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Air conditioning and global inequality

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ABSTRACT

As global temperatures go up and incomes rise, air conditioner sales are poised to increase dramatically. Recent studies explore the potential economic and environmental impacts of this growth, but relatively little attention has been paid to the implications for inequality. In this paper we use household-level microdata from 16 countries to characterize empirically the relationship between climate, income, and residential air conditioning. We show that both current and future air conditioner usage is concentrated among high-income households. Not only do richer countries have much more air conditioning than poorer countries, but within countries adoption is highly concentrated among high-income households. The pattern of adoption is particularly stark in relatively low-income countries such as Pakistan, where we show that the vast majority of adoption between now and 2050 will be concentrated among the upper income tercile. We use our model to forecast future adoption, show how patterns vary across countries and income levels, and discuss what these patterns mean for health, productivity, and educational inequality.

1. Introduction

Sales of residential air conditioners have tripled since 1990 to almost 100 million units annually (International Energy Agency, 2018). That means that every hour, 10,000+ new residential air conditioners are sold somewhere on the planet. As with many durable goods, air conditioning adoption follows an "S"-like pattern (Gertler et al., 2016). As incomes rise, adoption can spike dramatically (Wolfram et al., 2012). Many middle-income countries are approaching the steep part of this S-curve, and so air conditioner sales are poised to increase rapidly (Davis and Gertler, 2015).

Recent studies explore the economic and environmental impacts of increased use of air conditioning. Air conditioning decreases heat-related mortality (Barreca et al., 2016; Burgess et al., 2017; Carleton et al., 2018), increases productivity (Heal and Park, 2016), and improves learning outcomes (Park et al., 2020). But air conditioning is also electricity-intensive, so widespread adoption requires significant investments in electricity generation and transmission infrastructure (Wenz et al., 2017; Auffhammer et al., 2017) and implies large increases in carbon dioxide emissions (International Energy Agency, 2018). In addition, the refrigerants used in air conditioning are themselves a potent greenhouse gas, exacerbating the climate impacts (Shah et al., 2015; Shah et al., 2017).

Relatively little attention has been paid, however, to the implications of air conditioning for global inequality. In this paper, we use household-level microdata from 16 countries to characterize empirically the relationship between climate, income, and residential air conditioning. We compiled for this paper one of the most comprehensive household-level datasets ever assembled on air conditioning. With data from China, India, the United States, Pakistan, Nigeria, and 11 other countries, our data include representative samples from over 50% of the total global population. We match these microdata at the sub-country level with rich climate data.

At the core of our model are a series of adoption curves relating annual household income to air conditioning adoption. In our model, we allow these adoption curves to differ by climate. We find that both income and climate predict air conditioner adoption, but that it is the interaction between the two that is particularly important. In relatively cool areas, air conditioner adoption is near zero for all income levels. In warmer areas, however, we find a close relationship between household income and air conditioner adoption, with sharp increases in air conditioning starting at annual household income of about $10,000 USD.

We then combine this model with forecast income and climate levels to predict future adoption of air conditioning. Between now and 2050,

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our model predicts large increases in residential air conditioning. Across all 16 countries our model predicts that the fraction of households with air conditioning will increase from 35% in 2020 to 55% in 2050. We find that both income and climate matter for these projections, but that income matters much more, explaining 85% of the growth in air conditioning by 2050. Our results imply therefore that income growth is far more important than the speed of global warming for determining future adoption of air conditioning.

In contrast to previous studies, our results describe not only aggregate adoption, but also how outcomes vary across households with different income levels. Our results show that both current and predicted future usage of air conditioning is overwhelmingly concentrated among high-income households. Not only are households in high-income countries much more likely to own air conditioning, but within countries adoption is highly concentrated among high-income households. The pattern of adoption is particularly stark in relatively low-income countries. For example, our model predicts that the fraction of households with air conditioning in India will increase to 50% by 2050, but with pronounced differences in ownership rates between households with different income levels.

This increased saturation of air conditioning could save millions of lives. A recent estimate in the literature implies that in India alone 630,000 people die each year from high temperatures, with this increasing to 1.4 million deaths per year by 2050 (Burgess et al., 2017). Assuming air conditioning reduces heat-related mortality by 80% (Barreca et al., 2016), our predicted saturation levels imply 550,000 fewer deaths per year by 2050 and 9.2 million fewer cumulative deaths by 2050, with a disproportionate number of avoided deaths occurring among the highest income tercile.

Avoided mortality is just one of a broad stream of private benefits from air conditioning. In the paper we discuss the implications of our results for health, productivity, education, and human capital accumulation. Differential adoption of air conditioning puts vulnerable households at a growing disadvantage, threatening to exacerbate existing disparities in society. Air conditioning is perhaps the single most consequential form of adaptation to climate change, and yet is simply unavailable to large parts of the global population.

2. Results

2.1. Air conditioning adoption curves

Fig. 1 plots air conditioning adoption curves for our sixteen sample countries. For all countries there is a pronounced positive correlation between household income and ownership of air conditioning. At low income levels air conditioning is relatively rare but then starting at about $10,000 USD saturation levels increase sharply, before eventually leveling off at high income levels.

These patterns are consistent with S-shaped adoption curves that have been widely observed for other types of durable goods (see, e.g.,

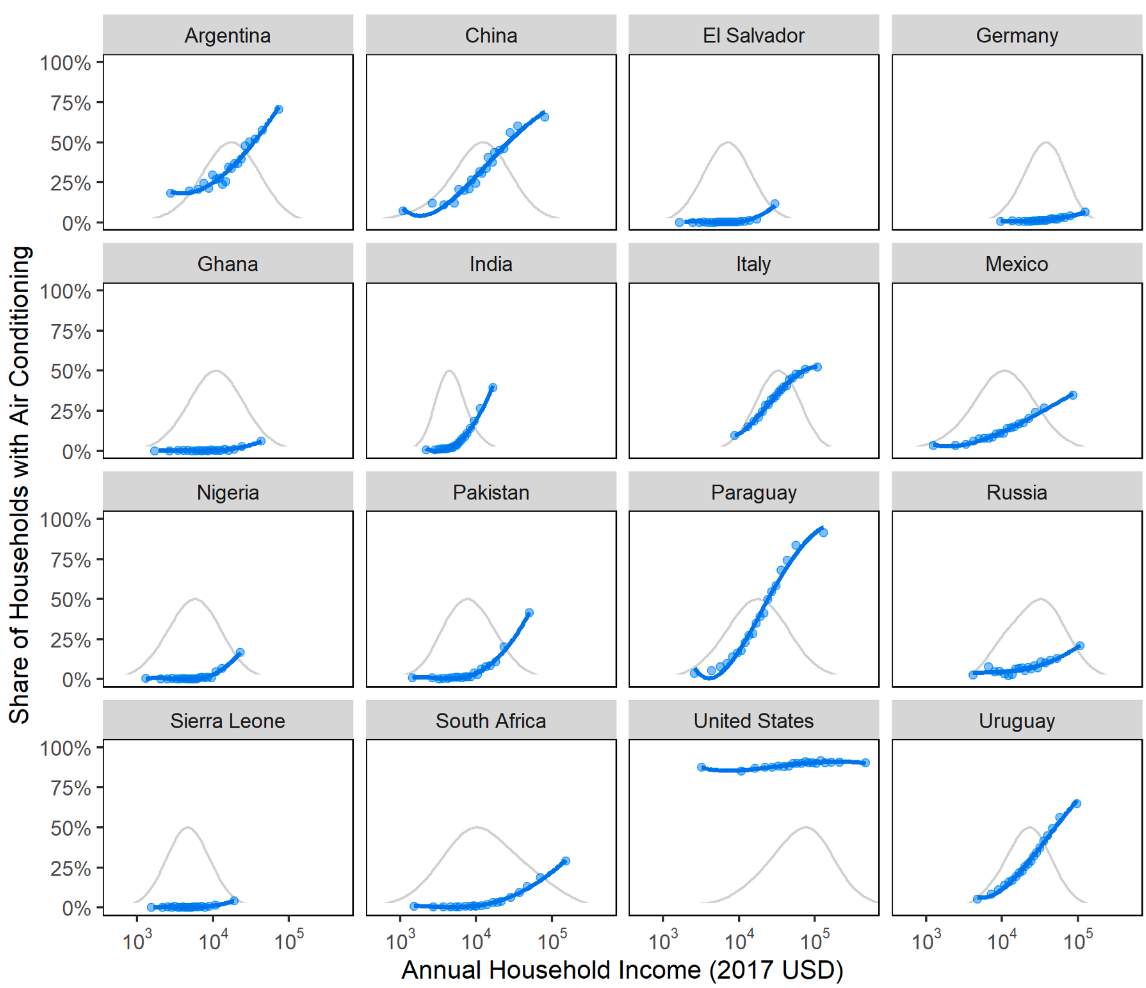

Fig. 1. Air Conditioning Adoption Curves. **Notes:** This figure shows air conditioning adoption curves for each of our sixteen sample countries. The blue points represent the average penetration of air conditioning for each income decile. The blue line is a cubic best fit through these points to illustrate the S-shaped adoption pattern observed in the data. The grey line is a density plot illustrating the income distribution in each country. Income levels throughout have been converted to 2017 US PPP Dollars.

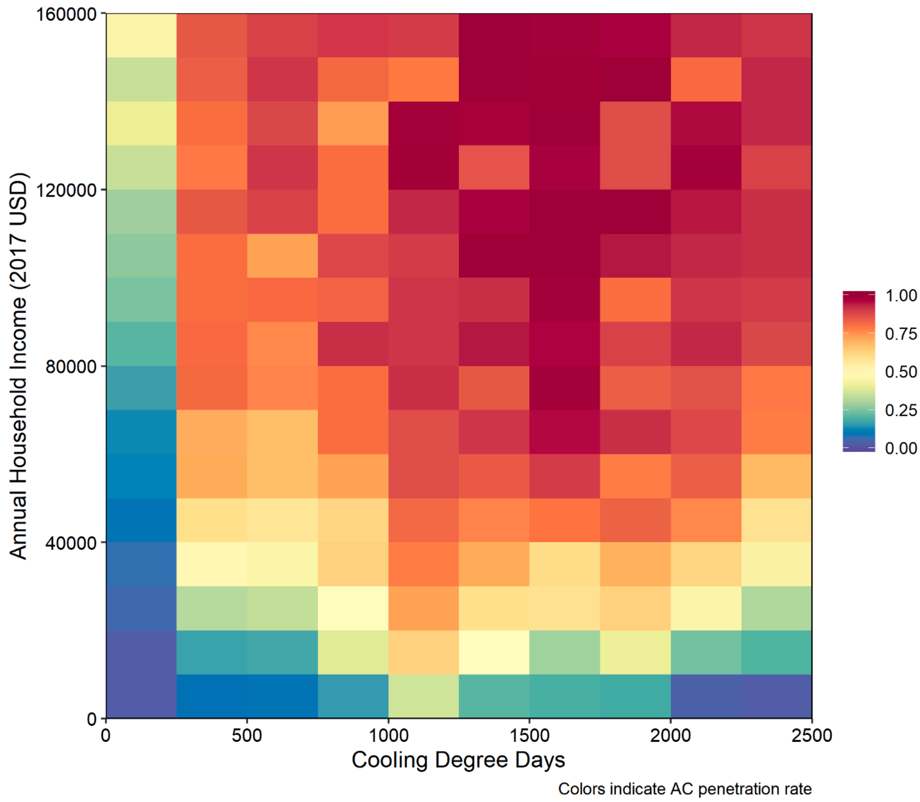

Fig. 2. Air Conditioning Heatmap. **Notes:** This figure illustrates how penetration of air conditioning varies with respect to income and CDDs pooled across our sixteen sample countries. The colors indicate the penetration rate. Cells are only plotted if they had a minimum of fifty observations.

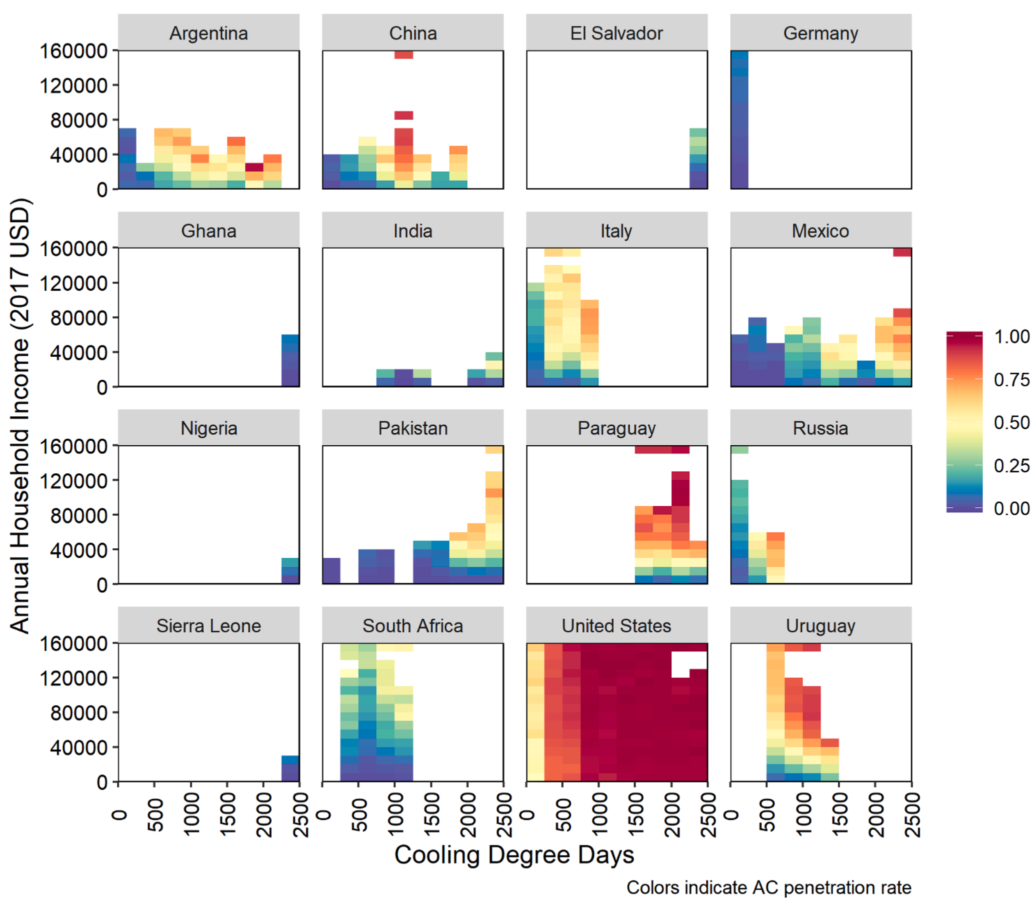

Fig. 3. Air Conditioning Heatmaps by Country. **Notes:** This figure illustrates how penetration of air conditioning varies with respect to income and CDDs for each of our sixteen sample countries. The colors indicate the penetration rate. Cells are only plotted if they had a minimum of fifty observations.

Wolfram et al., 2012; Gertler et al., 2016). Davis and Gertler (2015) performs a similar analysis for air conditioning, but using data from only a single country, Mexico. Our study expands and generalizes that previous work to include a large and diverse set of countries, and to focus explicitly on inequality, a topic that has received very little attention in the literature.

These empirical adoption curves motivate our econometric model of air conditioning adoption. Our preferred model uses a regularized logistic regression which requires the adoption curve to have the same approximate shape globally, but allows the steepness to be modified by climate. We also allow the curve to be shifted vertically by country-specific factors that are not purely related to climate (e.g. preferences). See supplementary materials for full details.

2.2. Model identification

Figs. 2 and 3 show how air conditioning varies with respect to income and cooling degree days (CDDs) across our 16 sample countries. Fig. 2 shows the pooled across our entire sample and Fig. 3 shows the results separately for each of our sixteen sample countries. White is used to denote cells where there is insufficient coverage. For example, in Germany most households experience fewer than 500 CDDs annually whereas in Ghana, most households experience more than 2000 CDDs annually (Biardeau et al., 2020).

These heatmaps illustrate the inherent richness of our microdata. Whereas previous studies of air conditioning adoption have tended to focus on the United States and other high-income countries (Sailor and Pavlova, 2003; Biddle, 2008; Mansur et al., 2008; Rapson, 2014), our inclusion of a large sample of households from low- and middle-income countries differentiates our study and provides much more information on how adoption changes over lower income levels.

There is rich variation both between and within countries, with households experiencing a wide range of different income levels and climate exposures. The heatmaps illustrate the expected pattern with air conditioning increasing in both incomes and CDDs, with the combination of both high incomes and high CDDs leading to the most widespread adoption.

Model identification relies on this broad coverage. We have good support for low- and medium-income households across a range of climates. We also have good support for high-income households at cool and moderate climates. Probably the biggest challenge, however, is high income households in hot climates. This is perhaps unsurprising - historically many of the hottest places have tended to also be poorer, with the richest nations often located in more temperate parts of globe (e.g. Europe, North America). We take several steps to address this limitation including pooling our data in a 2000+ CDD category to ensure that we have a sufficient number of observations. See the Appendix for details.

2.3. Model fit

Fig. 4 illustrates the fit of our econometric model. Each panel presents data and model predictions for a particular country. We focus here on how the model estimation traces out this S-shaped adoption curve as a function of household incomes. In our model the sensitivity of air conditioning adoption to changes in income is allowed to vary depending on the level of CDDs and vice versa. The lines therefore summarize how our model estimated penetration rates for air conditioning vary with income at a given level of CDDs. The plotted points then summarize the underlying observed data used to fit the model; specifically the points are the average penetration rate by income decile at a given level of CDDs.

Overall, the model provides a good approximation to the empirical pattern. Country-level shifts are relatively small for most countries with the primary exception of the United States, which exhibits a strong preference for air conditioning at all income and climate levels. Air conditioning has long been a part of U.S. culture, and this vertical shift may reflect cultural preferences as well as access to cheap and reliable electricity.

As we might expect, the adoption curve rises steeply as households surpass incomes of $10,000 USD, before flattening off as adoption approaches saturation at incomes in excess of $100,000 USD. The adoption curves are significantly steeper for higher levels of CDDs. This indicates that adoption is more sensitive to changes in income in areas with hot climates than in areas with cool climates.

Fig. 4 can also give some insight into how sensitive adoption is to changes in climate at different levels of income. The plotted adoption curves are all separated by equal intervals of CDDs. As such, areas where they are tightly bunched suggest adoption is not very sensitive to changes in CDDs. This bunching can be observed across the income distribution once CDDs have exceeded around 1500. Incremental warming at this point does little to steepen the adoption curve. In cooler climates, on the other hand, incremental warming can rapidly steepen the adoption curve. This is most pronounced at higher income levels where even modest increases in CDDs can lead to large shifts in adoption.

2.4. Projections by country

Fig. 5 plots projected air conditioning penetration by country during the period 2010–2050. Points represent the average level of penetration for a given country in 2010, 2020, 2030, 2040 and 2050. These projections were calculated using our econometric model based on projections for incomes, population and climate change from IIASA's Shared Socioeconomic Pathways (SSPs). For income growth we assume equal percentage increases across the entire income distribution of each country in line with the growth rate of average per capita GDP. This means levels of relative income inequality within each country remain unchanged from current levels. See Appendix for details.

Our results imply large growth in air conditioning, particularly among low- and middle-income countries. India experiences dramatic growth, from below 10% in 2010 to 50% in 2050. China grows dramatically as well, albeit from a higher starting point, but reaching almost 75% saturation by 2050. Latin American countries Mexico, Argentina, Paraguay, and Uruguay all grow rapidly. Air conditioning surges in Italy from 30% to above 50% by 2050.

In contrast, growth is much smaller in the United States, where air conditioning is already near ubiquitous. If anything, further increases in income tend to reduce ownership gaps in the United States, with low-income households catching up with other households. Germany and Russia experience low levels of air conditioning throughout, with climates that remain relatively cool even by 2050.

Finally, the African countries Sierra Leone, Ghana, Nigeria, and South Africa are particularly interesting. Starting from a low base, these countries experience several-fold increases in air conditioning. For example, Sierra Leone goes from near 0% to 10% in 2050.

Across all 16 countries our model predicts that the fraction of households with air conditioning will increase steadily from 26% in 2010, to 35% in 2020, to 43% in 2030, 50% in 2040, and 55% in 2050. With the total population in our 16 countries expected to increase from 3.9 billion to 4.7 billion, this implies that the total number of air conditioning units across our 16 countries increases from 295 million in 2010 to 691 million in 2050. See Appendix Table 3 and Appendix Fig. 4 for details. These aggregate projections are roughly in line with forecasts from previous work based on aggregate data (International Energy Agency, 2018).

2.5. Key drivers of adoption

Air conditioning adoption is driven by both rising incomes and a warming global climate. But which factor plays a larger role? Fig. 6 plots the results from a decomposition analysis we performed by country. We apply standard comparative statics to our model, holding fixed one

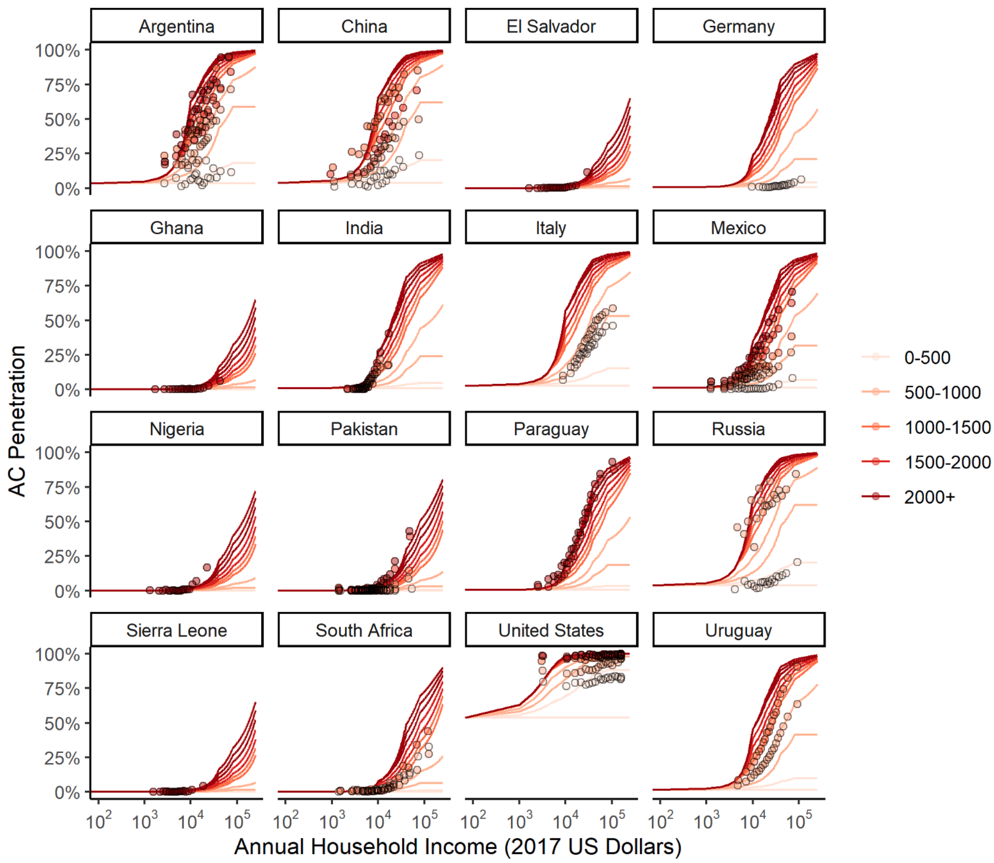

Fig. 4. Estimated Model for Air Conditioning Penetration by Country. **Notes:** This figure illustrates the fit of our econometric model across the sixteen countries in our sample. The lines summarizes how the predicted penetration of air conditioning from our model varies with income at a given level of CDDs. The plotted points then summarize the underlying observed data used to fit the model; specifically the points are the average penetration rate by income decile at a given level of CDDs. Points are only plotted if they had a minimum of ten observations.

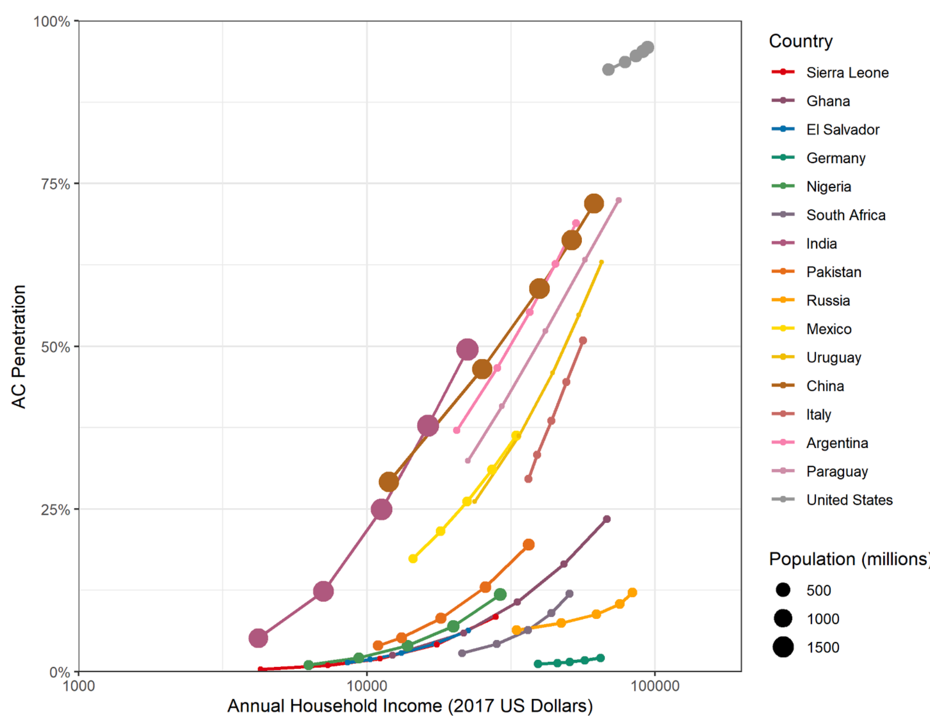

Fig. 5. Projected Air Conditioning Penetration by Country, 2010–2050. **Notes:** This figure shows how projected penetration rates for air conditioning vary with income levels. Colors denote the sixteen countries in our sample. Each point shows the penetration rate at a different level of average income based on estimates for 2010, 2020, 2030, 2040, and 2050. The size of each point is scaled relative to the population of each country.

factor at a time.

The results indicate that income explains 85% of the growth in air conditioning over this period. Global warming matters, but countries with warm climates like Ghana, India, Nigeria, Pakistan, and Sierra Leone are already warm enough to induce rapid adoption of air conditioning. Further warming has little additional impact on adoption, and so in these countries income, not climate, is the limiting factor.

Instead, where we see global warming mattering more is in relatively cooler countries. Argentina, China, Italy, and Uruguay, in particular, have many regions which in 2010 are not quite warm enough to drive widespread demand for air conditioning, but the incremental warming between 2010 and 2050 is enough to push these areas past the threshold. Even in these cooler countries, however, it is notable that income growth remains very important. For example, in China at least 80% of the growth in air conditioning is driven by income, with only 20% driven by climate.

2.6. Inequality in adoption

Fig. 7 plots air conditioning shares by household income tercile for all 16 countries. Income terciles are calculated country-by-country, so this provides an opportunity to assess the within-country pattern.

Our model predicts that air conditioning will continue to be highly concentrated among high-income households. Almost all income terciles experience rapid increases in air conditioning, including low-income terciles in relatively low-income countries like India. However, the gap between high-income and low-income households remains pronounced in all years.

Interestingly, a few countries see evidence of convergence. China is a good example of this. Between 2030 and 2050 penetration for the high-income tercile grows modestly from 80% to 88%, likely reflecting saturation for these households. Over the same period the low-income tercile grows much more rapidly from 33% to 51%. Even so, this convergence still leaves a large gap in access to air conditioning between high- and low-income households.

Furthermore, in some countries inequality actually gets worse. Take Pakistan, for example. By 2050 38% of households in the high-income tercile have air conditioning, compared to only 5% in the low-income tercile. A similar story is evident in many African countries with air conditioning penetration for the lowest-income tercile remaining below 4% in South Africa, Nigeria, and Sierra Leone.

Thus even by 2050 there remains a pronounced inequality gap in almost all countries, with low-income households substantially less likely to have access to air conditioning. This inequality gap has received relatively little attention in the existing literature, and has important implications for productivity, education, and health, as we discuss next.

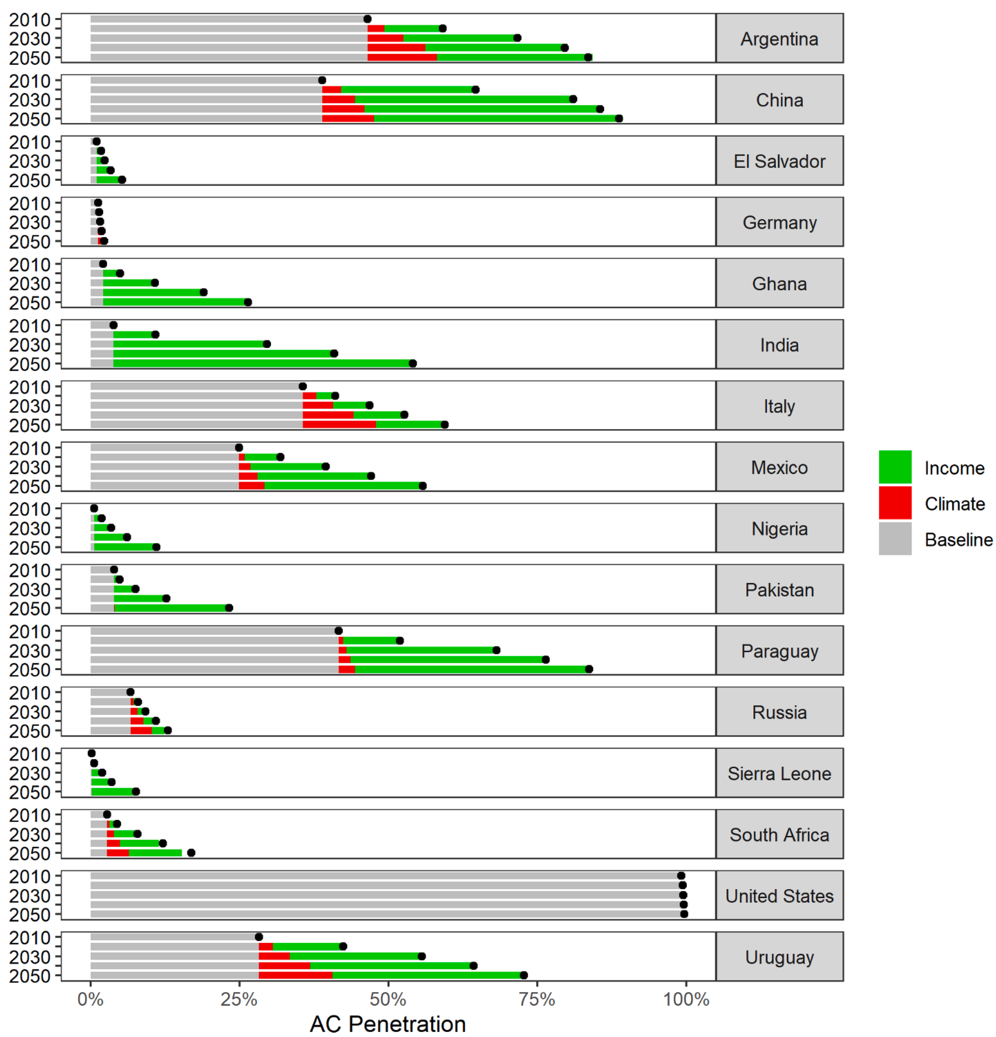

Fig. 6. Decomposition of Growth in Air Conditioning Penetration, 2010–2050. **Notes:** This figure shows the results from a decomposition analysis we performed by country. The grey bars indicates the baseline level of air conditioning in each country in 2010. The black points then show air conditioning penetration in 2010, 2020, 2030, 2040, and 2050. Finally the colors indicate the fraction of growth since 2010 due to income and global warming, respectively.

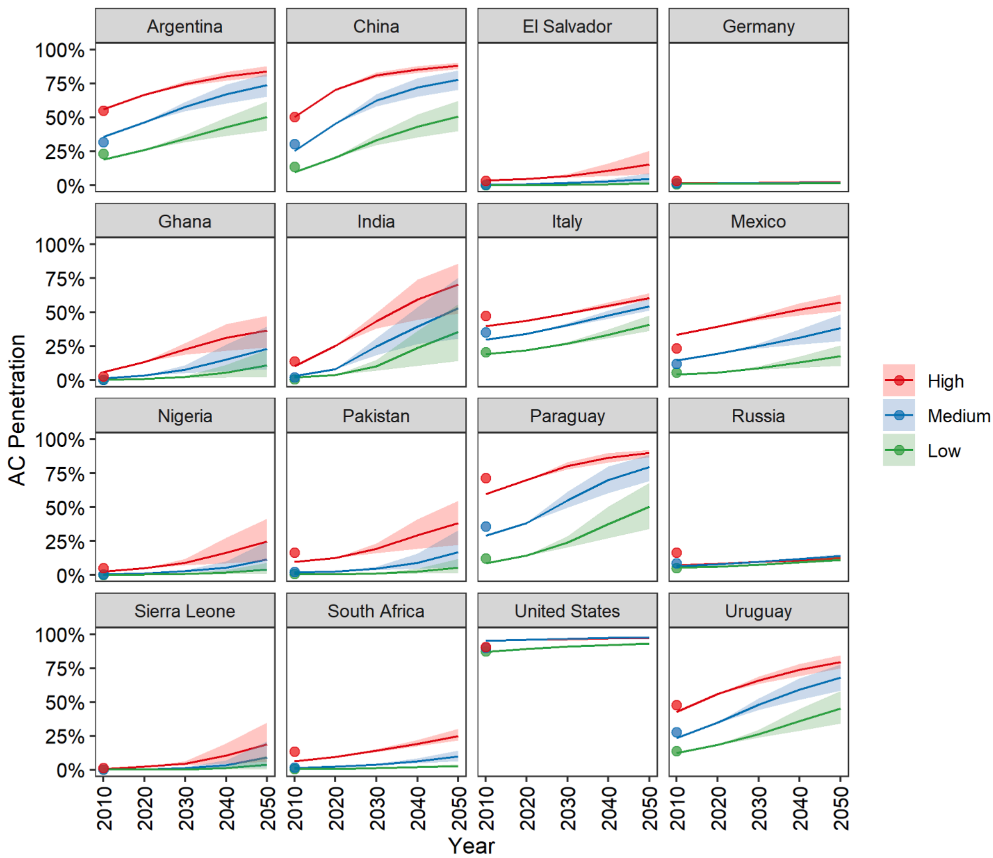

Fig. 7. Air Conditioning Penetration by Country by Income Tercile. **Notes:** This figure shows our predictions for air conditioning penetration over time and by income tercile. Colors denote income terciles and are calculated by country based on 2010. We plot the population-weighted average penetration level for each income tercile for 2010, 2020, 2030, 2040 and 2050. The central line plots the average across the five SSP scenarios and the confidence intervals are based on the maximum and minimum values for the five SSP scenarios.

2.7. *Mortality impacts*

In India alone increased saturation of air conditioning could save millions of lives, with these avoided deaths concentrated in the highest income tercile. Estimates from Burgess et al. (2017) imply that 630,000 people die each year in India from high temperatures, with this increasing to 1.4 million deaths per year by 2050 due to population growth and higher temperatures.

Our model predicts large increases in air conditioning in India over this time period. In our preferred model, the percentage of households in India with air conditioning increases from 12% in 2020, to 25% in 2030, to 38% in 2040, and to 50% in 2050. Our model predicts large and persistent differences in adoption between income groups. By 2050, for example, our model predicts 69% adoption in the highest income tercile, compared to 48% and 32% in the middle- and lowest- income terciles, respectively.

Previous research finds that air conditioning significantly mitigates heat-related mortality. Barreca et al. (2016) use 6+ decades of U.S. mortality data to show that U.S. heat-related mortality declined by 80% with the adoption of air conditioning. Assuming air conditioning will reduce heat-related mortality for air conditioning adopters in India by this same 80%, our estimates imply 550,000 fewer deaths per year by 2050, and 9.2 million fewer cumulative deaths between now and 2050, with a disproportionate number of these avoided deaths occurring among the highest income tercile. See supplementary materials for detailed calculations.

3. Discussion

Existing estimates point to large potential growth in global air conditioning, as well as the accompanying strain on the energy sector and growth in emissions (International Energy Agency, 2018). We use data at the individual household level to analyze how air conditioning adoption will vary by income and show that many of the world's poorest households will be exposed to increased heat associated with climate change without the important mitigating influence of air conditioning. We provide calculations that emphasize the differential implications this trend will have for mortality in the face of rising temperatures and show that a growing number of poorer households will succumb to heat-related mortality by 2050.

Previous work has also tied heat to slower learning and lower test scores (Park et al., 2020). With the richer households able to insulate their children from rising temperatures, and children of wealthier parents accumulating more human capital, this bodes ill for intergenerational income mobility. These are just two examples – mortality and learning – known to be affected by heat and mitigated with air conditioning, but there may well be additional impacts on poor households without air conditioning. In the short run, as the current global recession brought on by the coronavirus pandemic stalls income growth, the gap between rich households, who already own air conditioners, and poor households, who are not yet able to buy them, is widening.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gloenvcha.2021.102299.

References

Auffhammer, Maximilian, Baylis, Patrick, and Hausman, Catherine H. 2017. Climate Change is Projected to Have Severe Impacts on the Frequency and Intensity of Peak Electricity Demand Across the United States. Proc. Natl. Acad. Sci., 114(8): 1886–1891.

Barreca, Alan, Clay, Karen, Deschenes, Olivier, Greenstone, Michael, Shapiro, Joseph S., 2016. Adapting to climate change: the remarkable decline in the u.s. temperature-mortality relationship over the twentieth century. J. Pol. Econ. 124 (1), 105–159.

Biardeau, Léopold T., Davis, Lucas W., Gertler, Paul, Wolfram, Catherine, 2020. Heat Exposure and Global Air Conditioning. Nature Sustainability 3 (1), 25–28.

Biddle, J., 2008. Explaining the Spread of Residential Air Conditioning, 1955–1980. Explor. Econ. Hist. 45 (4), 402–423.

Burgess, Robin, Deschenes, Olivier, Donaldson, Dave and Greenstone, Michael. 2017. Weather, Climate Change and Death in India. Working Paper.

Carleton, Tamma, Delgado, Michael, Greenstone, Michael, Houser, Trevor, Hsiang, Solomon, Hultgren, Andrew, Jina, Amir, Kopp, Robert E., McCusker, Kelly, Nath, Ishan, et al. 2018. Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits. University of Chicago Working Paper.

Davis, Lucas W., Gertler, Paul J., 2015. Contribution of air conditioning adoption to future energy use under global warming. Proc. Nat. Acad. Sci. 112 (19), 5962–5967.

Gertler, Paul J., Shelef, Orie, Wolfram, Catherine D., Fuchs, Alan, 2016. The demand for energy-using assets among the world's rising middle classes. Am. Econ. Rev. 106 (6), 1366–1401.

Heal, Geoffrey, Park, Jisung, 2016. Temperature stress and the direct impact of climate change: a review of an emerging literature. Rev. Environ. Econ. Pol. 10 (2), 347–362.

International Energy Agency. 2018. The Future of Cooling: Opportunities for Energy-Efficient Air Conditioning. International Energy Agency.

Mansur, Erin T., Mendelsohn, Robert, Morrison, Wendy, 2008. Climate change adaptation: a study of fuel choice and consumption in the U.S. energy sector. J. Environ. Econom. Manage. 55 (2), 175–193.

Park, R. Jisung, Goodman, Joshua, Hurwitz, Michael, Smith, Jonathan, 2020. Heat and Learning. Am. Econom. J.: Econom. Pol. 12 (2), 306–339.

Rapson, David, 2014. Durable goods and long-run electricity demand: evidence from air conditioner purchase behavior. J. Environ. Econom. Manage. 68 (1), 141–160.

Sailor, David J., Pavlova, A.A., 2003. Air conditioning market saturation and long-term response of residential cooling energy demand to climate change. Energy 28 (9), 941–951.

Shah, Nihar, Wei, Max, Letschert, Virginie, and Phadke, Amol. 2015. Benefits of Leapfrogging to Super-Efficiency and Low Global Warming Potential Refrigerants in Room Air Conditioning. Lawrence Berkeley National Laboratory Working Paper.

Shah, Nihar, Khanna, Nina, Karali, Nihan, Park, W., Qu, Yi, and Zhou, Nan. 2017. Opportunities for Simultaneous Efficiency Improvement and Refrigerant Transition in Air Conditioning. Lawrence Berkeley National Laboratory Working Paper.

Wenz, Leonie, Levermann, Anders, Auffhammer, Maximilian, 2017. North–south polarization of european electricity consumption under future warming. Proc. Nat. Acad. Sci. 114 (38), E7910–E7918.

Wolfram, Catherine, Shelef, Orie, Gertler, Paul, 2012. How will energy demand develop in the developing world? J. Econom. Perspect. 26 (1), 119–138.