36.5	0.0	0.0	99.4	52.5	2.3	0.0
RCP 6.0									
SSP 1	% of low-income pop	2.9	8.3	0.0	47.6	44.6	51.7	0.0	0.0
	% of exposed urban pop	44.3	39.3	0.0	0.0	99.4	52.9	0.0	0.0
SSP 2	% of low-income pop	2.9	7.9	28.7	43.8	44.6	51.8	0.0	0.0
	% of exposed urban pop	44.3	37.1	17.3	0.0	99.4	52.1	0.0	0.0
SSP 3	% of low-income pop	2.9	9.3	26.1	44.7	44.6	63.8	55.1	54.0
	% of exposed urban pop	44.3	57.2	46.1	56.7	99.4	84.5	51.0	51.5
SSP 4	% of low-income pop	2.9	9.6	25.9	31.0	44.6	61.9	49.3	39.1
	% of exposed urban pop	44.3	69.9	39.8	24.6	99.4	98.3	40.6	23.9
SSP 5	% of low-income pop	2.9	8.3	0.0	47.3	44.6	51.5	52.7	0.0
	% of exposed urban pop	44.3	39.1	0.0	0.0	99.4	52.3	2.4	0.0
RCP 8.5									
SSP 5	% of low-income pop	2.9	12.7	51.3	57.9	44.6	55.1	56.1	0.0
	% of exposed urban pop	44.3	43.8	2.7	0.0	99.4	52.2	2.5	0.0