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# Impacts of a warmer world on space cooling demand in Brazilian households

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## ABSTRACT

Air Conditioning (AC) appliances are a highly effective adaptation strategy to rising temperatures, thus making future climate conditions an important driver of space cooling energy demand. The main goal of this study is to assess the impacts of climate change on Cooling Degree Days computed with wet-bulb temperature ($CDD_{wb}$) and household space cooling demand in Brazil. We compare the needs under three specific warming levels (SWLs) scenarios (1.5 °C, 2 °C and 4 °C) to a baseline with historically observed meteorological parameters by combining $CDD_{wb}$ projections with an end-use model to evaluate the energy requirements of air conditioning. The effects of the climate change were isolated, and no future expansion in AC ownership considered. Carbon dioxide ($CO_2$) emissions associated with AC energy demand are also calculated. Results show an increase in both average $CDD_{wb}$ and AC electricity consumption for the global warming scenarios in all Brazilian regions. The Northern region shows the highest increase in $CDD_{wb}$ (187% in $CDD_{wb}$ for SWL 4 °C), while the Southeast presents the highest AC energy consumption response (326% in the AC energy consumption for SWL 4 °C) compared to the baseline. At the national level, $CDD_{wb}$ and the AC energy consumption in all SWLs scenarios grow by 70%, 99% and 190%, respectively.

## 1. Introduction

Space cooling is the fastest growing energy use within the building sector, a sector that accounted for around 28% of total global energy-related carbon-dioxide (CO2) emissions and for approximately one third of global final energy use in 2018 [1]. In emerging economies, such growth is mostly associated with rising incomes [2], but also due to high temperatures and prolonged heat waves [2]. Thus, the potential increase in demand for space cooling, which has grown by more than three times between 1990 and 2018 [3], is a critical energy issue.

The use of space cooling technologies is an autonomous form of adaptation available to households and workers to minimize climate change impacts and maintain comfortable temperature levels at homes and workspaces. Air conditioners (ACs) for indoor cooling are relatively low-cost and a highly effective adaptation strategy [2]. However, adaptation to climate change through the use of cooling appliances will increase energy consumption and, depending on the energy mix, leading to higher GHG emissions [4,5], initiating in this way a positive feedback loop further amplifying future needs for adaptive measures [6,7]. Therefore, analyzing the consequences of temperature increase on energy demand is extremely important to determine possible climate change mitigation and/or adaptation interactions, as well as to enhance energy demand forecasts [8]. Furthermore, the use of more efficient cooling technologies could considerably reduce the energy consumption associated with increasing temperatures [9]. In this regard, policies to promote energy efficiency of AC appliances are important to build a sustainable future [10] and are object of new studies [11,12].

There are different approaches to analyze the effect of ambient air temperature on energy consumption. Numerous studies have explored the use of the Cooling Degree Days (CDD) indicator to understand the possible impacts of increased air temperature on cooling energy demand in buildings [10,13,14]. CDDs are defined as the cumulative sum of the positive differences between daily mean ambient air temperature and a base threshold temperature over a certain time period (e.g. month or year) [15]. Although this indicator does not consider climate parameters such as solar irra-

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diation or parameters regarding the building's envelope and type, it is commonly used as a proxy to calculate space cooling energy demand to maintain thermal comfort levels in residential and commercial buildings [16,17]. Some studies have applied top-down approaches, in which CDD data are merged with other relevant variables, such as income and energy prices, to provide a measurable final energy consumption results [7,18]. This approach requires the availability of long historical datasets and is usually used in comparison studies for different countries [19]. Other studies [20,21] have implemented a variant of CDD accounting for humidity, referred to wet-bulb CDD ($CDD_{wb}$). $CDD_{wb}$ essentially replaces outdoor air temperature or the dry-bulb temperature ($T_d$), with outdoor air temperature accounting for Relative Humidity (rh) computed using wet-bulb temperature ($T_{wb}$) [17].

However, other relevant factors, such as equipment efficiency, population size, AC appliance ownership, and building characteristics such as building materials, envelope and type, [2] also influence the energy demand for space cooling. A growing number of studies have been directed toward the use of CDD combined with other approaches to provide energy-related results [18,22,23]. Bottom-up models, or buildings detailed simulation models, are largely used for single country analyses. These models require a significant amount of detailed data [19]. This kind of approach is used to understand the role of building types on the demand for heating or cooling loads, or to understand the role of efficiency measures on total energy consumption, using the CDD as one modeling parameter [14,24,25].

Regarding geographical coverage, most studies have investigated the effects of climate change on cooling energy consumption in developed countries [4,26–29]. However, there are fewer studies that investigate the impact of air temperature on indoor cooling services and energy demand in emerging economies [9,30], and specifically in Brazil [7,25]. Regional studies are relevant for this kind of analysis given their greater granularity with respect to local climate and socioeconomic circumstances, which can be used to further explore regional differences [28]. This is particularly the case of Brazil, where the country's five geographical regions present different social-economic and climate patterns [7,25].

Brazil is a relevant case study, being a tropical developing country with a warm climate and an income driven rise in ownership of AC equipment. The country's AC ownership rate in the residential sector increased by 9% per year between 2005 and 2017, and is expected to continue to grow [31]. However, existing studies about the impacts of climate change on space cooling in Brazil assess the effects of air temperature and humidity on energy demand without considering different patterns of consumption and regional effects [7,25,32], or possible technological changes [12,33]. To date and to the authors' knowledge, no study has specifically analyzed Brazil with a focus on its regional particularities, less so by applying a hybrid methodology that integrates the use of CDDs and end-use modelling.

This paper assesses the impacts of climate change on thermal parameters, and how this would affect space cooling energy consumption in Brazilian households. Future climate projections from an ensemble of thirteen experiments of the HadGEM3-A 3.0 [34] and EC-EARTH3.1 [35] General Circulation Models (GCMs) under three Specific Warming Level (SWL) scenarios (1.5 °C, 2 °C and 4 °C) are used to assess the effect of climate change, *ceteris paribus*, on a static energy system for Brazil. The methodological approach is divided into two parts for each SWL scenario: (i) climate data analysis and calculation of $CDD_{wb}$; and (ii) the application of an end-use model to estimate total electricity demand for space cooling. The role of improved energy efficiency is also assessed and discussed to understand the extent to which it could avoid positive feedbacks from AC as an adaptation measure.

The structure of the paper is organized as follows. Section 2 describes the research methodology Sections 3 and 4 present the study's results and discusses its main findings and limitations, suggesting improvements for future work. The conclusions of the study are found in Section 5.

## 2. Methodology

The methodological procedure used in this study is articulated into two parts, which are summarized in Fig. 1 and detailed in the following subsections. The first part computes gridded/regional CDDs based on wet bulb temperature ($T_{wb}$), calculated using near-surface dry bulb temperature ($T_d$) and the relative humidity of the air (rh). By incorporating rh, $CDD_{wb}$ accounts for a better thermodynamic limit on human metabolic heat transfer [36], particularly relevant for humid regions like Brazil [17,21,20]. Although $CDD_{wb}$ do not contains information on human behavior nor on buildings' features for a precise estimation of cooling energy needs, it can provide a comparative measure of ambient thermal comfort [37], being a spatially explicit indicator of gross demand for space cooling.

We considered three scenarios of SWL describing different adaptation challenges and changes in future projected $CDD_{wb}$ relative to the baseline scenario – it indicates the locations where space cooling needs are projected to increase (or decrease). Based on $CDD_{wb}$ projections, we also compute dummy value matrices, here referred to as "on–off matrices", containing information about the number of days per year that cooling appliances need to be turned on in each municipality. The indication provided by the on–off matrices is used as an input for an end-use model to estimate the increase in space cooling electricity demand for the Brazilian residential sector, considering demography, appliance ownership, and efficiency rates.

### 2.1. Ambient thermal comfort indicator

#### 2.1.1. Dataset description

The study assessed a baseline scenario and three SWL scenarios assuming 1.5°C, 2°C and 4°C global average temperature increase when compared to pre-industrial levels. The data employed to calculate the $CDD_{wb}$ derived from two sources. The first data source includes historically observed meteorological variables and was obtained from the Global Land Data Assimilation System (GLDAS) [38]. The variables $T_d$ in degree Celsius (°C) and rh in percentage (%) were assembled from GLDAS at a daily timescale for the 1970–2009 period. They were used to elaborate the baseline scenario and to correct biases in future climate projections. GLDAS has global time series at a high spatiotemporal resolution (0.25° gridded at 3-hourly time steps [17,38]).

The second data source used refers to climate variables for each SWL scenario from the Helix project[1], which conducts simulations of present and future climate. The project uses two GCMs and their respective experiments: HadGEM3-A 3.0 (six experiments with a resolution of ~ 60 km) and EC-EARTH3.1-A (seven experiments with a resolution of ~ 40 km). Each experiment results in a different evolution of the average surface temperature over time, so the SWL period is defined by the year when global average temperature reaches the respective warming level (1.5 °C, 2 °C or 4 °C) plus and minus 15 years, resulting in a 30-year period for each scenario and each experiment. The variables retrieved from the Helix project database are maximum dry bulb air temperature ($Td_{max}$), minimum dry bulb air temperature ($Td_{min}$); and average rh, all at daily timescales. Data for the simulated historical period of 1981–2010 are also retrieved

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[1] For more information, see https://helixclimate.eu/

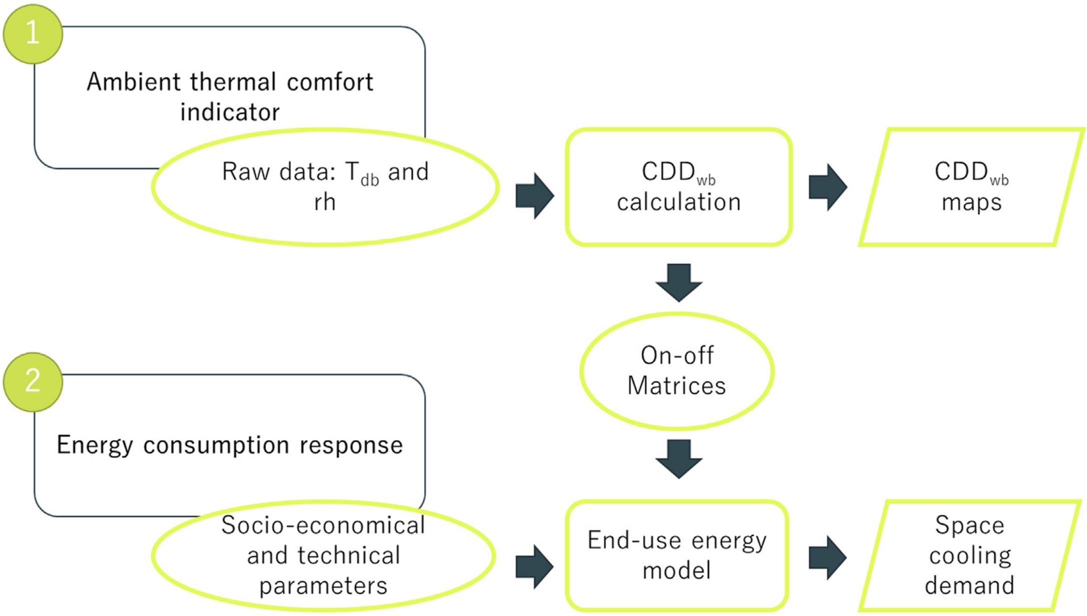

**Fig. 1.** Flowchart of the study method. Note: $T_d$ is the average daily near-surface dry bulb temperature (°C), and rh the average daily near-surface relative humidity (%). $CDD_{wb}$ is measured in °C-days.

from this database for the bias correction procedure, which is further detailed in the following section.

### 2.1.2. Climate data analysis and computation of $CDD_{wb}$

Due to limitations in climate models, such as spatial resolution constrains, simplified physics and thermodynamic processes, data simulated by GCMs are often biased [39]. Thus, projected climate data were analyzed and treated to remove GCM biases before the $CDD_{wb}$ calculation. The bias correction was based on the raw climatic data of $T_d$ and rh from GLDAS [17], using a methodology of nudging or simple bias correction. It calculates the variation between the observed historical[2] data and the simulated historical data, which is then added to the modeled projections of future SWL scenarios [40]. Specifically, for the rh data, as the values are limited between zero and 100%, a restriction is imposed to keep parameter values within this range after calibration. The grid conversions of GCMs (coarser resolution) to GLDAS (0.25°), and the subsequent data operations involved in bias corrections were performed using the Climate Data Operators (CDO) software [41]. The bias corrected $T_d$ and rh were used to calculate the average $T_{wb}$ for the baseline and for each GCM experiment for each SWL scenario using the Eq. (1), following Stull [42]:

$$T_{wb} = T_d * atan(0.152 * (rh + 8.314)^{0.5}) + atan(T_d + rh) - atan(rh - 1.676) + 0.00392 * rh^{1.5} * atan(0.023 * rh) - 4.686 \quad (1)$$

where $T_{wb}$ is the wet bulb temperature (°C), $T_d$ is the average daily dry bulb temperature (°C) calculated as an arithmetic average of the maximum and the minimum temperature (°C), and *rh* is the relative humidity in %. The *atan* symbol stands for the arctangent operator. A detailed explanation of the physical coefficients values in the equation is available in Stull [32].

Following the computation of $T_{wb}$ on the 6 (7) individual ensemble members of HadGEM3-A 3.0 (EC-EARTH3.1-A), we extract the median $T_{wb}$ across the combined 13 ensemble runs for each SWL. The subsequent single daily time series spanning 30 years for each SWL scenario was then used to compute the long-term daily averages, thus resulting in a single daily time series of a representative future year, for each SWL scenario.

Thereafter, the calculation of $CDD_{wb}$ for the baseline and each SWL scenario was performed. The methodology to compute the $CDD_{wb}$ considers the daily average of the $T_{wb}$ and a reference temperature ($T_{base}$). The $CDD_{wb}$ calculation follows [17] by using an adapted equation of the American Society of Heating, Refrigerating and Air Conditioning [15], presented in Eq. (2) as:

$$CDD_{wb} = \sum_{i=1}^{n} (T_{wb} - T_{base})^{+} \quad (2)$$

where $T_{base}$ is representative of a threshold value for the use of air conditioning in °C, and '+' indicates that only positive values are considered for summation over the time period n (typically months or year).

Different studies assume different values for $T_{base}$, typically ranging from 18 °C to 25 °C [17]. In this work, the reference temperature adopted, on a conservative basis, is 24 °C. It must be noted though that like $T_d$, $T_{wb}$ is also measured in °C. Typically for a given environmental condition, by definition, $T_{wb}$ is lower than $T_d$. The accumulated monthly or annual $CDD_{wb}$ therefore also register lower degree-days compared to CDD (based on $T_d$). The reference temperature chosen in this study can be therefore considered as being equivalent to a higher $T_{base}$ if measured on a dry-bulb scale. For a detailed discussion, readers are guided to [17].

$CDD_{wb}$ maps were created for the baseline and SWL scenarios for visual analysis of the gross cooling needs over the Brazilian territory due to the different warming levels using the QGIS 3.4 software [43]. Therefore, we define in this work $CDD_{wb}$ as an index for ambient thermal comfort needs of a region.

Matrices with dummy values are generated for each scenario, in which "one" is attributed to the days when $T_{wb}$ is greater than $T_{base}$ and "zero" otherwise. These matrices contain information about the days in the representative year of each scenario when a cooling device in a given location is used to reach a given indoor temperature. In other words, it provides information on the days of use of AC appliances, which are an input for the end-use energy demand model. Hereafter, these matrices are denominated "on–off matrices".

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[2] For more information, see Mistry (2019) [17]

### 2.2. Energy consumption response

#### 2.2.1. Space cooling energy demand

An end-use model is developed and applied to assess the energy consumption response to changes in temperature and relative humidity. The model considers demographic and socioeconomic characteristics and uses outputs from the $CDD_{wb}$ calculation, through "on–off matrices", to project air conditioning electricity consumption for Brazilian households.

Demographic characteristics are important when assessing the impact of climatic variables on energy consumption, especially because of the particularities of Brazil. The country has an extensive area with an unequal population density [44,45]. While the country has an average population density of 22.4 people per square kilometer, the country's Southeast region has an average density of 139.3 against 4.1 people per square kilometer in North region (Table 1). Therefore, ambient thermal comfort needs, indicated by $CDD_{wb}$, in a location may not be translate into relevant energy consumption if local population is small.

**Table 1**
Population per square kilometer in Brazil.

| Region | Population | Total area (km$^2$) | Population density |
|---|---|---|---|
| North | 15,864,454 | 3,851,281 | 4.1 |
| Northeast | 53,041,263 | 1,551,991 | 34.2 |
| South | 27,386,891 | 924,565 | 29.6 |
| Southeast | 80,364,410 | 576,743 | 139.3 |
| Midwest | 14,058,094 | 1,606,239 | 8.8 |
| Brazil | 190,715,112 | 8,510,821 | 22.4 |

Source: [44,45].

The same geographical differences are observed when considered socioeconomic characteristics [46,47]. In this paper this heterogeneity is reflected by the differences observed in ownership rate of an AC unit across regions, that is dependent of cultural and economic household characteristics, besides climate parameters [7].

End-use energy models can be applied at different geographical levels, depending mostly, on the data availability [19]. In our study, gridded weather data are available at a high granularity. Despite this, technical parameters for the AC units are only available for Brazilian macro-regions.

As the energy model used here relies on parameters at the regional level, the average daily dry bulb temperature ($T_d$) and on–off matrices were first converted from grids to the Brazilian municipalities' polygons[3]. Next, $T_d$ data for each of the 5,569[4] Brazilian municipalities were crossed with on–off matrices data, that indicates the days when an AC unit is in use for ambient cooling. Municipalities data were then aggregate to the macro regional[5] level using a temperature-population weighted methodology for days of use. Using this approach, the ambient temperature ($T_{amb}$) for each Brazilian macro region was calculated for the end-use model.

Subsequently, the thermal load of AC appliances was calculated. The thermal load, or cooling load, is proportional to the heat transfer needed to achieve an indoor set temperature. The higher the outdoor temperature, the more energy air conditioning consumes to guarantee the same indoor temperature set by the user [48]. A set of 20 thermal loads for representative AC devices were calculated according to four scenarios (baseline plus SWLs) and five geographical regions in Brazil. The calculation was inspired by [49] and follows Eqs. (3) and (4) bellow:

$$Q_{i,j} = Q_s * L_{i,j} * h \tag{3}$$

in which:

$$L_{i,j} = \sum\nolimits_{d=1}^{365} l_{i,j} = \sum\nolimits_{d=1}^{365} \frac{(T_{amb,i,j} - T_{int})}{(T_{amb,s} - T_{int,s})} \tag{4}$$

where, $Q$ is the thermal load in kWh; $i$ is the scenario (baseline and SWL); $j$ is the geographical region in Brazil; $Q_s$ is the nominal thermal load of an appliance in standard conditions in kWh; $L$ is the annual thermal load correction[6]; $h$ is the hours of use; $l$ is the daily thermal load correction factor; $T_{amb}$ is the average external/outdoor temperature in °C; $T_{int}$ is the average indoor temperature of use (set as 24 °C); $T_{amb,s}$ is the external temperature on standard test conditions (set as 35 °C); and $T_{int}$ is the indoor temperature of use on standard performance test conditions (set as 26.7 °C)[7] [49].

The thermal load correction factor ($l$), is calculated for those days in each scenario when an AC appliance is used to reach a set indoor temperature, given by the on–off matrices. Temperatures difference effects on the annual load ($L$) depends on the annual days of use and the outside temperature ($T_{amb}$).

The effects of different external temperatures are isolated using one representative standard AC device[8] for each of the 20 cases. In each case, the increase in the thermal load of the representative AC is a result of different estimated ambient temperature scenarios. The same logic is assumed for by the Unit Energy Consumption (UEC), Eq. (5). Considering the same Coefficient of Performance (COP) – standardized technical parameter –, the increase in thermal load is equal to the increase in energy needs [33,50]:

$$UEC_{i,j} = \frac{Q_{i,j}}{COP} \tag{5}$$

Finally, the total air conditioning electricity consumption for the different temperature scenarios and geographical Brazilian regions was calculated following Eq. (6) [6,7]:

$$EC_{airconditioning,i,j} = UEC_{i,j} * pop_j * ownershiprate_j \tag{6}$$

where, $EC_{airconditioning}$ is the air conditioning electricity consumption; $i$ is the scenario (baseline and SWL); $j$ is the regions; $pop$is the population; and $ownershiprate$is the percentage of households with AC equipment.

The parameters used in Eq. (6) are presented in Table 2. The daily hours of use were based on [31]. Capacity of the representative AC unit was set as 2.6 kW and COP set as 3.02 W/W [33]. Ownership rates for each region were taken from [47]. These values represent the average parameters for a representative AC unit in Brazil in 2000–2010, period of our historical temperature data.

Recent studies show that the power capacity of an average AC unit for Brazil increased in the last years [31,49], especially considering the penetration of split AC technology replacing window ACs [47]. Also, in 2020, there was an update in the Brazilian labeling program for AC units. The new metric considers a seasonal efficiency index, replacing the earlier COP metric [51], and was adopted to account for the increased penetration of the inverter AC technology [52,53]. The inverter technology improves the efficiency of an AC unit since it can work on full or partial loads,

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[3] A zonal statistics-based script was developed in the R software [46] for that purpose, using the median values of the pixels inside the municipal polygons.

[4] Brazil as of present has 5,572 municipalities [44], but three of them (Raposa, Lucena and Fernando de Noronha) were not independent municipalities during the database's timeframe.

[5] Brazil officially divided into 5 macro geographical regions: North, Northeast, South, Southeast and Midwest. This macro region definition is been used since 1970 [44].

[6] The correction factor considers air-conditioner operation at different external temperatures in comparison to the reference external temperature of 35°C, applied in air-conditioners performance tests.

[7] Air conditioning performance depends on dry temperature effects difference, the effects of humidity are not important for the appliance operation.

[8] Same standard technical parameters, same internal temperature set and same threshold temperature of decision to use.

**Table 2**
Technical and socio-economic parameters for electricity air conditioning household consumption for base case and sensitivity.

| Region | Base case | | | Sensitivity | | |
|---|---|---|---|---|---|---|
| | Ownership rate (%) | COP (W/W) | Q (kW) | Ownership rate (%) | States considered | COP (W/W) |
| North | 14.8 | 3.02 | 2.6 | 29.2 | Amazonas | 4.75 |
| Northeast | 5.1 | | | 10.0 | Piauí | |
| South | 8.2 | | | 19.1 | Santa Catarina | |
| Southeast | 13.0 | | | 26.6 | Rio de Janeiro | |
| Midwest | 7.5 | | | 12.9 | Mato Grosso do Sul | |

Source: [31,33,47]

and this can only be accessed with the use of a seasonal metric [2]. The Cooling Seasonal Performance Factor (CSPF), now adopted in Brazil as a new energy efficiency' label, will be able to better reflect the new AC appliance fleet[9].

As our methodology to define energy demand considers power consumption variation according to external temperature variations, it can be considered aligned with CSPF methodology. For that, we chose to keep COP as a single historical metric and do not change to the new CSPF standard. This approach helps us to isolate the impact of temperature increase in the energy consumption, when comparing climate parameters observed historically with future scenarios. So, the chosen AC unit did not suffer variations during the scenarios and remained the same as in the average for the historical period considered.

Finally, the associated GHG emissions from the projected additional electricity consumption were calculated for each SWL scenario applying three different annual electricity grid emission factors for Brazil. GHG emissions due to electricity consumption depends on the fuel mix used for electricity generation. In the case of Brazil, the grid emission factor varies annually, largely due to the variability of hydropower [54]. Therefore, we tested the impact of three different grid emission factors, assuming the average, lowest and the highest historical emission factor in the period ranging from 2015 to 2019 (respectively 0.0896 $tCO_2$/MWh, 0.0246 $tCO_2$/MWh and 0.1355 $tCO_2$/MWh [54]).

### 2.2.2. Sensitivity analysis

Energy efficiency is considered an important measure to reduce space cooling energy demand [53,55]. The use of efficient appliances could help avoid the feedback loop associated with global warming scenarios [2].Therefore, for a given thermal load requirement, higher AC COP values have the potential to reduce air conditioning energy demand. A sensitivity analysis for the energy efficiency of AC appliances was thus deemed necessary and conducted as explained below.

According to the Brazilian labeling program [56], appliances can be identified according to their efficiency level. The most efficient appliances available in the market are classified as label "A", while label "D" is granted to the lowest efficiency devices. The COP values for ACs available in the market in 2017 vary between a minimum requirement of 2.30 W/W (label D) and 3.23 W/W (label A) [56]. Such a range is close to the COP mean value found for international markets, 3.0 W/W [2]. However, when compared to the best available technologies worldwide, these technologies are still lagging. The best AC international devices present COP values above 6.0 W/W, almost twice the value found in the Brazilian market. The new labels defined in Brazil in 2020 come closer to the best available technology observed internationally. For 2025, an inverter AC with label "A", considering a seasonal metric (CSPF), will have a minimum efficient requirement of 7.00 W/W. However, window AC appliances should not have a significant increase in its standard [51]. Considering this new seasonal metric, AC sales in Brazil would be better aligned to the best technology available in the world [2]. Nevertheless, the average efficiency of existing appliances will also depend on the existing stock and its lifespan [49,57].Taking this into consideration, efficiency improvement scenarios [2,58] and a market survey led by the Brazilian Energy Research Company [31] were analyzed to set a value for the sensitivity analysis. A COP value of 4.79 W/W was assumed, an almost 60% increase, in line with the best AC available in Brazil [56]. It is important to highlight, that in the last 12 years there has been only an increase of 8% in average AC efficiency levels in Brazil [31].

We also tested the sensitivity of result to different ownership rates. In Brazil there was a significant increase in AC ownership rate between 2005 and 2017, of 9% per year [31]. This was mostly due better affluence conditions observed in the country [313359]. Looking into the future, higher temperatures will be an additional factor increasing AC ownership rates even more [7]. To capture the temperature and economic-related heterogeneity of ownership rates, the highest AC ownership rate among the States in a specific region was selected as benchmark for that region[10] (Table 2).

For both sensitivity analyses, the emissions associated with energy consumption were calculated. Once again, three different emissions grid values were chosen to account for the uncertainty of these parameter.

## 3. Results

### 3.1. Ambient thermal comfort and energy consumption response

Fig. 2 shows the distribution of $CDDs_{wb}$ over the Brazilian territory for the historically observed data and the SWL scenarios. Municipalities with population higher than half a million people in 2010 are highlighted in circles. Results show that the highest growth in $CDD_{wb}$ occurs in locations with low population density. For instance, the two largest cities of Brazil – São Paulo and Rio de Janeiro, both in the Southeast region – are relatively less impacted in the SWL scenarios than municipalities in the North region, which have a much smaller population density (Table 1). The exception to that trend is the city of Manaus, which is in the center of the Amazon rainforest, in the North region of the country, and has the seventh largest population of Brazil [45].

Fig. 3 shows the monthly distributional effect of temperature in household energy use for Brazilian geographical regions. It shows the number of days per month that space cooling is needed in a region to reach the threshold ambient thermal comfort temperature, given by the average of all municipalities contained in that region. This result comes from the municipalization of the on–off matrices data.

The different Brazilian regions maintain their seasonal behavior for AC use in the projecting SWL scenarios. The curve shows a val-

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[9] Air conditioner producers and retailers have until 2025 to adapt to the new metric [51].

[10] The Federation Units are a more aggregate geographical level when compared to the municipalities, but unfortunately, ownership data for municipalities were not available.

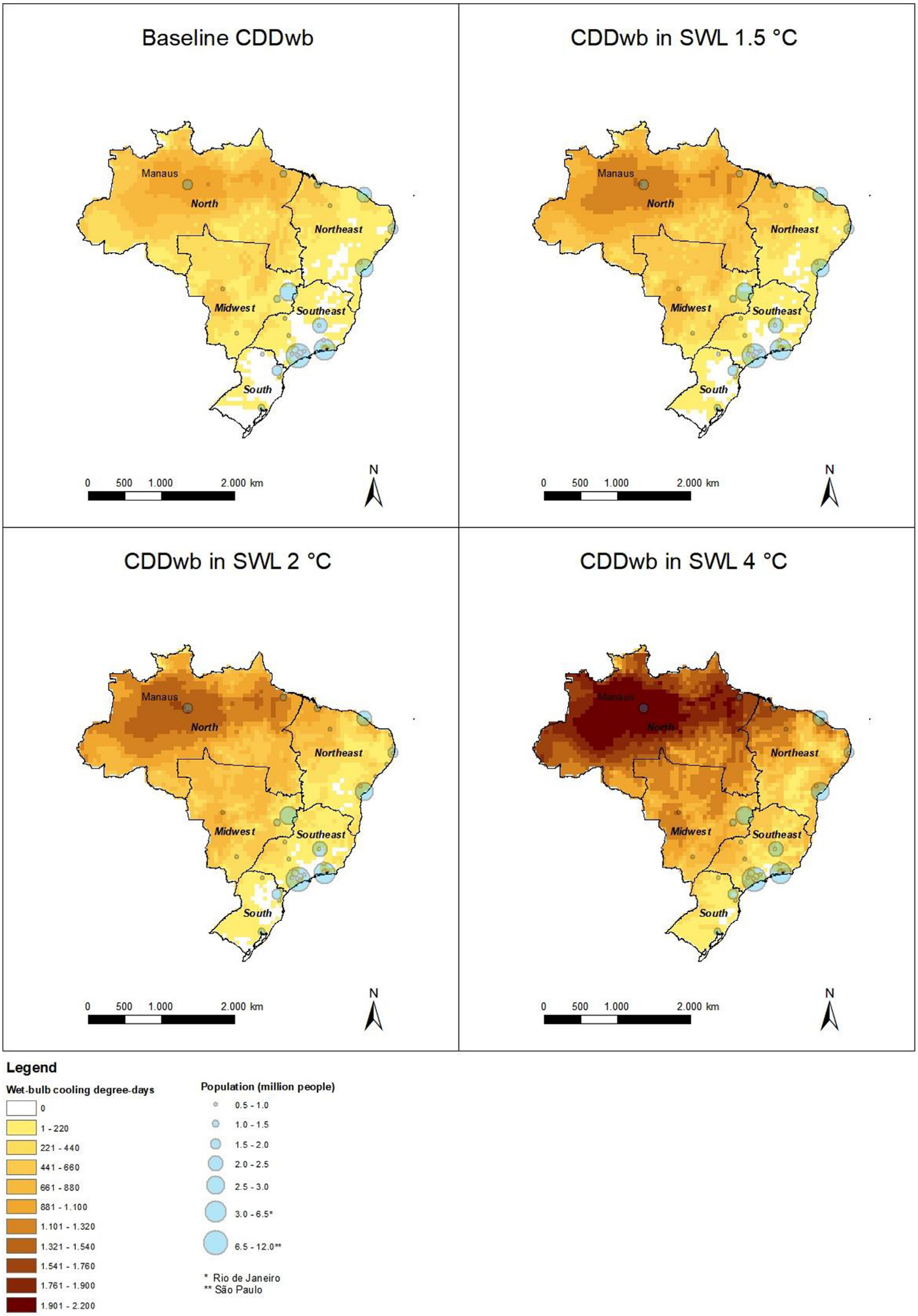

**Fig. 2.** Annual $CDD_{wb}$ (°C-days) in the baseline and the specific warming level scenarios.

ley during cold months, especially in winter (June to August). It should be noted, however, that space cooling is needed even during the winter in the Brazilian North and Northeast regions. It is also important to note that, in the SWL 4 °C scenario, South, Southeast and Midwest space cooling off-season lasts two months less when compared to the baseline and the other SWL scenarios.

According to the results presented in Table 3, the North region shows the lowest percentage increase in days of use in all the SWL

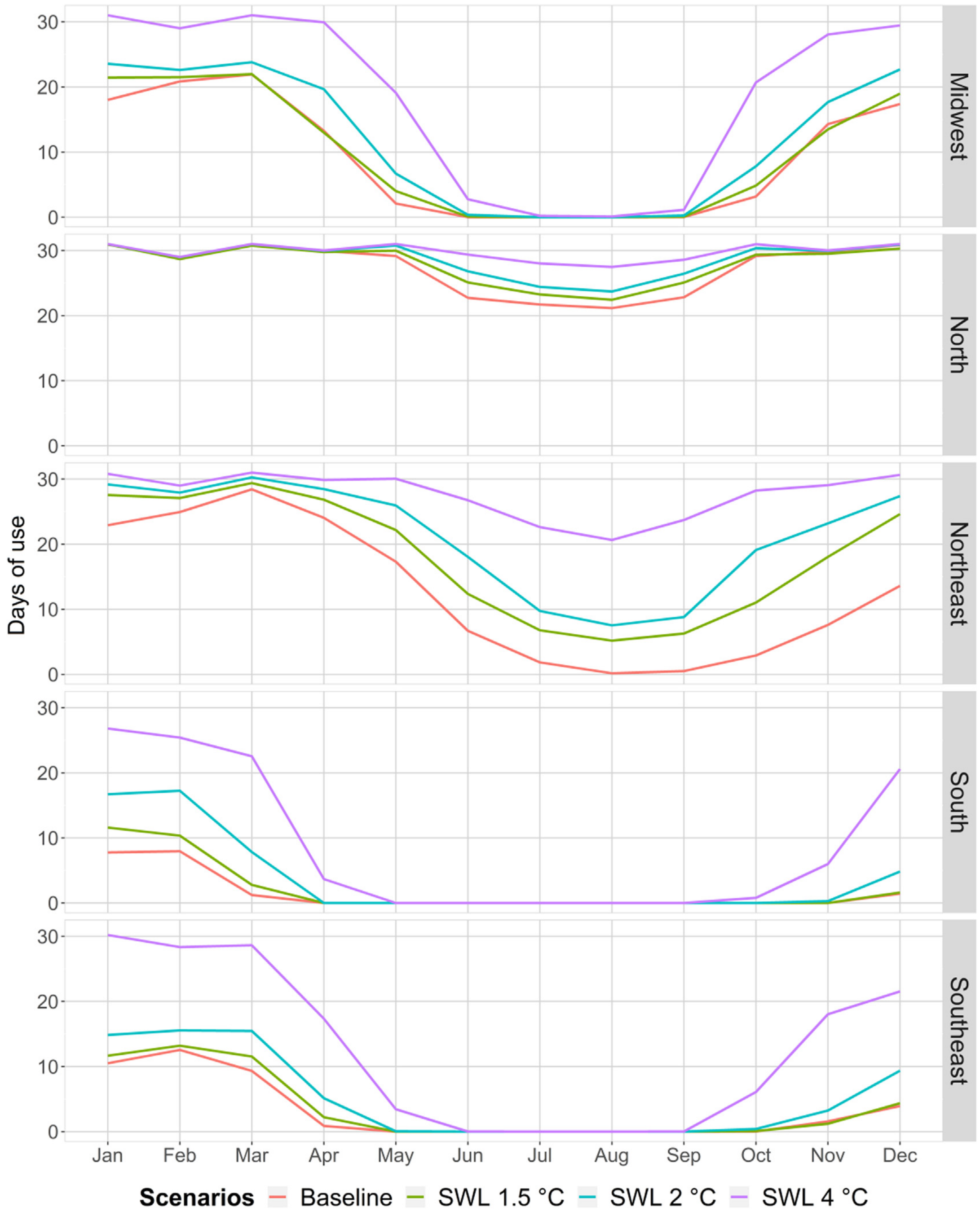

**Fig. 3.** Space cooling days of use per month in Brazilian regions from on-off matrices.

**Table 3**
Ambient thermal comfort response assuming a representative AC device compared with the Baseline scenario.

| Region | SWL 1.5 °C scenario | | SWL 2 °C scenario | | SWL 4 °C scenario | |
|---|---|---|---|---|---|---|
| | Δ annual days of use | Δ thermal load factor | Δ annual days of use | Δ thermal load factor | Δ annual days of use | Δ thermal load factor |
| North | 2% | 53% | 5% | 78% | 9% | 155% |
| Northeast | 44% | 30% | 70% | 44% | 120% | 85% |
| South | 44% | 119% | 161% | 180% | 489% | 431% |
| Southeast | 13% | 152% | 64% | 194% | 295% | 325% |
| Midwest | 7% | 104% | 31% | 166% | 100% | 346% |
| Brazil | 25% | 63% | 50% | 89% | 127% | 169% |

Note: Brazil values was calculated as a weighted-population average.

scenarios. This is because the region already has an average of 328 days of use in the baseline scenario. So, the number of days that needs space cooling services in the region has already saturated. Despite this, the North has a relevant increase in thermal load in SWL scenarios due to the increase in ambient temperature, as shown in Fig. 2.

The most significant impacts in relative terms are observed in the South and Southeast regions. In the South region, less than 50 days of use are estimated for most municipalities in the baseline scenario. This is explained by the fact that the South is the Brazilian's coldest region. However, in the SWL scenarios some municipalities surpass 100 days of use. Also, on average, the impact of temperature on energy consumption response in the South region is estimated to an almost 5-fold increase. As for the Southeast region, the highest impact comes from the thermal load effect in lower temperature SWL scenarios, with the effect of days of use becoming more relevant at warmer SWLs.

For Brazil, as seen in Table 3, the average AC equipment days of use increases more than 100% in SWL 4 °C. This would substantially impact the need for space cooling and consequently the associated energy consumption. Nevertheless, it is important to notice that the individual behavioral conditions, and cultural aspects not considered, could influence the decision to use an AC. Results above are only an indication of thermal comfort through a $CDD_{wb}$ analysis.

Fig. 4 shows results for the ambient thermal comfort evaluation, indicated by average $CDD_{wb}$, and the respective energy demand response. The North is the region with the highest average $CDD_{wb}$ in all scenarios. However, due to its low population density (Table 1), the potential impact on energy demand is not large. Nevertheless, the region's share in total AC energy consumption of Brazil is still meaningful because of the high average ownership rate in its major cities.

On the other hand, as the SWL rises, the share of the Southeast in total AC demand also increases, becoming the most relevant. However, its absolute growth in average $CDD_{wb}$ is quite modest in comparison to the North, Northeast and Midwest regions. This can be explained by the high population density of the Southeast region (Table 1), as well as its high average ownership rate (Table 2).

The results for the South region are a particular case. The increase in average $CDD_{wb}$ and the AC energy demand are low compared to other regions in absolute terms. However, the region shows a large relative growth in both parameters for higher SWL. This growing thermal discomfort in a region not used to warmer conditions can induce significant local impacts, especially regarding behavioral aspects.

Comparing the trends of increase in the average $CDD_{wb}$ and the AC energy consumption at the national level (Fig. 4), both curves show similar behaviors. Notwithstanding, a local level assessment of thermal comfort evaluation and response shows different increase trajectories for the parameters.

Fig. 5 shows $CO_2$ emissions associated with AC electricity consumption in Brazil for the proposed scenarios, assuming current values for energy efficiency and historical grid emission factors. Considering the historical average for the grid factor, $CO_2$ emissions in the baseline are 0.62 Mt of $CO_2$ and increase by 70%, 99% and 190% in the SWL 1.5 °C, SWL 2 °C and SWL 4 °C scenarios, respectively. The effects of a variation in these parameters and their impact on $CO_2$ emissions can be very significative and is assessed also in Fig. 5.

It is important to notice the role of the grid emission factor. Assuming Brazilian lowest historical value of grid emission factor, representing a decarbonization of electricity generation scenario, an increase in energy consumption would not necessarily increase $CO_2$ emissions.

### 3.2. Sensitivity analysis

Fig. 6 shows the results of a sensitivity analysis for the energy efficiency in the AC energy consumption. Considering an energy efficiency improvement of 59% in AC appliances, or a 4.79 W/W COP, the energy consumption response drops by 37% in the SWL scenarios. In absolute terms, this represents a saving of 4.3 TWh per year in the in the SWL 1.5 °C scenario and of 7.4 TWh in the SWL 4 °C scenario. The contribution of efficiency measures becomes even more important when considering the evolution on ownership rates of AC appliances in Brazil. Accounting for the potential increase in AC ownership increases Brazilian energy consumption by about 125%. Efficiency devices in this case could avoid 16.6 TWh energy consumption yearly on the highest temperature scenario.

As a sensitivity test for the COP values, we evaluated the efficiency improvement needed to keep the same level of energy consumption as in the baseline temperature scenario and compare it to the current best available technology observed in Brazil. In order maintain baseline energy consumption, AC efficiency would need to improve to a COP value of 5.15, 6.02, and 8.77 for the SWLs 1.5 °C, 2 °C and 4 °C scenarios, respectively. The average efficiency levels to compensate the effects of a temperature increase in energy consumption in SWL 1.5 °C and SWL 2 °C scenarios are below the new standards of the Brazilian labeling program [51]. However, for SWL 4 °C the challenge will be bigger, requiring average COP levels of the best available technology observed internationally in 2018 [2].

$CO_2$ emission levels decrease significantly with higher efficiency AC equipment. Table 4 shows that the use of a better appliances could avoid more than 1.0 Mt of $CO_2$ yearly in the ownership base case scenario and could achieve a save of 2.3 Mt under higher rates of AC appliance ownership[11].

Both the energy consumption and the $CO_2$ emissions present a considerably smaller relative growth for warmer climate conditions in the high efficiency scenario, meaning that policies fostering energy efficiency can attenuate part of the impacts of higher temperatures on energy demand and associated $CO_2$ emissions for additional space cooling needs.

## 4. Discussions and limitations

Space cooling currently represents a significant share of residential electricity demand in Brazil (about 14%) and is expected to increase with climate-induced temperature growth [31]. A strong relationship between climate change and higher energy demand for thermal comfort has been reported in the literature [9,29,60]. However, no data was found on the association between $CDD_{wb}$ methodology to end-use energy demand models, providing a comprehensive assessment of energy demand impacts, considering climate, demographic, technical and socioeconomic variables The methodology used could be easily adapted to different regions or countries and combines an easy approach to evaluate behavioral aspects of consumption combined with climate change scenarios.

This study assessed the energy implications of an increased number of days with high thermal load requirements for operating AC equipment by using $CDD_{wb}$ projections as input in an end-use energy model, which brings two main advantages. Firstly, the georeferenced grid of the on–off matrices makes it possible to evaluate regions at different scales according to the necessary input used in an end-use model. Secondly, the methodology also considers a metric appropriated to humid countries and regions, like in Brazil, by including relative humidity for temperature set point.

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[11] The highest historical emission grid factor is assumed.

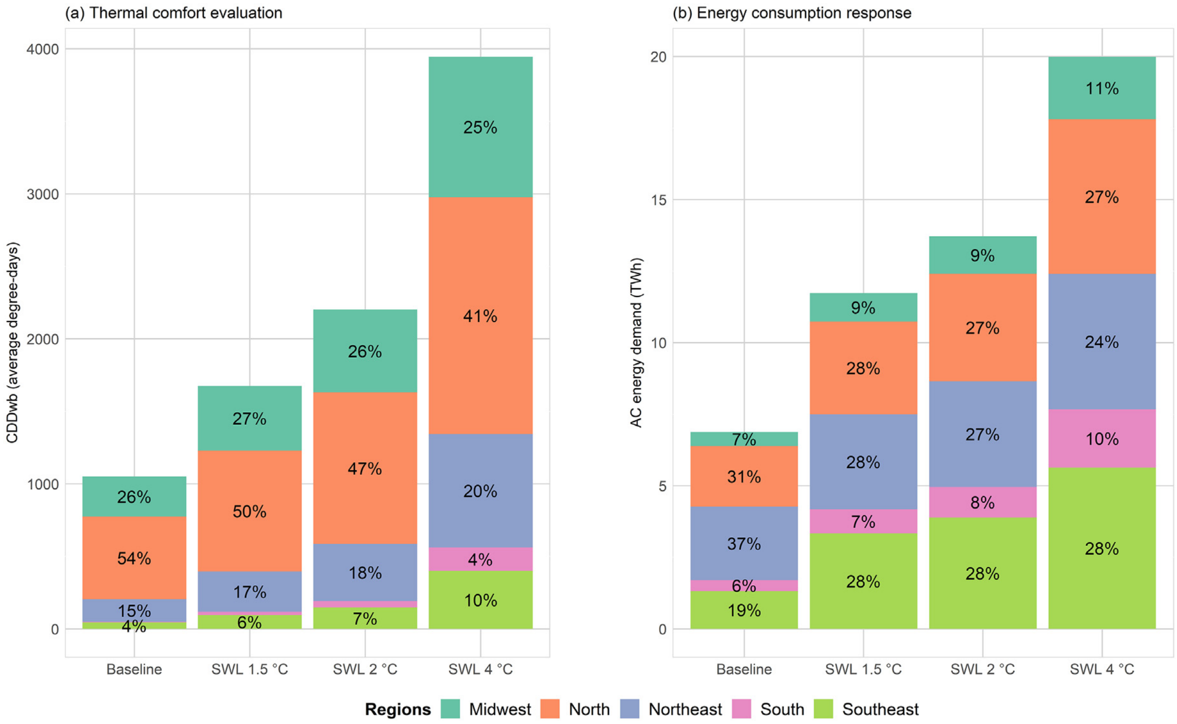

**Fig. 4.** Ambient thermal comfort evaluation versus (a) energy consumption response (b) by SWL scenarios and regions.

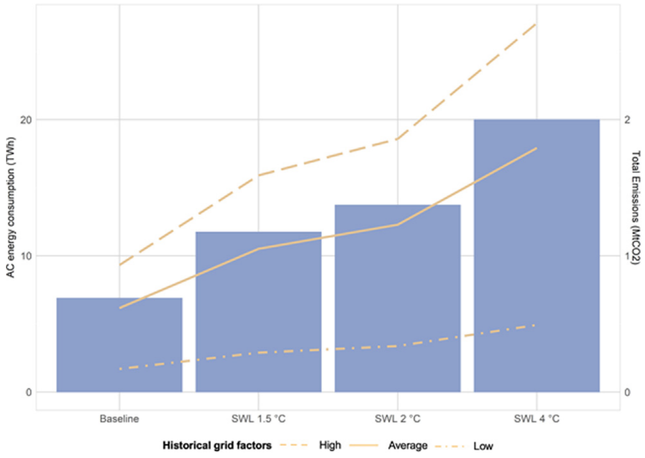

**Fig. 5.** Electricity consumption and associated CO2 emissions by scenario.

Results show an overall annual average increase in $CDD_{wb}$ and energy demand across all SWL scenario. The seasonal pattern of space cooling, however, is not expected change significantly, if not in terms of duration, with the high-use season lasting for a longer period of time in some regions.

In addition to temperature, we highlight the importance of other geographical and socio-economic drivers', namely population and income. Although $CDD_{wb}$ can be a good approximation of the ambient thermal comfort, actual aggregate energy consumption also depends on population density. These socio-economic drivers', such as population and income, are also important to assess for the trends in ownership rates and in the types of AC units used. In Brazil, there is a deficit in achieving ambient thermal comfort in many households, mostly due to budget constraints [61]. Consequently, rising income alone could intensify the total energy demand for space cooling in the country. This has been, to some extent, observed in the first decade of this century[3359]. Considering population and income increase alone, the ownership rate of space cooling appliances in Brazil can reach 96 AC units per 100 household in 2035, compared to a current average of 40 units [31]. The same trend of growth is observed for the power capacity of the appliances and the performance.

The outcomes of these socio-economical drivers, associated with increasing temperatures, could lead to higher energy consumption impact than those shown in this work, as shown by our sensitivity analysis. As also shown in the sensitivity analysis, efficiency improvements AC appliances can play an important role in attenuating the increase in energy use associated with rising temperatures. A comparison between the typically available AC technology in Brazil and the international efficiency standard indicates that the country is still far behind from the best efficiency level observed [262]. The lack of updated data for technical parameters in Brazil to estimate energy demand in detailed end-use models is a limitation for studying Brazil. Many assumptions were made in this paper to go around this. Certainly, this can be improved in future studies as more information becomes available.

Energy efficiency policy in the buildings sector in Brazil is highly based on labeling programs [62], which are less ambitious than those observed in other countries [59]. If higher efficiency levels are to be achieved, more ambitious energy efficiency policies will be needed. The trade-off between climate change mitigation and adaptation – higher energy demand for space cooling and respective GHG emissions – could be reduced by a continued decarbonization of the grid through higher use of renewables. Nevertheless, renewable energy is generally more vulnerable to climate change impacts [56]. This is specially the case of Brazil, where hydropower is the major source of electricity generation and could be severely impacted [57–59]. Higher energy demand and climate impacts on hydropower could have systemic repercussions across the power sector, with higher loads and higher use of fossil fuel power generation [26,60]. Conducting integrated power system analyses considering multiple impacts on the power sector

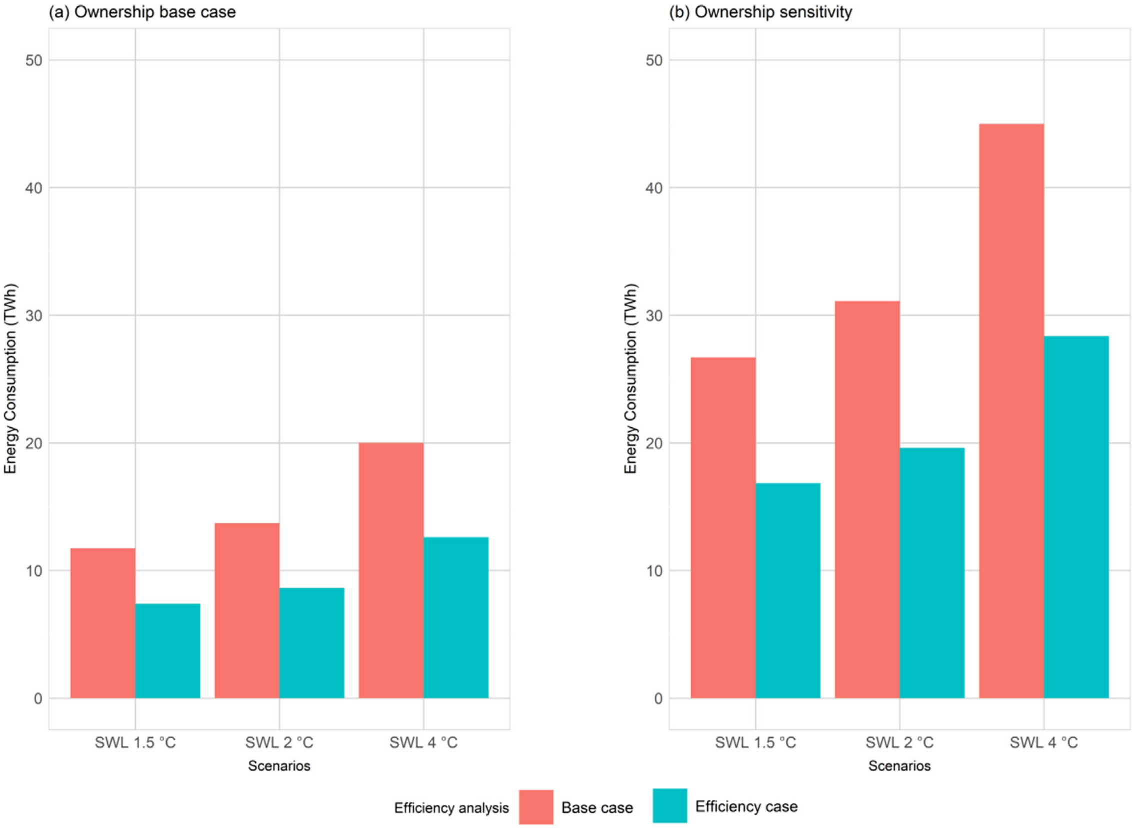

**Fig. 6.** Energy consumption response with efficient AC appliances and standard AC appliances by different ownership scenarios.

**Table 4**
Avoided emissions with the use of efficient AC appliances in different ownership sensitivity cases.

| Avoided emissions (Mt of CO2 / year) | Ownership base case | | | Ownership sensitivity case | | |
|---|---|---|---|---|---|---|
| | High | Average | Low | High | Average | Low |
| SWL 1.5 °C | 0.6 | 0.4 | 0.1 | 1.3 | 0.9 | 0.2 |
| SWL 2 °C | 0.7 | 0.5 | 0.1 | 1.6 | 1.0 | 0.3 |
| SWL 4 °C | 1.0 | 0.7 | 0.2 | 2.3 | 1.5 | 0.4 |

is recommended for future work. The methodology proposed here can be easily adapted to be included in energy systems models, integrating the demand results with supply-side climate impacts.

Moreover, the use of a unique temperature set point, despite the differences in terms of thermal acceptance and the wide range of climatic conditions between the country's regions, is a limitation of this study. Previous work show that there is a significant variation in acceptable indoor temperature in Brazil, ranging from 14 °C to 32 °C, depending on the location and methodology used [63]. Since this paper analyzes all Brazilian regions, a base temperature set at 24 °C can be considered a suitable fitting. To some extent, the use of $T_{wb}$ based on each region's relative humidity attenuates this simplification.

Finally, there is a lack of updated data for Brazil's technical parameters to estimate detailed energy demand for different municipalities, an improvement is recommended in future studies as more information becomes available. The methodology proposed here can be easily adapted to be included in energy systems models at any level, integrating the results of demand with other climate impacts and other sectors.

## 5. Conclusions

This study showed how Brazilian households can be affected by different climate change scenarios through variations in ambient air temperature and relative humidity and assessed its respective energy implications by merging the analyses of $CDD_{wb}$ with an end-use model for electricity demand. The isolate effect of climate change scenarios in the use of AC units was estimated and showed a significative increase between 70% and 190%, depending on the scenario.

A high-resolution analysis of the $CDD_{wb}$ indicator gives different measures of ambient thermal comfort accounting for both temperature and relative humidity, which are useful for large countries such as Brazil, which spans different latitudes and varying topography. Spatiotemporal heterogeneity in $CDD_{wb}$ across Brazil provides a comprehensive visual indication of the distribution of impacts on the ambient thermal comfort in different warming scenarios. Moreover, this study showed that on–off matrices, a by-product of the $CDD_{wb}$ calculation, can be useful inputs for end-use energy models as a regionally distributed proxy for the time-of-use variable.

Given Brazil's geographical and social heterogeneity, ambient thermal discomfort and energy consumption response are not linked across all regions. The study shows the relevance of identifying these singularities, showing a significant difference between increases in regional energy consumption. Thermal impacts on regions not densely populated, as the North region that has the highest value of $CDD_{wb}$ across all SWL scenarios, showed less relevant impacts on energy use. Also, current regional disparities in AC equipment ownership, in absolute terms, indicate that the Southeast and South regions are expected to have larger increases in energy demand for space cooling. However, this effect could be widespread across the country as AC equipment ownership increases in all regions to justly provide thermal comfort to a larger share of the population. Higher space cooling equipment ownership may, indeed, be stimulated by warmer temperatures [18], leading to even broader energy demand impacts than those projected in this study [30].

The paper isolates the temperature effects on space cooling, but the effects of ownership increase are only demonstrated through a sensitivity analysis. Combining temperature and more AC appliances in Brazil can significantly increase energy demand, with a potential rise of 125%. It is important to highlight that temperature changes may also affect AC user behavior, a topic left for research in the future. Results from the sensitivity analysis indicate that energy efficiency can reduce the growth in energy consumption observed in warming scenarios. This suggests that the promotion of energy efficiency can be a suitable mitigation measure for the energy sector, reducing trade-offs with climate change adaptation measures. Expanding these results to a global scale, where space cooling needs are significant [60], efficiency could play a key role. The potential carbon emissions avoided by energy savings from efficiency measures depends on the fuel mix of the power sector. In Brazil, a 59% improvement of efficiency is feasible, compared to other countries, but would require more aggressive energy efficiency policies than those currently in place in the country [31].

The results presented in this paper can therefore guide decision-makers to implement better mitigation and adaptation measures regarding thermal comfort and energy consumption response at the national and regional levels.

## 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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