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Heat exposure and global air conditioning

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Air conditioning adoption is increasing dramatically worldwide as incomes rise and average temperatures go up. Using daily temperature data from 14,500 weather stations, we rank 219 countries and 1,692 cities based on a widely used measure of cooling demand called total cooling degree day exposure. India, China, Indonesia, Nigeria, Pakistan, Brazil, Bangladesh and the Philippines all have more total cooling degree day exposure than the United States—a country that uses 400 terawatt-hours of electricity annually for air conditioning.

Air conditioner sales are booming worldwide, especially in warm countries with growing economies. For example, Thailand, Indonesia and Vietnam increased air conditioner sales by 60, 129 and 159%, respectively, over the past 5 years according to data from Euromonitor International. As is the case with many durable goods, air conditioner adoption follows an 'S'-like pattern[1]. At low levels of income adoption, rates are near zero, but then as incomes rise, adoption can spike dramatically[2,3]. Many low- and middle-income countries are approaching the steep part of this S-curve, and so are poised to experience rapid air conditioner adoption[4].

This is mostly good news. Air conditioning brings relief on hot days, makes people more comfortable and increases productivity[5]. During extreme heat events, air conditioning can make the difference between life and death[6,7]. In the United States, heat-related mortality decreased more than 70% with the spread of air conditioning, saving an estimated 20,000 lives each year[8].

At the same time, meeting this increase in air conditioning poses an enormous challenge. A typical air conditioner uses 20 times more electricity than a ceiling fan, so air conditioning growth can significantly increase total electricity consumption. In the United States alone, air conditioning uses 400 terawatt-hours of electricity annually, representing 17% of total residential electricity consumption and 12% of total commercial electricity consumption (see Supplementary Information Section 1.5 for details).

Recent studies have also emphasized the role of air conditioning in driving peak electricity demand[9,10]. Growth in air conditioning increases the intensity and frequency of peak events, requiring large investments in electricity generation and transmission infrastructure[11]. Energy suppliers need accurate predictions about where and when air conditioning adoption will occur if this increased demand is going to be met efficiently.

Moreover, most electricity worldwide continues to be generated using fossil fuels. Thus, growing air conditioner adoption could mean hundreds of millions of tonnes of increased carbon dioxide emissions[12]. In addition, the refrigerants used in air conditioning are themselves a potent greenhouse gas. Predicting future demand for air conditioning is crucial for the recent Kigali Agreement, which seeks to significantly reduce the use of hydrofluorocarbons[13].

In this paper, we compile recent data on population and temperature—two key determinants of potential air conditioning use. We use 10 years of daily data from 14,500+ global weather-monitoring stations to calculate cooling degree days (CDDs) for 219 countries and 1,692 cities. We combine these weather data with highly disaggregated population measures to calculate a measure of CDDs that reflects the climatological conditions where people live.

We then multiply population-weighted CDDs by population to get a measure of the total CDD exposure in each country and city. This is the total number of CDDs experienced annually by a country's (or city's) population. For example, a country with 1,000,000 people and 3,000 average annual CDDs would have a total CDD exposure of 3 billion.

This measure has been used in previous studies to quantify air conditioning potential[14,15]. However, we avoid such an interpretation because this measure ignores a large number of economic, demographic and technological factors. For example, this measure scales linearly with population, and thus ignores cross-country differences in household size. This imperfect metric nonetheless provides a valuable first step and a jumping-off point for more comprehensive analyses.

Results

Figure 1 shows a plot of our global CDD estimates. Vast areas of the world are orange and yellow, indicating 3,000+ and even 4,000+ CDDs annually. The map highlights Africa, the Middle East, India and Southeast Asia as the areas with the most extreme high temperatures. The highest CDDs on the planet are found in Northern Africa along a horizontal band passing through Mauritania, Mali, Niger, Chad and Sudan.

Large areas of the world are also purple and black, indicating fewer than 1,000 CDDs annually. This includes many of the highest-income areas of the world, including Western Europe, the United States, Canada, South Korea and Japan. In this paper, we focus on CDDs, but for areas above 35.0° latitude, heating degree days are at least as important as CDDs[10,16,17].

Table 1 ranks the top ten countries globally by total CDD exposure. India is at the top of the list with 1.3 billion people and 2,848 annual CDDs. Strikingly, India represents 28% of total global CDD exposure, with 14 times the CDD exposure of the United States and more than twice the CDD exposure of any other country. The top four countries (India, China, Indonesia and Nigeria) have almost half of the total global CDD exposure.

The list is dominated by low- and middle-income countries with warm climates. Except for the United States, all of the countries in the top ten have an annual gross domestic product per capita under US$10,000. There are eight countries with more total CDD exposure than the United States, many of which have substantially smaller populations, such as the Philippines, with only one-third of the population but four times the CDDs. Except for China, all of the countries in the top ten have at least twice as many CDDs as the United States.

Our CDD estimates are population weighted and thus reflect where people live in each country. As we show in the Supplementary

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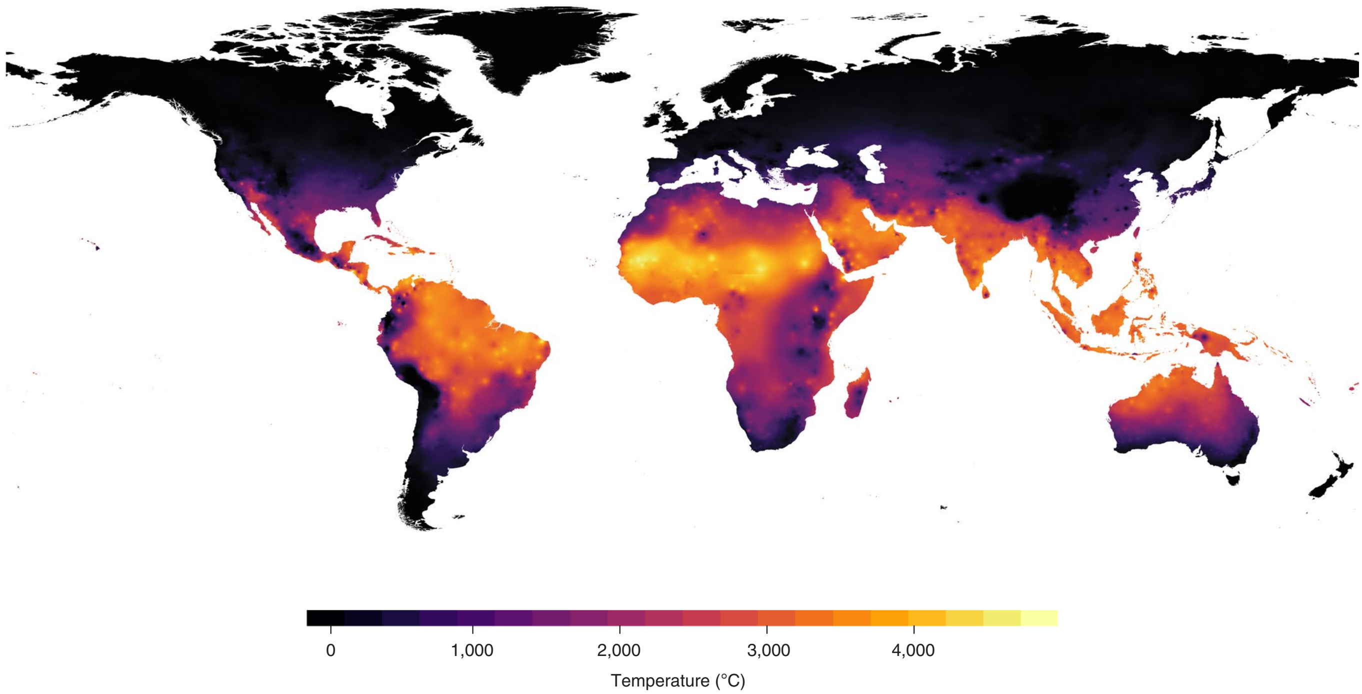

Fig. 1 | Global CDDs. Average annual CDDs for the period 2009–2018. We calculated CDDs as the sum of the daily mean temperatures above 18.3 °C (65 °F). The underlying temperature data were drawn from 14,500+ land-based monitoring stations tracked by the US National Climatic Data Center. The resolution is 5 km × 5 km.

Table 1 | Rankings by total CDD exposure

	Country/city	Population (in millions)	Population-weighted annual CDDs	Product of population and CDDs (in billions)	Global share (%)
Top ten countries					
1	India	1,309	2,848	3,728	28
2	China	1,397	1,009	1,410	10
3	Indonesia	258	3,284	848	6
4	Nigeria	181	3,429	621	5
5	Pakistan	189	2,504	474	4
6	Brazil	206	2,108	434	3
7	Bangladesh	161	2,644	426	3
8	Philippines	102	3,266	332	2
9	United States	320	867	277	2
10	Vietnam	94	2,777	260	2
Top ten cities					
1	Mumbai, India	21.0	3,544	74.6	0.6
2	Delhi, India	25.7	2,831	72.8	0.5
3	Dhaka, Bangladesh	17.6	2,955	52.0	0.4
4	Karachi, Pakistan	16.6	3,108	51.6	0.4
5	Manila, Philippines	12.9	3,572	46.2	0.3
6	Kolkata, India	14.9	3,047	45.3	0.3
7	Lagos, Nigeria	13.1	3,227	42.3	0.3
8	Tokyo, Japan	38.0	1,040	39.5	0.3
9	Jakarta, Indonesia	10.3	3,772	38.9	0.3
10	Bangkok, Thailand	9.3	3,995	37.0	0.3

This table ranks the top ten countries and cities worldwide by total CDD exposure (that is, the product of population and annual CDDs). Country and city ('urban agglomeration') population data are from the United Nations. Annual CDDs were calculated as the sum of daily average temperatures above 18.3 °C. We report annual average CDDs for the period 2009–2018. For countries, we calculated population-weighted CDDs using global population estimates at the 5 km × 5 km level from the Gridded Population of the World project. Temperature data are from 14,500+ land-based monitoring stations tracked by the US National Climatic Data Center. See the Supplementary Information for a complete list of sources and additional details.

Information Section 2.3, population weighting is particularly consequential for large countries with diverse geographies. For example, we show that people in Brazil tend to live in relatively cool areas, while people in China tend to live in relatively warm areas.

A novel feature of our analysis is that we also used a bootstrap simulation to calculate 95% confidence intervals for all estimates. Previous related analyses ignored sampling variation and thus overstated the certainty of their results. As we show in Supplementary Tables 2–4, population-weighted CDDs are precisely estimated for countries with a large number of weather-monitoring stations, including most of the countries in the top ten. Notably, there is no overlap in the top four countries' confidence intervals, and sampling variation is unlikely to meaningfully change the ordering of the top ten countries.

Table 1 also ranks the top ten cities worldwide. India again takes a prominent role, with three cities in the top ten. Mumbai, by itself, has total CDD exposure equal to 25% of the total CDD exposure for the United States. The list is dominated by cities in low- and middle-income countries. The only city in the top ten from a high-income country is Tokyo, due primarily to its very large population, and the top US city (Miami) appears at number 39. See Supplementary Tables 2–7 and the Supplementary Data for a complete list of countries and cities.

Our CDD estimates are a significant improvement on previous estimates. Several related studies[4,14,15,18,19] used CDD estimates from a World Resources Report published in 2003[20]. However, these estimates are quite dated, based on data from 1977–1991. We show in Supplementary Figure 4 that our CDD estimates are considerably higher for virtually all countries, reflecting the global warming that has occurred over this period. According to the National Oceanic and Atmospheric Administration, the ten hottest years in recorded history globally have all occurred since 1991, so incorporating recent temperature data is crucial.

Discussion

Almost 3 billion people (40% of the world's population) live in the tropics, mostly in low- and middle-income countries, and most are currently without air conditioning. Our estimates of total CDD exposure point to the enormous potential growth in air conditioning in these countries. India, by itself, has an almost unfathomable amount of potential demand for cooling, both because it is so hot and because so many people live there. However, our rankings also feature many middle-income countries, such as China, Indonesia, Brazil and the Philippines, all of which are poised to dramatically increase air conditioner use in the near future.

Our paper contributes to a small amount of existing literature on global demand for air conditioning. Previous studies have shown that electricity consumption increases on hot days[21,22], and that there is a positive correlation between income and having an air conditioner[4,18,19,23]. Several previous studies have focused on India[24–26], with relatively few global analyses[14,18].

Much is left to be done. As we emphasized above, CDD exposure is a highly imperfect measure of air conditioning potential. For example, we explained that this measure scales linearly with population, and thus ignores cross-country differences in household size. There are also cross-country differences in building size, construction methods, materials, urban form and many additional economic, demographic and technological factors that are not accounted for with CDD exposure.

Another important factor is access to electricity. Air conditioning adoption is being made possible, in part, due to increases in electrification. For example, in Bangladesh, electricity now reaches 80% of the population, up from 20% in 2000. In Indonesia, electricity now reaches nearly 95% of the population, up from 50% in 2000. There are still nearly 1 billion people worldwide without access to electricity, but this number is expected to decrease significantly over the next decade[27].

What air conditioning adoption will mean for electricity consumption depends on technological change. If air conditioners can be made more energy efficient, due to induced innovation or economies of scale[28,29], this could reduce the energy consumption impacts considerably. Similarly, if growth in renewables can reduce the carbon intensity of electricity, this could mitigate the carbon dioxide impacts[12].

Air conditioning adoption and usage also depend on prices. Putting a price on carbon dioxide emissions would increase electricity prices and thus slow air conditioning adoption and encourage energy efficiency. Carbon policy would also incentivize less energy-intensive forms of cooling. Evaporative cooling, for example, is a viable alternative in many parts of the world. Making homes better insulated and using natural shade, cool roofs and passive cooling systems are also lower-energy approaches to cooling[30].

Methods

CDDs are a widely used measure of cooling demand. We calculated CDDs as the sum of daily mean temperatures above 18.3 °C (65 °F). For example, a day with an average temperature of 28.3 °C has ten cooling degrees, whereas a day with an average temperature below 18.3 °C has zero cooling degrees. This particular threshold of 18.3 °C has been widely used in previous studies (see the Supplementary Information Section 1.1 for references).

Our estimates vary predictably with alternative temperature thresholds. In Supplementary Tables 8 and 9, we report results for 15.6 °C (60 °F), 21.1 °C (70 °F) and 23.9 °C (75 °F). Total global CDD exposure is 40% higher under the first threshold, and 34 and 62% lower under the third and fourth thresholds, respectively. The ranking of the top four countries is unchanged by the chosen threshold and, overall, the ranking of the top ten countries remains quite stable under all specifications.

After calculating CDDs for each day, we summed across all days in the calendar year to calculate annual CDDs. The annual measure thus reflects both the number of days with hot weather and the intensity of heat on those days. Our calculations used average daily temperatures from 14,500+ land-based monitoring stations worldwide tracked by the US National Climatic Data Center.

We ignored humidity. Research has shown that both temperature and humidity impact human mortality[31] and there are several metrics, such as the US National Oceanographic and Atmospheric Administration's heat index, that combine temperature and humidity to give a more true measure of perceived thermal comfort.

We combined our CDD estimates with global population estimates at the 5 km × 5 km level from the Gridded Population of the World project, to calculate population-weighted annual average CDDs for the period 2009–2018. We calculated weather information for this 5 km × 5 km grid using inverse distance weighting, and then aggregated up to regions, countries and cities using shapefiles and other geographic information from Natural Earth.

The Supplementary Information provides a detailed description of all of the data sources and methodologies, as well as additional descriptive information, results and robustness checks. For example, we calculated an alternative set of results using gridded temperature predictions from Berkeley Earth, thus addressing several potential concerns about data quality. Overall, the results from this and other alternative analyses are quite consistent with our baseline results.

Data availability

This research relies entirely on publicly available data. Detailed information on all sources is available in the Supplementary Information, and additional results and other materials are available in the Supplementary Data. Source data for Fig. 1 are provided with the paper.

Code availability

All code and related materials used in the analysis are available as Supplementary Software.

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Author contributions

All authors conceptualized the research. L.T.B. collected, processed and cleaned the data. L.T.B. constructed the figures and tables. All authors contributed to writing, reviewing and editing the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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