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Future cooling gap in shared socioeconomic pathways

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Abstract

The extent to which societies will globally be able to adapt to climate change is not well understood. Here we analyze socioeconomic dimensions of adaptive capacity of populations to deal with heat stress and find income, urbanization and income inequality to be important factors in explaining adaptation to heat stress with air conditioning (AC). Using the scenario framework of the Shared Socioeconomic Pathways (SSPs), we estimate the future cooling gap, which represents the difference between the population exposed to heat stress and the population able to protect against heat stress with AC. Depending on the scenario of socioeconomic development, total population affected by the cooling gap may vary between 2 billion and 5 billion people in 2050, with the scenario-dependent range widening further towards the end of the century. Our analysis shows vast regional inequalities in adaptive capacity for one of the most universal manifestations of climate change, underscoring the need to account for the different potential levels of adaptive capacity in assessments of climate change impacts.

1. Introduction

Exposure to abnormal heat can cause various adverse effects on human health, from thermal discomfort to lethal outcomes [1]. Heat stress also negatively affects economic activity by reducing labor productivity [2, 3] as well as cognitive performance [4]. Effects of heat stress are also linked to societal problems such as intimate partner violence [5], suicide [6] and broader social conflicts [7]. Impacts on human health occur through extreme events such as heat waves or droughts, but also through gradual changes in average temperatures. Recent scientific advances have attributed heat impacts on health to anthropogenic climate change [8, 9] and there is ample evidence that these impacts will become even more prominent under increased global warming [10, 11]. Heat stress becomes amplified in urban areas due to the urban heat island effect [12], making populations in cities additionally vulnerable. With urbanization projected to spread in all scenarios of socioeconomic development [13], this effect is expected to become even more pronounced.

A way to alleviate the impacts of heat stress is to adjust indoor temperatures with the use of a cooling device, such as a fan or an air conditioning (AC) device. However, owning a cooling device is not only dependent on exposure to climatic conditions, but also on socioeconomic factors, such as having enough income to be able to afford a cooling device, meaning that the overall impact of heat stress hinges on the ability to adapt to it. In this study we explore how the capacity for adaptation varies in different scenarios of future developments of societies and of climate. We show how current and future inequalities in socioeconomic conditions create differential vulnerability to climate change. Combined with exposure to climate hazards, better understanding of vulnerability enhances the ability to detect hotspots of climate impacts around the world [14].

Previous research focused mostly on modelling the effects of the uptake of cooling strategies on energy demand and implications for climate change mitigation [15–18]. Economic impacts due to changing demand for cooling and heating have also been explored, with a finding that stringent mitigation action can help to hedge the risks to socioeconomic development [19]. Without questioning the importance of research on future energy demand, here we take a different angle and focus instead on the adaptation aspect of cooling, understanding the access to AC as a reflection of the ability of societies to adapt to the challenge of a broad conception of heat stress measured by cooling degree days (CDDs). Previous studies at the intersection of heat stress and socioeconomic vulnerability dealt with the equitability of access to cooling resources and projections of vulnerability due to heat exposure on the local level [20, 21], while here we contribute with a global perspective.

We take the ownership of AC as a proxy for adaptation action against heat stress, regarding AC as one of the simplest and most effective cooling options at the household level and taking advantage of the fact that its implementation can be traced through census data and other country-level sources. We link the socioeconomic adaptive capacity for cooling with climate-induced need for cooling to determine the *cooling gap*, which expresses the difference between the population exposed to heat stress and the population with the capacity to adapt to it through the use of AC [22].

Our study builds on previous research [15, 17, 22], by providing a temporal perspective on the cooling gap over the course of the 21st century, and by using a substantially larger sample of countries and testing for different threshold metrics of heat discomfort. Using the scenario framework of the Shared Socioeconomic Pathways (SSPs) and the Representative Concentration Pathways (RCPs), we create country-level projections of adaptive capacity to deal with heat stress and of future population exposed to heat stress.

Insights into the temporal and spatial evolution of adaptive capacity are important for better understanding of future climate impacts, yet they are disproportionally less represented in quantitative research compared to mitigation strategies and mitigation challenges. In climate impacts research, better representation of adaptative capacity and vulnerability would improve the framing of climate risk under different socioeconomic conditions [23]. Constraining the expectations of adaptation also reinforces the need for urgent and stringent mitigation and challenges the notion that adaptation and mitigation efforts can be substitutable [24].

Within the broader spectrum of the global agenda for sustainable development, lack of access to cooling is a dimension of energy poverty that has implications for the sustainable development goals (SDGs) [25], most directly the SDG 7 on Energy Access, but through multiple economic, social and health effects of heat stress, progress towards SDGs 1 (poverty), 2 (zero hunger), 3 (good health and wellbeing), 5 (gender equality), 8 (decent work and economic growth), 10 (reduced inequalities), 11 (sustainable cities and communities) and 13 (climate action) is also made more difficult [14, 15]. Providing a temporal perspective on how this dimension of energy poverty evolves can inform the Agenda about what the socioeconomic conditions need to evolve in parallel or need additional policies.

Focusing on adaptation to heat stress by means of AC, however, comes with a caveat. The increased use of AC is contributing to the greenhouse gas emissions both through rising demand for electricity and through their use of refrigerants—short-lived climate pollutants such as hydrofluorocarbons [26]. This in turn creates a positive feedback with climate change and the need for even more adaptation in the future. For this reason, AC is a contested adaptation option and has been termed maladaptation [27]. These are important interlinkages to understand, for anticipating future energy demand and for shedding light on how large the need for adaptation will be in the future and for what must be considered in adaptation planning. However, ACs are and will continue to improve in efficiency and their refrigerants will be better controlled [26]. Combined with low carbon electricity systems which will be widespread by the 2050s in mitigation scenarios, powering ACs may not be as consequential for emissions. Ultimately, example of the cooling gap that arises from unequal access to AC can serve as a heuristic tool to showcase adaptation gaps because of socioeconomically vulnerable populations exposed to increasing climate hazards.

2. Methods

2.1. AC data

In this analysis we focus only on the AC ownership at the household level. However, the stock of ACs in commercial and residential sectors is very similar and continues to grow at a similar pace [26]. Data for AC ownership is gathered from several sources which together cover 67 countries or about 80% of the global population, a substantially larger sample than in previous research which used similar approaches. Most of the additional coverage comes from the Global Data Lab [28] which provides subnational survey and census data on the ownership of electrical appliances, here aggregated to the national level for a cross-country analysis. The full sample covered here can be seen in figure 1.

For a better overview, most of the results in the rest of this study will be presented with the countries from our sample grouped in eight geographical regions. An overview of countries and the data sources for the AC sample in each region can be found in the supplementary table 2 (available online at stacks.iop.org/ERL/16/094053/mmedia).

2.2. Cooling degree days (CDDs)

To calculate mean annual CDDs, we use the population-weighted (w_g) average by grid cell (g_i)

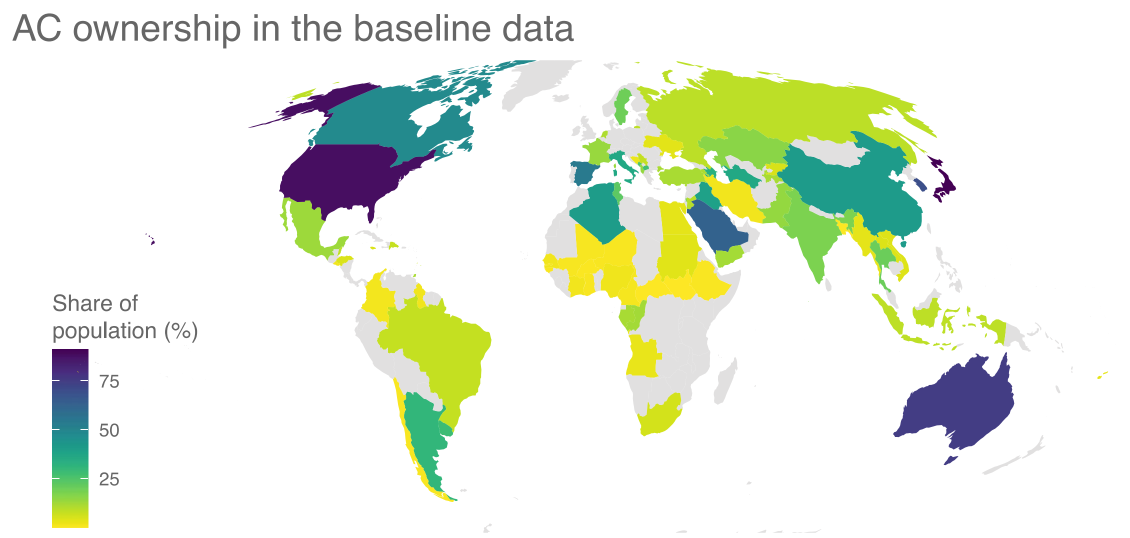

Figure 1. Data on AC ownership from multiple sources, used for the base specification of the statistical model.

within each country (i), of the annual sum of the positive difference between the average daily temperature ($T_{d,g}$) and the set point temperature (T_{sp}):

$$CDD_i = \frac{1}{pop_{tot}} \sum_{\forall g \varepsilon i} pop_g \left(\sum_{d=1}^{365} \left(T_{d,g} - T_{sp} \right)^+ \right),$$

where $T_{\mathrm{sp}}\ \varepsilon$ (18 °C, 20 °C, 22 °C, 24 °C) and $pop_g > 10\ \mathrm{km}^{-2}$.

We use gridded daily mean surface air temperature data from five CMIP5 global circulation models downscaled and bias-corrected to 0.5° (approximately 50 km at the equator) [29]. For climate scenarios we use the RCPs: RCP2.6, RCP4.5 and RCP6.0 with respective global mean temperatures 1.7 °C (1.6 °C); 2 °C (2.5 °C) and 1.9 °C (2.9 °C) in 2050 (2100) [30] higher compared to the pre-industrial level. A more detailed description of the climate forcing data can be found in the supplementary material.

Mean annual CDDs were calculated using 21 years of data centered at each decade (2010–2100) to capture the gradual change in rising temperatures and smoothen out the effects of inter-annual variability. Population weighting was done using gridded population projections for the five SSPs [31] similarly at decadal timesteps and 0.5° resolution.

2.3. Model

To estimate the future cooling gap, we combine the projections of future AC availability and future population exposed to heat stress. AC availability projections build on the two-stage modeling approach used in the seminal papers [15, 17, 32] that established the relationship between AC ownership, climatic conditions and AC availability. This approach expresses AC availability as a quotient of AC ownership (actual rates of AC ownership in a given population) and a climate parameter. The climate parameter—climate maximum saturation—defines the theoretical climatic requirements for cooling, based on the energy demand for cooling that starts above a certain temperature threshold (for more detail on climate maximum saturation, see the supplementary material). For example, if 50% of households in a country own AC, and the maximum saturation determined by the climatic conditions is also 50%, then AC is 100% available. The extent of AC availability thereby depends on the ability to own AC when needed. In previous studies, it was expressed as a function of income, which the most straightforward determinant of whether an AC device can be purchased or not. Here we add urbanization—meant to capture the increased demand for AC in urban areas [16]—and income inequality—to reflect heterogeneity in access to energy and household appliances [33]—as dimensions of the socioeconomic profile that might influence the availability of AC. Key concepts and the modeling steps are summarized in figure 2.

We test the conversion from AC ownership to AC availability, with four different set point temperatures (18 °C, 20 °C, 22 °C and 24 °C) that define the climate maximum saturation, and later select the regression model based on the minimum residual between the four estimates and use these country-specific temperature combinations because they improve the model accuracy and the projections.

To study the relationships between AC availability and the socioeconomic covariates we used beta regression with a logit link function, suitable for instances in which the dependent variable takes values in the interval between 0 and 1 [34]. We find that in addition to using income (proxied by GDP per capita), urbanization and inequality as socioeconomic covariates enhance the explanatory power of the regression model. Regression results are provided in supplementary table 1.

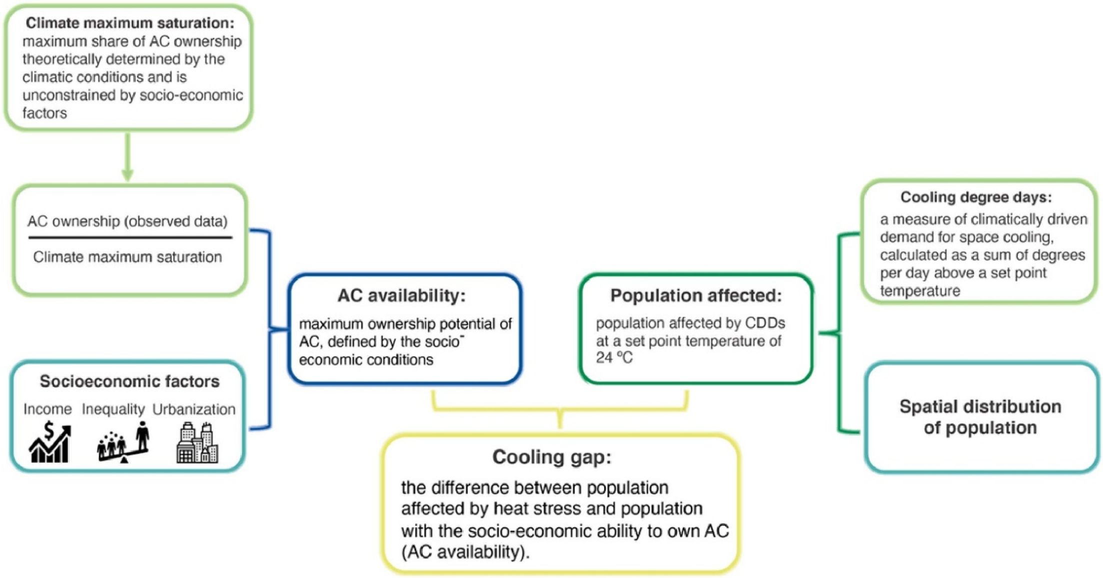

Figure 2. Conceptual representation of the modeling steps and explanations of key terminology.

The statistical model for the observational period rests on the following equation:

$$AC\ Availability_{i,t} = \beta_0 + \beta_1 GDP_{i,t} + \beta_2 Inequality_{i,t} + \beta_3 Urbanization_{i,t} + \varepsilon_{i,t}.$$

Coefficient estimates obtained from the beta regression model are imposed on projections of GDP [35], inequality [36] and urbanization [13] which, based on the same equation, calculate future values of AC availability in the scenario framework of shared SSPs, a commonly used set of scenarios of future socioeconomic development [37] (detailed descriptions of each scenario can be found in the supplementary material).

Population exposed to heat stress is calculated by coupling the estimates of population weighted CDDs, with population projections to estimate future exposure to heat stress. The set point temperature used to estimate population exposed to heat stress is 24 °C, which was the temperature at which the residual was the smallest for most countries in the regression analyses used above (see supplementary figure 2). Then, we calculate populations in areas with at least 50, 100, 200 and 400 CDDs, and define the exposed population as the median value. Uncertainties of the different temperature thresholds and counts of CDDs can be seen in the supplementary figure 3, together with several representative countries falling into a given temperature-count bracket.

Finally, to calculate the cooling gap, we calculate the difference between population exposed to heat stress and the share of population with access to AC (AC availability):

$$Cooling\ gap = Population\ exposed\ to\ heat\ stress \times (1 - AC\ Availability)\,.$$

Limiting the estimates to this upper bound of tested temperatures is a conservative approach, compared to the previous research which typically takes the daily mean temperature as the temperature threshold for cooling 18 °C [15, 38], meaning the estimates of heat exposure would be even higher if we considered areas where cooling is demanded at lower CDD thresholds.

It should be noted, however, that many different metrics of heat stress can be found in research. A large body of work has dealt with the impacts of *extreme* heat stress (e.g. heat waves) [39–42], which can have more adverse and more severe impacts on human health than the heat stress metric that is underlying this analysis. This means that the conception of heat stress here spans thermal discomfort that can be alleviated with 'mild' AC and severe heat stress that requires, for example, the AC to run overnight. For estimates of energy demand, it is important to understand the intensity and the duration of the AC use, but our analysis focuses on whether people have access to AC and thereby our definition of heat stress can be more flexible. Accounting for other parameters that determine the severity of heat stress, such as the deviation from the monthly mean, humidity, number of consecutive days of heat stress or the diurnal period (i.e. difference between daily maximum and daily minimum temperature which would allow for insights on the recovery period from heat) would be a valuable contribution in future applications.

3. Results and discussion

3.1. AC availability

Figure 3 shows the projections of future AC availability, with country-level estimates averaged on the level

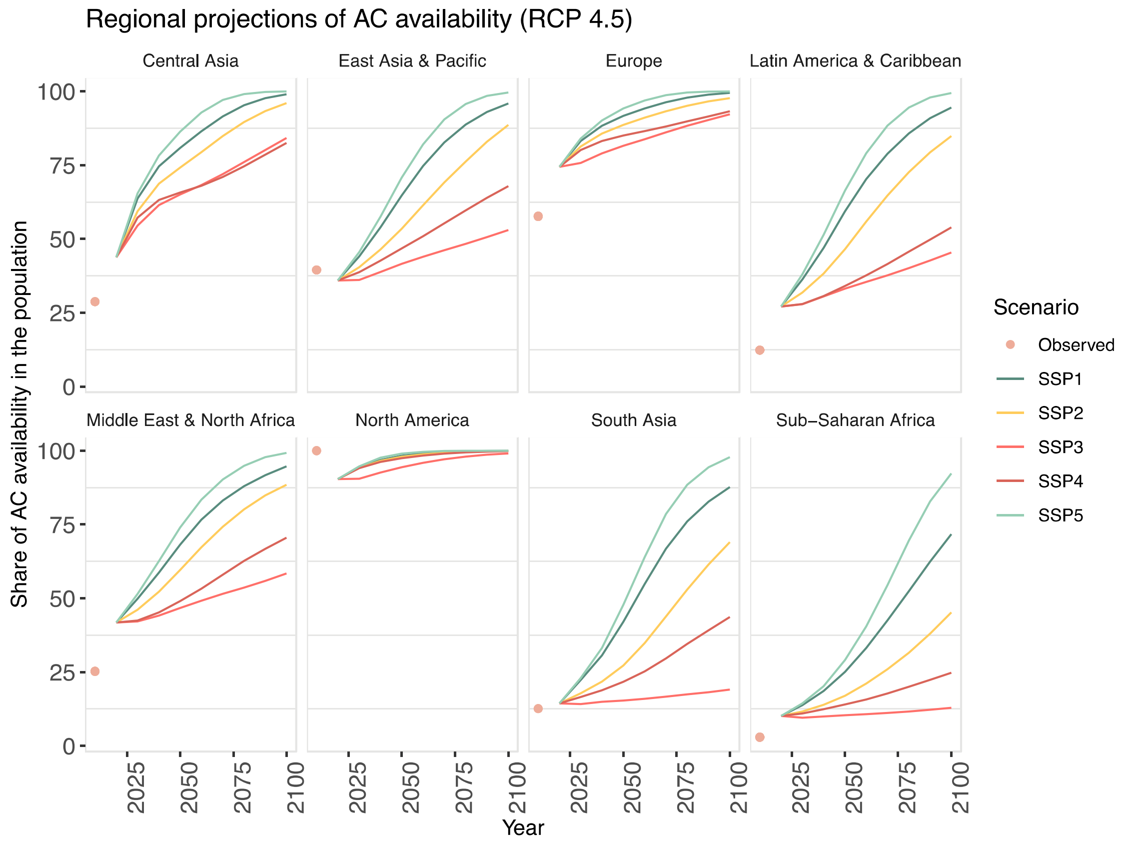

Figure 3. Observed and projected rates of AC availability for eight large geographical regions.

of eight geographical regions, based on the climate forcing scenario RCP 4.5—the central scenario used throughout the analysis. High AC availability reflects high levels of income and urbanization and on average low levels of income inequality.

North America (in the sample represented by Canada and the United States) is the only region that displays 100% AC availability, followed by Europe at about 60%. Both regions display little scenario difference in their future AC availability, implying that adaptive capacity to use AC is high, and will remain high in the future in all scenarios of socioeconomic development. The other six regions, meanwhile, differ substantially in the degree of scenario dependence. The difference is the largest for South Asia and Sub-Saharan Africa, which in scenarios of low and sluggish socioeconomic development (SSP3 and 4) see a stagnation or a marginal increase to about 25% of AC availability by the end of the century, in the middle-of-the-road scenario SSP2 reach about 60% and 40% respectively by 2100, and in scenarios of fast socioeconomic developments, reach saturation rates between 75% and 100% over the same time period. East Asia and the Pacific, Latin America and the Caribbean, Middle East and North Africa also display scenario differences, with about a 50-percentage point spread between scenarios at the end of the century. AC availability in Central Asia is expected to increase in all scenarios, with difference in 2100 between the 'worst' and 'best' case scenario of 25 percentage points.

3.2. Heat stress exposure

Figure 4 shows estimates of heat stress used to calculate cooling gap. Population exposed to heat stress was calculated on the grid cell level using gridded climate data and gridded population data and aggregated to the country-level for the purposes of the analysis conducted here. Already today, the population in the Southern Hemisphere is disproportionally affected by heat stress, with much of the Sahel region, Sub-Saharan Africa and most of South Asia having over three quarters of their populations exposed to heat stress. Going towards 2050 in mid-range scenarios for both population growth and climate (SSP2 and RCP 4.5), increasing shares of population in the northern hemisphere are affected, and in 2100, almost entire populations in all countries except for the Nordic countries and Great Britain are exposed to some sort of heat stress and heat discomfort in these two scenarios. Uncertainties in the climate scenario for 2050 and 2100 for RCPs 2.6 and 6.0 are available in the supplementary figure 5.

3.3. Cooling gap projections

Figure 5 shows the absolute population affected by the cooling gap—i.e. people exposed to heat stress,

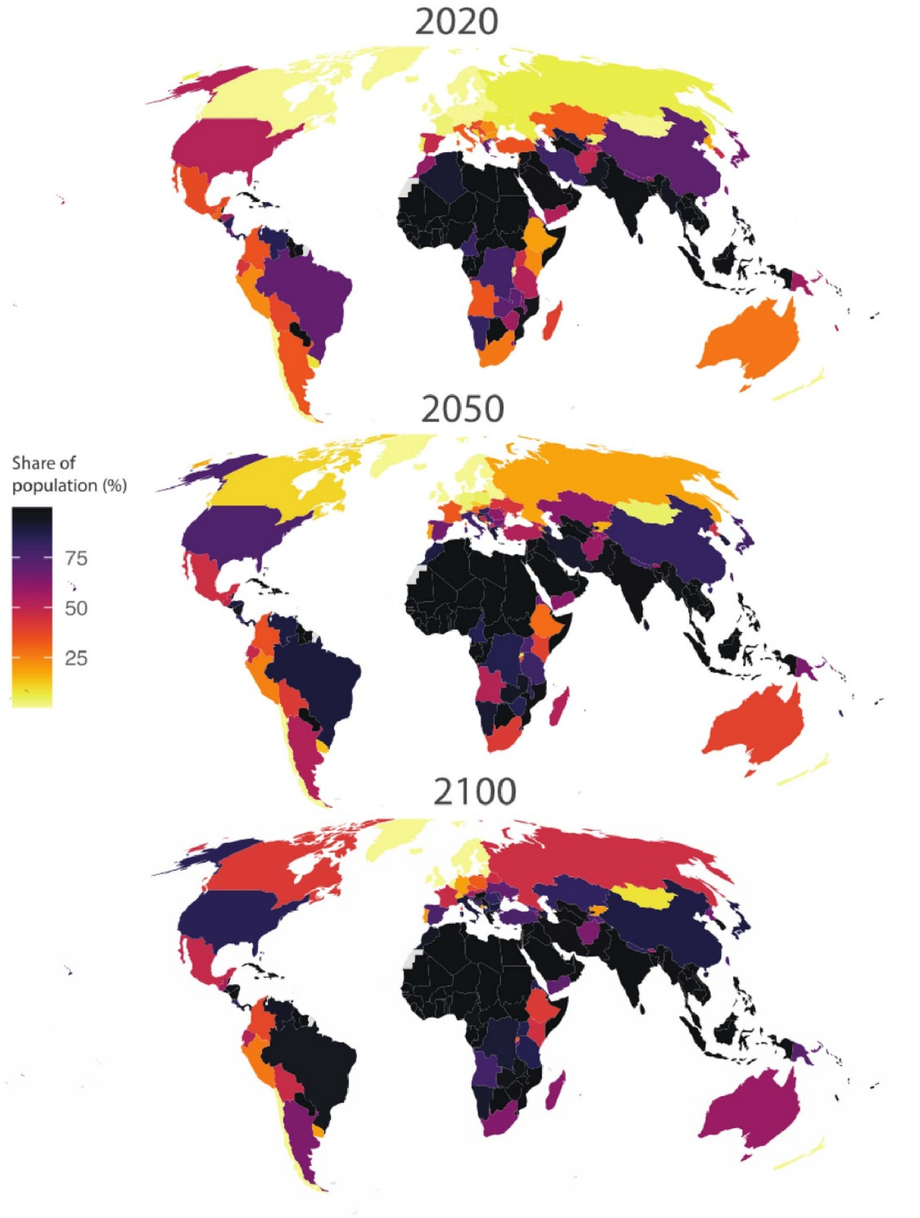

Figure 4. Population exposed to heat stress measured by CDDs above the set point temperature of 24 °C in 2020, 2050 and 2100. Increase in population is based on SSP2 scenario and CDDs increase is in RCP 4.5.

but without access to AC. We focus on two time slices: mid-century and end of century, for emissions scenario RCP 4.5 and SSPs 1–3 which span the scenarios of low challenges to mitigation and adaptation (SSP1), medium challenges to mitigation and adaptation (SSP2) and high challenges to adaptation and mitigation (SSP3) (for paucity we show only three scenarios, but they capture almost the entire range of estimates). In 2050, South Asia stands out as the region with the largest population affected by the cooling gap, with almost 1.5 billion people affected in the middle-of-the-road scenario, and the scenario spread between 0.8 billion in SSP1 and over 2 billion people in SSP3. The second most affected region is Sub-Saharan Africa (∼0.7 billion in SSP1, 1.1 billion in SSP2 and 1.3 billion in SSP3), followed by East Asia & Pacific (∼0.3 billion in SSP1, 0.5 billion in SSP2 and 0.8 billion in SSP3). By the year 2100, the number of people affected by cooling gap globally reduces substantially for scenario of fast socioeconomic development (SSP1; 0.5 billion) and to a medium degree in the scenario of largely continuing the current development trends (SSP2; 1.9 billion). Meanwhile, population affected drastically increases in SSP3—a scenario of fast population growth and slow socioeconomic development—reaching almost 3 billion in South Asia and 2.5 billion in Sub-Saharan Africa. These results imply that even in scenarios of fastest socio-economic development, millions of people in regions of the Global South will inevitably be affected by heat stress. At the same time, in the scenario of slow and unequal global development (SSP3), 5.2 (7.2) billion people in 2050 (2100) could be without adequate protection against heat stress.

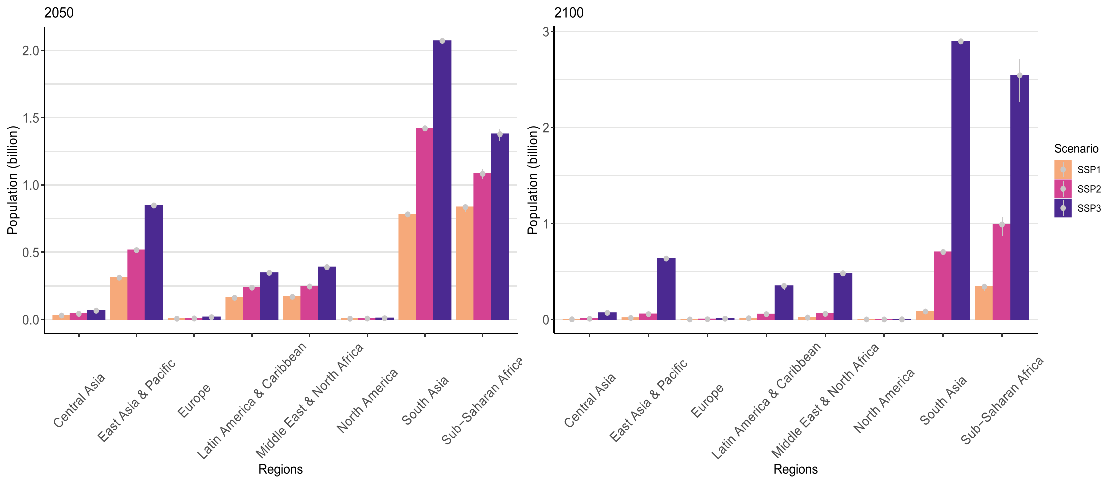

Figure 5. Absolute population estimates affected by cooling gap in 2050 and 2100. The central estimate for heat stress is based on RCP4.5, and the whiskers indicate the spread of the emissions scenarios. The bars are grouped in eight geographical regions and shown for three SSP scenarios.

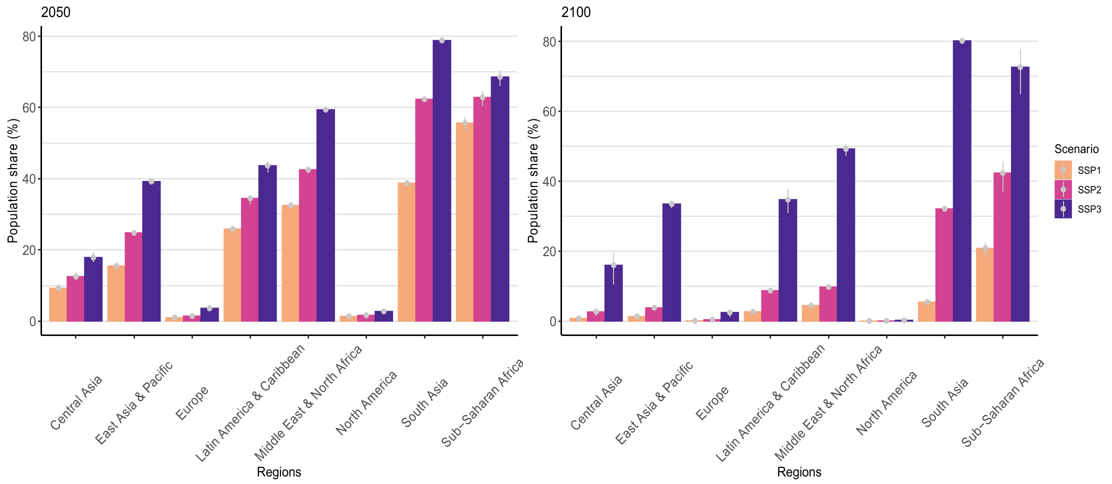

Figure 6. Share of population affected by cooling gap in 2050 and 2100. The central estimate for heat stress is based on RCP4.5, and the whiskers indicate the spread of the emissions scenarios. The bars are grouped in eight geographical regions and shown for each of three SSP scenarios.

When the cooling gap is regarded in relation to the total population of these regions (figure 6), the picture becomes different, with Sub-Saharan Africa now having the highest shares of population affected by cooling gap across all scenarios except for SSP3 and in both time periods. The region affected the least is North America. As shown in figure 4, North America already is and is projected remain largely unconstrained in terms of its adaptive capacity to heat stress, and its population is projected to stagnate or even shrink in most scenarios. In the worlds of SSP3, almost 80% of people in South Asia and 70% Sub-Saharan Africa would be exposed to heat stress without the adaptive capacity to deal with it, both in mid-century and in the long run. The access to AC can be improved by mid-century in scenarios of faster income growth, urbanization, reduced inequality and slower population growth, but only at the end of the century are these regions projected to display similar levels of cooling gap to today's rich countries of Europe and North America. Somewhat smaller, but still substantial portions of people are going to be affected in these scenarios also in Latin America and the Caribbean, and in the Middle East and North Africa regions. Significant improvements can be brought about in the SSP1 pathway, but only towards the end of the century.

Figures 5 and 6 also show the spread of estimates across the three RCP scenarios. As noted earlier in the section on heat stress exposure, the heat stress metric used here is generally not very sensitive to the climate scenario, but some regions still display differences up to 10 percentage points. Because of the nature of the three RCP scenarios used here, which do not markedly differ until later in the century, the climate signals become significantly pronounced only later, which is the reason for seeing more visible impacts of the different emissions scenario only on graphs for 2100. The way we measure heat stress makes little difference in outcomes in terms of population affected for the most affected regions of Central Asia and Sub-Saharan Africa. These locations already have large portions of populations affected, and the situation is projected to worsen even if we would globally get on a more stringent mitigation pathway, primarily because the areas already get substantial heat stress and population will keep on growing in all scenarios, at least until the mid-century. The apparent independence from the climatological component should be interpreted with caution also because it does not speak to the more severe impacts of heat *extremes* (i.e. extreme heat waves and events related to heat waves such as droughts or wildfires) that are projected to occur already at 2 °C global mean temperature increase above the pre-industrial period, though could be dampened if the warming is limited to the Paris Agreement goal of 1.5 °C [43]. Nevertheless, the CDD metric used for estimating heat exposure here reflects the need for AC in a broad sense and while this need might become more pressing in the future, we are not able to assess how pressing it will become depending on the level of warming, but merely that it is there and that populations will seek for adjusting their thermal comfort.

Even though the most affected regions here are consistently in the Southern Hemisphere, previous research finds that a growing number of households in Europe is struggling to meet their needs for cooling [44], and the same might hold for North America despite its consistently high estimates of AC availability. This finding will become more pertinent with higher rates of people living in cities [45]. Spatial resolution of our research does not allow for analyses on that level, but it is important to keep in mind that even in the regions portrayed here as best-off, there could still be portions of populations affected by cooling gap or energy poverty in a broader sense.

This analysis could be further elaborated upon with several additional considerations. Firstly, although we cover—to our best knowledge—the biggest sample of country-level data on AC saturation, 67 countries are far from a full global coverage which would of course yield even more precise estimates. Secondly, we consider only one type of cooling option, whereas other devices such as fans are also used for cooling. Third, the use of CDDs to measure heat stress exposure has its shortcomings. CDDs do not allow for a distinction between thermal comfort demands by people who *want* AC without severe risks of heat stress and people who *need* AC to survive. Also, CDDs increase linearly with population, which ignores the variation household sizes around the world [46]. This metric also does not account for differences in building standards and types, as better quality of insulation reduces need for indoor cooling [47]. Lastly, physiological adaptation of the body to heat stress is evident in people in hotter climates being less sensitive to high temperatures [42], and this can be expected to take place to some extent in the future as well. Future research could tackle these shortcomings by using different heat stress metrics, or consider heat extremes and their duration which would also have disproportionately negative effects on the poor [48].

These limitations notwithstanding, with this study we expand the previous methodological approaches to account for the multidimensionality of climate change adaptation and contribute to the research field with a perspective of adaptive capacity as a function of different socioeconomic factors. Projections of climate change impacts currently do not explicitly account for whether there is a potential for adaptation in the first place and how this potential might change in the future and around the world, and analyses such as the one presented in this paper provide pathways to do so.

4. Conclusion

This study presents a toolkit for analyzing adaptive capacity across countries and over time, focusing on the use of AC as an adaptation option for coping with heat stress. We expand the previously used statistical models, and use income, income inequality and urbanization to show future estimates of AC availability.

By coupling projections of AC availability with estimates of future heat stress based on exposure to CDDs, we produce estimates of the future cooling gap. The size of the gap between population that needs AC and the population able to afford AC predominantly depends on the scenario of socioeconomic development which is reflected in the large range between the scenario estimates. Between the scenario of low challenges to adaptation and mitigation (SSP1) and the scenario with high challenges to adaptation and mitigation (SSP3) total population affected by the cooling gap globally could vary between 2.3 and 5.2 billion people in 2050, and between 0.5 and 7.2 billion in 2100. Regional disaggregation shows large inequalities, with the future adaptive capacity in countries in the Global South depending greatly on the socioeconomic dynamics or factors such as income, urbanization and inequality, while the developed countries of the sample in this instance only show dependence on the climatic conditions.

Even in the most optimistic scenarios of the SSP framework, some of the vulnerable regions will not reach the same levels as in rich countries. As an important dimension of energy poverty, the extent of cooling gap and its scenarios presented here can be used for informing the attainability of sustainable development pathways of the different SDGs that depends on the broader socioeconomic dynamics.

The need to adapt to climate change is already apparent and will only become more pressing in the future. Our analysis shows that fast population growth that is not followed by socioeconomic development would expose more than three quarters of populations to unabated heat stress in some of the world's most populous regions, like South Asia, Sub-Saharan Africa and Latin America. The degree to which societies will be able to adapt in the future needs to be understood, in order to better estimate current and future climate impacts. This will help us avoid overestimating of the potential of adaptation and underestimating of the urgency of mitigation.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/marina-andrijevic/coolinggap.

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Author contributions

M A, E B and A M designed the research. M A performed the analysis with inputs from E B and A M. J S processed and prepared the air conditioning data. E B processed and prepared the climate data. M A led writing of the manuscript with contributions of E B, A M, J S and S F.

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