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ORIGINAL PAPER

Cooling access and energy requirements for adaptation to heat stress in megacities

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Abstract

As urban areas are increasingly exposed to high temperatures, lack of access to residential thermal comfort is a challenge with dramatic consequences for human health and well-being. Air-conditioning (AC) can provide relief against heat stress, but a massive AC uptake could entail stark energy demand growth and mitigation challenges. Slums pose additional risks due to poor building quality, failing to provide adequate shelter from severe climatic conditions. Thus, it is unclear how many people in the Global South will still lack access to basic cooling under different future climate and socioeconomic developments. We assess the impact of different shared socioeconomic pathways (SSPs) and climate futures on the extent of population lacking access to cooling where needed—the cooling gap—and energy requirements for basic comfort for a set of 22 megacities in the Global South. We find that different SSPs greatly influence the extent of future cooling gaps, generally larger in SSP3 due low income levels, and consequent limited access to AC and durable housing. Megacities in Sub-Saharan Africa and South Asia have the largest share of population affected, ranging from 33% (SSP1) to 86% (SSP3) by mid-century. Energy requirements to provide basic cooling for all are higher in SSP1 for most megacities, driven by urbanization, and can increase by 7 to 23% moving from 2.0 to 3.0 °C temperature rise levels. Strategies combining improved building design and efficient cooling systems can improve adaptation to heat stress in cities while reducing energy and emission requirements to reach climate and sustainability goals.

Keywords Cooling needs · Decent housing · Adaptation · Sustainable cities · Energy poverty · Developing countries

1 Introduction

Heat stress is an increasingly important issue for the health and well-being of populations exposed to high temperatures and humidity (World Health Organisation 2015). Deaths from heat waves are expected to rise up to 250,000 yearly by 2050 (World Health

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Organization 2014), depending on future climate change, while millions of people will be threatened by health and well-being problems. With 68% of the world population projected to live in urban areas by 2050 (UN-Habitat 2020), cities are expected to become the epicenter of future cooling energy demand (Bai et al. 2018; Khosla et al. 2021b). Urban heat island effect might further exacerbate heat risks in urban areas, particularly during heat waves (Heaviside et al. 2017). Investigating future heat stress scenarios in urban settlements is critical to support effective adaptation strategies. The wide range of climatic and social conditions found across cities around the world make this a challenging policy issue.

Lack of access to basic residential cooling where needed—the cooling gap—is increasingly considered a dimension of energy poverty, though still largely overlooked (Bhatia and Angelou 2015). With only 8% of the people in the hottest world regions possessing air-conditioning (AC) (IEA 2018), space cooling systems are often considered luxury. Previous studies showed that AC is needed under severe climatic conditions to ensure basic thermal comfort conditions and allow recovery between hot days (Dongmei et al. 2013). With rising incomes and progressive affordability, the penetration of AC units is expected to grow exponentially in developing countries (Akpinar-Ferrand and Singh 2010; Waite et al. 2017). Increased access to AC could be seen as a way to reduce the cooling gaps. However, it is not clear to which extent the AC adoption would contribute to meet basic comfort needs, as many people might still be left without adequate cooling (Andrijevic et al. 2021). Growing AC usage entails stark increase in peak loads and in electricity consumption and emissions, potentially worsened by climate change (Labriet et al. 2015; Santamouris 2016; Gi et al. 2018; Zhang et al. 2022), posing additional mitigation challenges. The uptake of cheap and inefficient AC units, use of refrigerants with high global warming potentials, and poor disposal practices can further exacerbate the problem (Sustainable Energy for All 2019). The waste heat from AC units drives even more ambient temperature increase, especially in cities, and demands for more cooling in a vicious circle (Salamanca et al. 2014). Access to electricity, though higher in urban than in rural contexts, still limits the uptake of even basic cooling devices, such as fans, particularly in instances when the reliability of electricity supply is poor (World Bank 2018). Finally, with almost one billion people still living in slums (UN-Habitat 2016), low-quality urban building stocks provide insufficient thermal comfort and require more energy to cool. Thus, there are important relationships between access to residential cooling and multiple sustainable development goals (SDGs) that are key to design cross-cut interventions (Khosla et al. 2021b) that are particularly relevant for sustainable cities and communities.

Recent studies have investigated scenarios of global AC adoption and cooling energy demand at a global (Santamouris 2016; Levesque et al. 2018; Biardeau et al. 2020; Mastrucci et al. 2021) and regional level (Akpinar-Ferrand and Singh 2010; Davis and Gertler 2015; Bezerra et al. 2021). However, estimation of population exposed to heat stress due to lack of access to basic cooling and energy requirements to provide basic cooling comfort to all have been rarely investigated (Davis et al. 2021; Pavanello et al. 2021). The amount of population in the Global South currently lacking access to basic cooling has been estimated at 3.4 billion (Sustainable Energy for All 2019) and between 1.8 and 4.1 billion (Mastrucci et al. 2019). Future socio-economic and climatic conditions will strongly influence both heat-stress adaptation and cooling-related mitigation challenges. A recent study (Andrijevic et al. 2021) estimated the extent of the global cooling gap in 2050 between 2 and 5 billion people across different socioeconomic development scenarios. Heat stress in urban areas has been analyzed by empirical and simulation studies, mostly for specific cities and regions (Fallmann et al. 2013; Lemonsu et al. 2015; Kumar et al. 2022). However, cooling gap scenarios across urban areas in developing countries are still largely unexplored.

As unprecedented city growth is expected in the Global South, megacities could increasingly become heat stress hotspots (Matthews et al. 2017), exacerbated by urban heat island effect. Thus, investigating the effect of different climate and societal developments on the extent of future urban populations affected by the cooling gap and energy requirements to provide cooling comfort for all is critical to effectively plan for strategies encompassing adaptation to heat stress and climate change mitigation.

We assess the impact of different societal and climate futures on cooling energy poverty gaps in a set of 22 megacities in the Global South, with cumulative population of 500 to over 600 million in 2050. We use a bottom-up framework combining modeling of cooling energy demand, AC access, and slum developments to project the city population lacking access to basic cooling and the energy required to provide basic indoor thermal comfort to all. We develop a set of nine mid-century scenarios combining three socio-economic pathways and three climate futures. We focus on the Shared Socioeconomic Pathways SSP1-3 (O’Neill et al. 2017) to represent a broad range of societal developments: SSP1 has low challenges to mitigation and adaptation, high urbanization, and high GDP growth; SSP3 has high challenges to mitigation and adaptation, low urbanization, and low GDP growth; SSP2 is in between the previous two and represents a continuation of current trends. We combine SSP1-3 with three temperature rise levels (1.5 °C, 2.0 °C, and 3.0 °C), representing a comprehensive set of climate futures and compare results against the base year 2010, assuming current climate conditions.

2 Methods

The methods build upon the bottom-up global building sectoral model MESSAGEix-Buildings (Mastrucci et al. 2021) and use the following modules: a space cooling energy demand model (CHILLED); dedicated AC adoption and slum development models; and a cooling gap calculator.

We consider a set of megacities in the Global South with at least 15 million population by 2050 in the central scenario SSP2 (Hoornweg and Pope 2017). Two cities (Mexico City and Nairobi) are excluded from the analysis due to low cooling requirements, resulting in a final set of 22 megacities (Table 1). For the analysis of results, we group cities by the six Global South regions used in the global energy-economy integrated assessment model MESSAGEix (Huppmann et al. 2019a): sub-Saharan Africa (AFR), South Asia (SAS), Middle East and North Africa (MEA), Other Pacific Asia (PAS), Centrally planned Asia and China (CPA), and Latin America and the Caribbean (LAM).

2.1 Cooling needs

We estimate the cooling energy needs using the CHILLED model (Mastrucci et al. 2019, 2021), based on spatially explicit variable degree days (VDD). Degree days (DD) is a widely used method to estimate the heating and cooling energy demand of buildings (Al-Homoud 2001). DD represents the sum of daily positive differences between the outdoor temperature and a reference temperature, called balance temperature, over a given time period, usually a year. In the standard DD method, the balance temperature is commonly assumed as fixed to a given, often arbitrary threshold. VDD methods advance standard DD by analytically calculating the balance temperature:

Table 1 Set of megacities included in this study and population projections

City	Country	Region[1]	Climate[2]	Population[3] (million)			
				2010	2050 SSP1	2050 SSP2	2050 SSP3
Kinshasa	Congo DRC	AFR	Tropical	9.1	34.4	33.3	26.3
Lagos	Nigeria	AFR	Tropical	10.6	34.3	36.3	37.5
Luanda	Angola	AFR	Arid	4.8	17.0	19.0	22.4
Dar es Salaam	Tanzania	AFR	Tropical	3.3	19.0	19.1	16.5
Karachi	Pakistan	SAS	Arid	13.1	39.3	37.0	32.0
Dhaka	Bangladesh	SAS	Tropical	14.8	43.9	37.5	31.8
Lahore	Pakistan	SAS	Arid	7.1	21.4	20.1	17.4
Hyderabad	India	SAS	Tropical	6.8	18.3	16.0	12.6
Bangalore	India	SAS	Tropical	7.2	19.6	17.1	13.4
Chennai	India	SAS	Tropical	7.6	20.4	17.9	14.1
Kolkata	India	SAS	Tropical	15.6	42.1	36.8	29.0
Delhi	India	SAS	Temperate	17.0	46.0	40.2	31.6
Mumbai	India	SAS	Tropical	20.1	54.3	47.4	37.3
Baghdad	Iraq	MEA	Arid	5.9	14.1	15.3	15.4
Cairo	Egypt	MEA	Arid	12.5	28.9	27.9	23.1
Manila	Philippines	PAS	Tropical	11.7	25.8	25.3	25.4
Jakarta	Indonesia	PAS	Tropical	9.7	19.2	18.0	15.6
Shanghai	China	CPA	Temperate	15.8	24.1	22.0	19.7
Beijing	China	CPA	Cold	19.6	29.9	27.3	24.4
Buenos Aires	Argentina	LAM	Temperate	13.1	16.4	18.1	20.9
Rio De Janeiro	Brazil	LAM	Tropical	12.2	14.5	15.7	17.9
Sao Paulo	Brazil	LAM	Temperate	19.6	23.3	25.3	28.7

[1] Regions in the global energy-economy integrated assessment model MESSAGEix. Further details available at the webpage https://iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE-model-regions.en.html

[2] Main climate group according to the Köppen–Geiger climate classification (Peel et al. 2007).

[3] Population data and projections based on existing literature (Hoornweg and Pope 2017).

$$T_{\mathrm{bal,m}} = T_{\mathrm{sp}} - \frac{g_{\mathrm{sol,m}} + g_{\mathrm{int}}}{H_{\mathrm{tr}} + H_{\mathrm{ve}}} \tag{1}$$

where $T_{\mathrm{bal,m}}$ (°C) is the balance temperature for the month m, T_{sp} (°C) is the desired indoor set point temperature, $g_{\mathrm{sol,m}}$ (W) is the heat flow from solar heat sources for the month m, g_{int} (W) is the heat flow from internal heat sources, H_{tr} (W/K) is the heat transfer coefficient by transmission, and H_{ve} (W/K) is the heat transfer coefficient by ventilation. The cooling VDD for the month m ($\mathrm{VDD}_{\mathrm{c,m}}$) is calculated as follows:

$$\mathrm{VDD}_{\mathrm{c,m}} = \sum_{d=1}^{\mathrm{Dm}} \left(\overline{T}_{\mathrm{out},d} - T_{\mathrm{bal,m}}\right)^{+} \tag{2}$$

where $T_{\mathrm{out,d}}$ is the average daily outdoor temperature, and D_{m} is the number of days in the month m. Only positive values are accounted in the sum. In this study, we focus on AC as one of the most common cooling technologies to provide indoor thermal comfort. The final energy requirements ($\mathrm{E_C}$) for AC is calculated with the following equations:

$$E_{\mathrm{c}} = P \bullet \frac{A_{\mathrm{f}}}{P} \bullet \sum_{m=1}^{12} \frac{\left(H_{\mathrm{tr}} + H_{\mathrm{ve}}\right) \bullet f_{\mathrm{c}} \bullet \mathrm{VDD}_{\mathrm{c,m}}}{\eta_{\mathrm{c}}} \tag{3}$$

where P is the population, A_{f}/P is the per-capita floorspace, f_{c} is the daily operation time fraction for the mth month, and η_{c} is the efficiency of the cooling system.

2.2 Access to air conditioning and slum development

We adopt a widely used AC penetration model from literature (McNeil and Letschert 2008; Isaac and van Vuuren 2009). Based on empirically estimated relationships, this model estimates AC ownership as a function of income, with climate determining the saturation level. The saturation level $\mathrm{AC}_{\mathrm{sat}}$ is given as a function of cooling DD (base 18.3 °C):

$$\mathrm{AC}_{\mathrm{Sat}} = 1 - 0.949e^{-0.00187\mathrm{DD}} \tag{4}$$

The AC adoption rate $\mathrm{AC}_{\mathrm{Adopt}}$ is calculated based on per-capita GDP in purchasing power parity (PPP) dollars:

$$\mathrm{AC}_{\mathrm{Adopt}} = \frac{1}{\left(1 + e^{4.152}e^{-0.237\frac{\mathrm{GDP}}{1000}}\right)} \tag{5}$$

We run the model for all selected megacities by using location-specific cooling DD (Mastrucci et al. 2019) and per-capita GDP projections from a spatially gridded dataset (Murakami and Yamagata 2019) consistent with the SSP framework (Dellink et al. 2017; Riahi et al. 2017). AC access results have been compared against measured data in previous work, showing discrepancies for some regions (Mastrucci et al. 2019, 2021). We correct the model results for the base year based on previous studies and available data, and report detailed description and results in the Supplementary Information, Section 2.1. While this AC penetration model is widely used at national scale, its application to individual cities might come with some shortcomings. Prior studies assessed urbanization as one of the main drivers of AC uptake (Andrijevic et al. 2021; Pavanello et al. 2021), and AC adoption curves might be steeper in urban areas compared to national averages, entailing potential slight underestimation in this study.

Slum development is driven by complex dynamics and depends on multiple factors (Roy et al. 2014). We apply an existing model (Mastrucci et al. 2021) to predict the share of urban population living in slums $\mathrm{Slum}_{\mathrm{share}}$ based on per-capita GDP:

$$\mathrm{Slum}_{\mathrm{share}} = 1.986 - 0.183\log(\mathrm{GDP}) \tag{6}$$

The model was fit using national slum data from UN-HABITAT, available from World Bank (World Bank 2020) and national per-capita GDP (Dellink et al. 2017). Slums are generally not suited for AC due to poor thermal characteristics of building envelopes. Therefore, we associate the projected AC adoption with the rest of the housing stock (formal housing). We examine uncertainty in AC adoption and slum development models and analyze the sensitivity of the results to the changes in model drivers in Supplementary Information, Sections 2.1 and 2.2.

2.3 Cooling gap and energy requirements

The space cooling assessment is based on the decent living energy (DLE) framework (Rao and Min 2017; Rao et al. 2019; Kikstra et al. 2021), aiming at estimating minimum energy requirements for decent living. Consistent with the DLE framework, we assume the following minimum requirements for decent housing (Mastrucci and Rao 2017; Kikstra et al. 2021): minimum housing space based on a reference floorspace of 10 m^2 per capita and minimum 30m^2 per household; durable housing materials; and AC availability where needed to provide shelter from high temperatures, used with a conservative set point of 26 °C and 4 h of daily operation to ensure basic thermal comfort.

We calculate cooling gaps as the difference between the total population requiring cooling for basic thermal comfort and the population with access to cooling. The need for cooling is assumed where $VDD > 0$ for more than 5 days per year (Mastrucci et al. 2019). We consider population living in slums as part of the cooling gap, assuming building construction quality not adequate to maintain comfortable indoor thermal conditions (Nutkiewicz et al. 2022). Minimum energy requirements to provide basic cooling for all are calculated in final energy terms assuming universal access to cooling, where needed, under the DLE assumptions described above. We calculate basic cooling energy requirements for all megacities in 2010 (base year) and in 2050 under different socio-economic and climate scenarios, and upscale results based on projected city population.

2.4 Input data

The input data consists of three main types: climatic, demographic and socio-economic, and building-related. All data generated during this study are included in this article and its Supplementary Information. The relevant sources for the external datasets analyzed in this study are reported in this section.

For climate, we use the dataset EWEMBI (EartH2Observe, WFDEI and ERA-Interim data Merged and Bias-corrected for ISIMIP), consisting of observed historical weather gridded data on a 0.5° grid resolution and daily time step (Lange 2016). To capture the full variability of recent climate, we use a series of daily data for 30 years (1980–2009). For simulation of future climatic conditions, we use daily data from the HadGEM2-ES GCM, downscaled and bias-corrected to 0.5° grid (Hempel et al. 2013), and select a 30-year transient timeslice, centered on the year at which the GCM crosses the temperature thresholds 1.5 °C (2006–2035), 2.0 °C (2023–52), and 3.0 °C (2053–82). The 30-year timeslice accounts for inter-annual and decadal variability of a gradually warming climate. We note that while crossing global mean temperature of 3 °C by 2050 is considered increasingly unlikely even under Current Policies scenarios, if climate response and feedbacks are at the upper end of uncertainties, this is still possible under higher emissions scenarios; e.g., see SR15 Scenarios Database (Huppmann et al. 2019b), and AR6 Scenarios Database (Byers et al. 2022). Climatic variables, including temperatures and solar irradiation, are extracted for each of the megacities at their city center coordinates (see Supplementary Information, Section 1.2).

Population data for 2010 and predictions for 2050 under SSP1-3 for the selected megacities are from literature (Hoornweg and Pope 2017). We project urban per-capita GDP at the city locations based on a downscaled spatially gridded dataset in literature (Murakami and Yamagata 2019).

We assume building characteristics consistent with existing literature and use an urban archetype representing prevailing construction practices in the Global South (Mastrucci et al. 2019). The archetype is a four-story building with concrete framing and roofing, brick masonry, and single-glazing windows (see Supplementary Information, Section 1.4). The main building characteristics are defined based on a literature review on housing with durable materials in developing countries, part of previous work (Mastrucci et al. 2019), to which we refer for more detailed information. Equipment for space cooling includes AC systems with 2.9 energy efficiency ratio (EER), corresponding to the current average in developing countries (IEA 2018).

3 Results

In the following sections, we analyze the population affected by the cooling gaps and energy requirements to provide basic cooling for all under different socio-economic and climate scenarios. Detailed results are reported in the Supplementary Information, Section 2.

3.1 Cooling gap projections

Different socio-economic developments substantially influence future levels of AC access and the extent of cooling gaps across urban areas in the Global South. While affluence levels increase in most of the studied regions, significant differences in per-capita GDP exist across countries and across SSP1-3 in 2050 (Fig. 1(a)). Urban GDP is generally higher in SSP1 and lower in SSP3, but AFR and parts of SAS and MEA experience limited GDP growth in all scenarios, while CPA and LAM have relatively high GDP. Climatic conditions are severe in many of the megacities in AFR, SAS, and PAS, mostly located in tropical and arid climatic zones with high DD, and milder in cities of CPA and LAM. In most locations, DD significantly differ between current climatic conditions and a 2.0 °C climate.

As a consequence of rising income and temperature levels, AC access improves in all selected cities while the share of slum population decreases by 2050 (see Supplementary information, Sections 2.1 and 2.2). However, the extent of population without access to AC or living in slums, and therefore potentially affected by the cooling gap, largely differs across locations and scenarios (Fig. 1(b)). Megacities in AFR and SAS have the largest share of population affected, ranging from 34% (SSP1) to 86% (SSP3) by mid-century. Absolute cooling gaps in 2050 are the largest in Kinshasa (25.5 to 31.9 million people), Lagos (23.0 to 35.1 million people), Karachi (22.2 to 30.5 million people), and Dhaka (13.6 to 29.5 million people).

Changes in the cooling gap between the base year and mid-century conditions (Fig. 1(c)) strongly depend on shifts in population and income levels across different SSPs. Three major clusters of cities can be identified based on the evolution of the cooling gap. The first cluster is characterized by cities with severe climate conditions, high population growth, and persistence of relatively low income levels in all considered SSPs, resulting in low level of AC adoption, large share of slums, and substantial increase in population affected by the cooling gaps by 2050. The first cluster includes cities in AFR (Luanda, Dar es Salaam, Lagos and Kinshasa), SAS except India (Lahore, Karachi and Dhaka), MEA (Baghdad), and PAS (Manila). In the second cluster, composed of all Indian cities in SAS, the evolution of the cooling gaps strongly depends on different societal futures, with diverging trajectories. In SSP1, higher population increase driven by urbanization is compensated by stark GDP level increase, resulting in massive AC adoption and consequent shrinking of the population affected by the gap, mostly

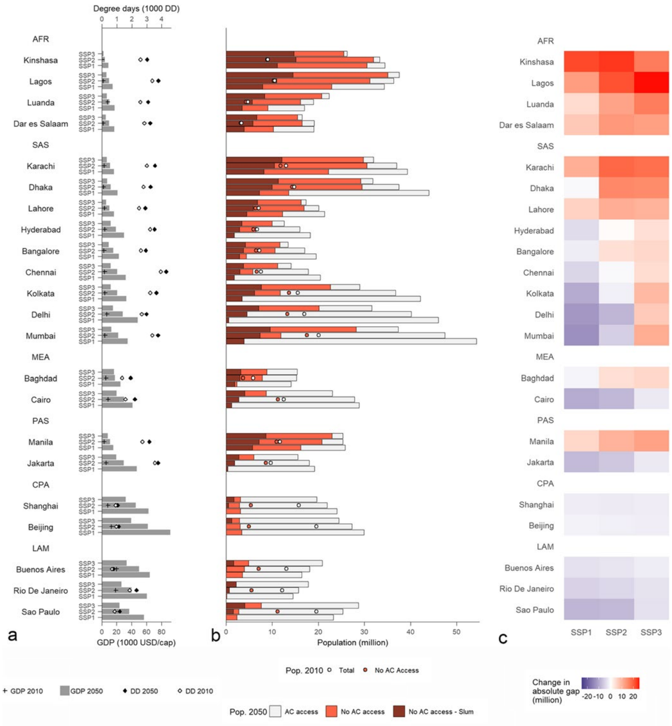

Fig. 1 (**a**) Drivers of air-conditioning (AC) access for a selection of megacities in the Global South: cooling degree days (base 18 °C) and GDP per-capita in the base year and in 2050 under different shared socio-economics pathways (SSP). (**b**) Population without access to air-conditioning where needed and total population in the base year and in 2050 under different SSP (2.0 °C climate). (**c**) Change in population without access to AC where needed between the base year and 2050 by SSP (2.0 °C climate). Results are grouped by the six Global South regions (Table 1).

composed of remaining slum dwellers. Conversely, in SSP3, lower population is counterbalanced by lower income levels and AC adoption, determining a progression of the cooling gap. SSP2 is in between, with cooling gaps staying substantially unchanged compared to today due to increased AC access compensating for population growth. In the third cluster, composed of the remaining cities, cooling gaps significantly decrease compared to the base year, driven by income rising, AC adoption, and slums eradication. For most locations in the third cluster, including MEA (Cairo), PAS (Jakarta), and LAM (Buenos Aires, Rio de Janeiro, and Sao Paulo), cooling gap reductions are substantial for SSP1 and lower for SSP3. In CPA (Shanghai and Beijing), cooling gaps shrink in all scenarios under major GDP growth and milder climate. The effect of temperature increase on AC adoption and, consequently, on the extent of population affected by the gap is generally low in comparison with the effect of socio-economic development (Supplementary Information, Section 2.1).

3.2 Cooling energy requirements

Minimum cooling energy intensities for basic space cooling per unit of floor surface area significantly vary depending on climatic conditions (Fig. 2a). Cities located in tropical

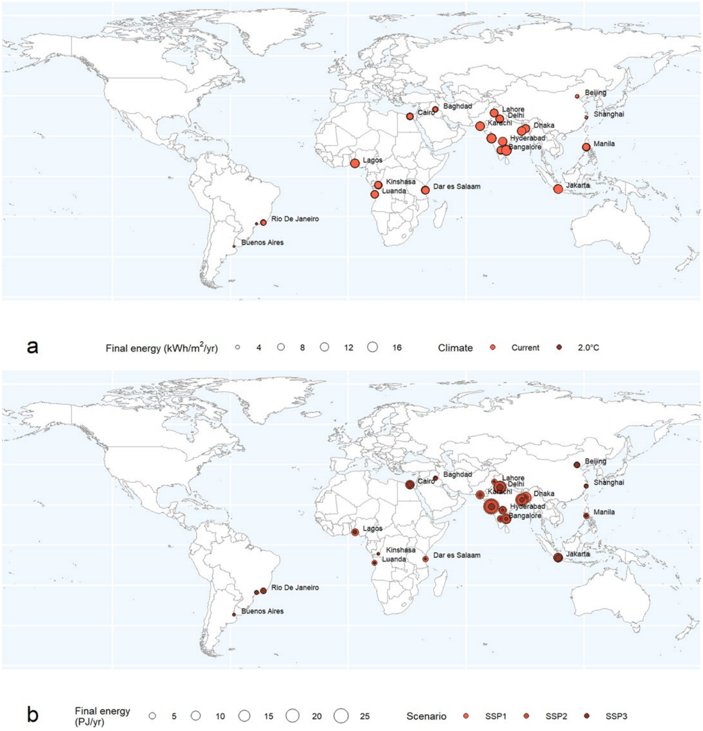

Fig. 2 **a** Final energy intensity per unit of floor surface area for basic space cooling using air-conditioning under different climates (current and 2.0 °C climate) for 22 megacities in the Global South. **b** Total final energy requirements for basic space cooling under projected air-conditioning access in 2050 for different shared socioeconomic pathways (SSP).

climatic zones have higher cooling requirements compared to other climates, ranging from 4.9 to 14.9 kWh/m^2/year under current climate, and 6.7 to 16.7 kWh/m^2/year under 2.0 °C climate. Cooling energy intensities vary across different climate futures, increasing by 7 to 23% when moving from 2.0 to 3.0 °C temperature rise levels.

Total minimum energy requirements for basic comfort under projected AC access (Fig. 2b) greatly depend on different socio-economic developments in addition to location- and climate-specific energy intensities. Concurrent high urbanization and GDP levels driving AC adoption generally results in higher energy levels in SSP1 compared to SSP2 and SSP3. Energy hotspots include cities in SAS and PAS with high population and increasingly high levels of AC access, especially in SSP1. Other cities with severe climate, especially in AFR, despite having high energy intensity requirements, experience lower total energy requirements due to lower GDP growth and limited access to AC. Cities in CPA and LAM, despite high level of AC access, have lower total energy requirements due to milder climates.

Final energy requirements to provide basic cooling for all are considerably higher as they account for people affected by the cooling gaps in addition to people with access to AC (Fig. 3a). These represent minimum energy requirements for adaptation to heat stress assuming that the cooling gap is closed by providing universal access to AC where needed. Most of the megacities experience large increases in total energy required for universal access to cooling in all 2050 scenarios, compared to the baseline, as a result of combined

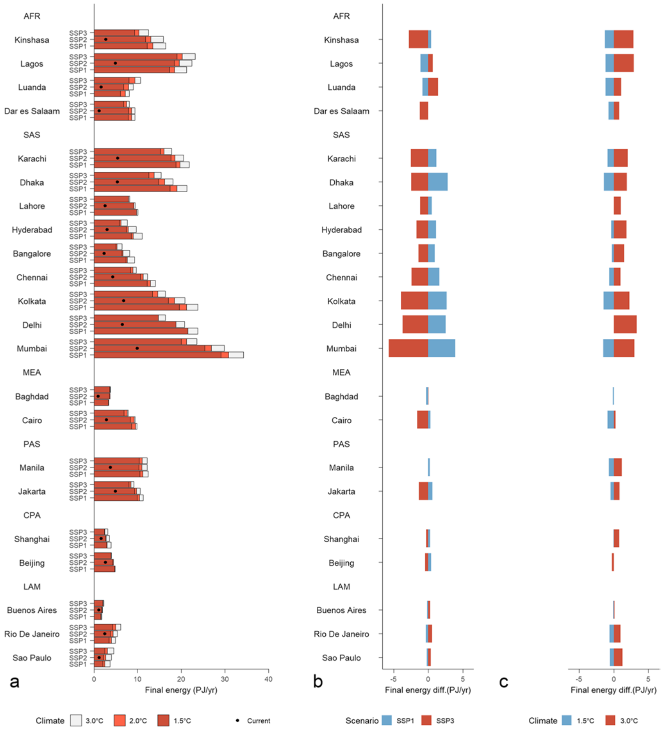

Fig. 3 Total final energy requirements under universal access to basic space cooling for a selection of megacities in the Global South. **a** Total final energy requirements in the base year and in 2050 under different shared socio-economics pathways (SSPs) and climate futures. **b** Difference between different SSPs (SSP1 and SSP3) and the reference scenario (SSP2) under fixed climatic conditions (2.0 °C) in 2050. **c** Difference between different climate futures (1.5 °C and 3.0 °C) and the reference scenario (2.0 °C) under fixed socio-economics (SSP2) in 2050. Results are grouped by the six Global South regions described in Sect. 3

population growth and temperature rise (Fig. 1). Cities with the highest cooling requirements in 2050 are mostly located in SAS and AFR, and include Mumbai (21.1 to 30.8 PJ/year), Lagos (18.4 to 20.2 PJ/year), Kolkata (14.6 to 21.2 PJ/year), and Karachi (16.0 to 19.7 PJ/year). Differences in mid-century energy requirements across SSPs (Fig. 3b) and climate futures (Fig. 3b) compared to a reference SSP2-2.0 °C scenario significantly vary across regions. Cities in AFR and SAS have the largest range of variation both across societal and climate futures. Energy requirements are generally higher in SSP1 compared to SSP2, due to larger urban population, and lower in SSP3 (with the exception of Lagos and Luanda). For most cities, the effect of temperature rise is proportionally higher when moving from 2.0 to 3.0 °C, than from 1.5 to 2.0 °C in 2050.

4 Discussion and conclusions

In this study, we presented scenarios of cooling gaps for a set of megacities in the Global South under different societal and climate futures. The total number of people affected by the cooling gap in this set of megacities ranges from 215 million (SSP1) to 364 (SSP3) in

2050. The total minimum energy requirements to provide basic space cooling for all with current technologies (AC) ranges between 201 (SSP3) and 247 PJ/year (SSP1) in 2050 under 2.0 °C temperature rise level, with higher values in SSP1 due to larger urban population. These values correspond to about 60 to 70% of the residential electricity used for cooling in China in 2017 (IEA 2019a).

Based on this analysis, two city hotspot archetypes can be identified:

i) Heat stress hotspots: cities where population growth is faster than income growth, AC access, and slum eradication, with consequent increase in the cooling gap.
ii) Cooling energy hotspots: cities where income is growing rapidly and cooling gaps are falling, but the stark uptake of AC is pushing rapid energy demand growth.

The set of cities composing the two hotspot archetype groups substantially differ across SSPs. Indian megacities are expected to represent cooling energy hotspots in SSP1, due to concurrent high population growth and AC uptake, and heat stress hotspots in SSP3 under low-income conditions. Conversely, other cities in SAS and in AFR belong to the heat stress hotspot group in all scenarios, as a result of relatively low income levels, low AC adoption, and high share of slums. While different climate futures have limited influence on the size of future cooling gaps, they substantially affect cooling energy requirements for basic thermal comfort. Cities in AFR and SAS have the largest total cooling requirements for universal access to cooling, and the largest range of variation expected under different societal and climate futures. The results of this study contribute in advancing the understanding on the cooling gap and energy requirements for universal access to basic cooling in urban areas that is essential to support decisions on strategies for adaptation to heat stress and climate change mitigation.

Reducing the cooling gap and cooling-related energy requirements is critical for adaptation to heat stress and climate change mitigation in urban areas and has important implication for achieving multiple SDGs. Holistic strategies encompassing the improved design of buildings, urban settlements, and cooling systems are key to address the cooling gap in its multifaceted nature. Our study shows that, for the set of selected megacities, a significant share of urban population will still be living in slums in 2050, with a share of 31% to 59% in SSP3 in AFR and SAS cities. The provision of durable homes fit for local climate conditions can greatly improve thermal comfort and adaptation to heat stress (SDG3) while reducing the need for active cooling and related energy consumption and emissions (SDG13). At the same time, it can contribute to improved living conditions, together with slums eradication (SDG11).

Passive building strategies, including cool roofs, natural ventilation, and shading (Santamouris et al. 2007; Kalua 2016; Manu et al. 2019; Urge-Vorsatz et al. 2020; Nutkiewicz et al. 2022), have proven to be effective in improving cooling comfort, while typically being affordable solutions. As the building stock in the Global South is set to double by mid-century (IEA 2019b), there is a great opportunity to provide energy efficient homes and avoid lock-ins while providing shelter for all (SDG 11).

Urban design and nature-based solutions can contribute to mitigate urban heat island, improve thermal comfort, and reduce cooling energy requirements (Phelan et al. 2015; Güneralp et al. 2017; Creutzig et al. 2018). Improved access to electricity and to affordable and efficient cooling systems (SDG7) is key for providing thermal comfort where active cooling is needed. Promotion of less-energy intensive affordable technologies, including evaporative cooling (Yang et al. 2019), can constitute a valid alternative to AC in specific climates and contribute to improve access to basic cooling. Adoption of refrigerant with low global warming potential in AC under the Kigali Amendment to the Montreal Protocol is vital in achieving climate goals (Wang et al. 2020).

Some limitations apply to this study. We focus on uncertainty related to socio-economic developments and future climates, as well as uncertainty inherent to the empirically based models for AC access and slums, and cooling energy calculation (see Supplementary Information, Section 2). Other dimensions of future uncertainty are relevant and will be explored in future work. In particular, technological development could influence the energy efficiency and uptake of cooling systems and building technologies. The capital costs of cooling systems and future cost reductions under technological improvements are potentially significant for cooling gap projections, and should be investigated in future work. As discussed earlier in the text, AC uptake in urban areas might follow steeper adoption curves, not fully represented in the empirical-based model used in this study. While we focus on minimum requirements for basic cooling, actual cooling system ownership and operation patterns might also vary across regions, households, and housing types (Khosla et al. 2021a; Zhang et al. 2021), and change based on future developments. The performance of cooling systems can also be affected by outdoor temperature levels and urban neighborhoods (Gracik et al. 2015) that we do not consider in this analysis. Energy requirements strongly depend on thermal comfort thresholds and behavior (Hu et al. 2019; Mastrucci et al. 2019), as shown by our sensitivity analysis in the Supplementary Information, Section 2.4. Further empirical work is required to better understand cooling behaviors in different regions (Khosla et al. 2021a) and improve representation in energy modeling. With improved data on housing, urban neighborhoods, cooling systems, and household characteristics and cooling behavior, representation of heterogeneity in access to cooling and energy requirements could be advanced. While this study accounts for different climate futures, daytime and nighttime temperatures in cities are also affected by the urban heat island effect. We plan to include urban heat island effect in future studies, explore a broader set of measures for adaptation to heat stress in cities, and cover analysis of cooling-related emissions. Use of remote sensing data, including urban data, can support better assessment of urban characteristic in relation to heat stress (Verdonck et al. 2018). Access to cooling is critical in the commercial and public sector, in particular healthcare and food supply chains, and will be addresses in future studies.

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Data availability The manuscript has data included as supplementary information.

Declarations

Research involving humans and/or animals Not applicable.

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