The climate spatial variability and its impact on the thermal energy simulation of buildings: a case study of São Paulo, Brazil

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1. Abstract

This study evaluated the impact of different weather stations on building energy simulations (BES) concerning local environmental factors. The investigation focused on eight distinct weather stations in São Paulo, Brazil, comparing their data's influence on thermal autonomy and cooling load in a low-income dwelling. Employing EnergyPlus for computational simulations, the outcomes were compared against the surrounding urban fabric and natural coverage indexes. The analysis revealed noteworthy differences between the weather stations with more natural vegetation and those densely urbanized. These disparities were particularly pronounced, with differences of up to fivefold observed in cooling degree hours (CDH) between these locations. Consequently, these discrepancies in weather inputs impacted cooling load predictions, portraying urbanized regions with markedly elevated cooling requirements relative to the more naturally covered areas. Regarding the correlation between the surrounding indexes, site coverage and vegetation cover were more impactful in predicting thermal autonomy and cooling load.

Keywords - Urban overheating, social housing, Brazilian climatic conditions, urban climate.

2. Introduction

Urban populations are particularly vulnerable to thermal risks due to rapid urbanization and increasing occurrences of extreme heat events. Understanding the factors that contribute to urban overheating and changing the urban-rural energy contrast is essential [1]. Social housing, often with lower thermal performance than the general housing stock, becomes especially exposed as weather patterns change and the urban heat island effect intensifies [2]. Vulnerable populations, such as those with low income or social isolation, bear a disproportionate mortality burden during extreme weather events [3].

Building Energy Simulation (BES) is a common approach for evaluating design alternatives and validating performance against regulatory and governmental requirements. The building performance depends on the building envelope (architectural choices, components and materials that define the relationships between the indoors and outdoors), the occupant behavior, and the weather. Therefore, weather data is a crucial input for BES tools [4]. Typically, the BES community relies on typical meteorological year (TMY) or test reference year (TRY) weather files to represent the weather of a location in a simulation process. However, TMY and TRY weather files are commonly developed from data recorded at distant airports, which may not accurately represent the urban region of interest. In this regard, BES tools usually adopt coefficient corrections to mitigate the presence of urbanity in the weather (especially on the wind speed); yet, it is still an approximation, and the urban landscape might be very heterogeneous.

Therefore, when using conventional weather data files, we may underestimate the effects of urban heat islands and other characteristics that would impose thermal penalties on the inhabitants of social housing in urbanized areas. When considering megacities like São Paulo, these effects can be even more pronounced due to the heterogeneity of an urban area of this magnitude.

In the case of São Paulo, some studies have already been conducted, but they consider surface temperatures in contrast to the internal thermal performance of buildings. Ferreira and Duarte [5] explored the relationship between land surface temperature, vegetation cover, and local climate zones. They found a strong negative correlation (>90%) between the land surface temperature of

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the local climate zone and its vegetation cover. Another study by the same authors [6] investigated the daytime and nighttime land surface temperatures over different urban forms in São Paulo. The compact local climate zone morphologies presented higher daytime land surface temperatures, with low-rise buildings being hotter than high-rise buildings by an average of 5°C. This higher temperature average suggests the difference can be even larger during extreme events.

Overall, this study contributes to the body of knowledge of the spatial variability of urban climate in a high-density city (São Paulo) and its ramifications for thermal performance in buildings. The findings can inform policymakers, practitioners, architects, and engineers on how different urban regions and urban design affect comfort and energy efficiency in the same metropolitan area.

Considering the above, this study aims to evaluate the spatial variability of the weather files in the urban zone of São Paulo, Brazil, and its impact on the thermal energy simulation of buildings.

3. Methods

The method of this study is composed of four main steps. Firstly, the weather data was obtained from eight weather stations (either getting existing weather files or creating weather files from weather stations). Then, the surroundings of each weather station location were characterized by considering urban indexes. A standard simulation model was simulated using the weather files on EnergyPlus, obtaining building performance indicators. Finally, the urban characteristics of each weather station location were compared to the simulation results and the weather data.

3.1 Weather data characterization

The metropolitan region of São Paulo measures around 1,600 km^2, with a population of 20 million [7]. It presents a Cfa classification (Humid subtropical climate) according to Köppen-Geiger and 2A (Hot humid) according to ASHRAE 169/2013 standard. The analyzed climatic stations are all located within the municipality of São Paulo, except for the station at Guarulhos International Airport, which is situated in the neighboring city of Guarulhos. Figure 1 presents general location and elevation data for all considered stations. The obtained climatic variables were Dry Bulb Temperature (°C), Relative Humidity (Pa), Atmospheric Pressure (Pa), Global Horizontal Irradiation (Wh/m^2), Wind Direction (°), and Wind Speed (m/s). The year 2021 was chosen because it had the highest number of available data.

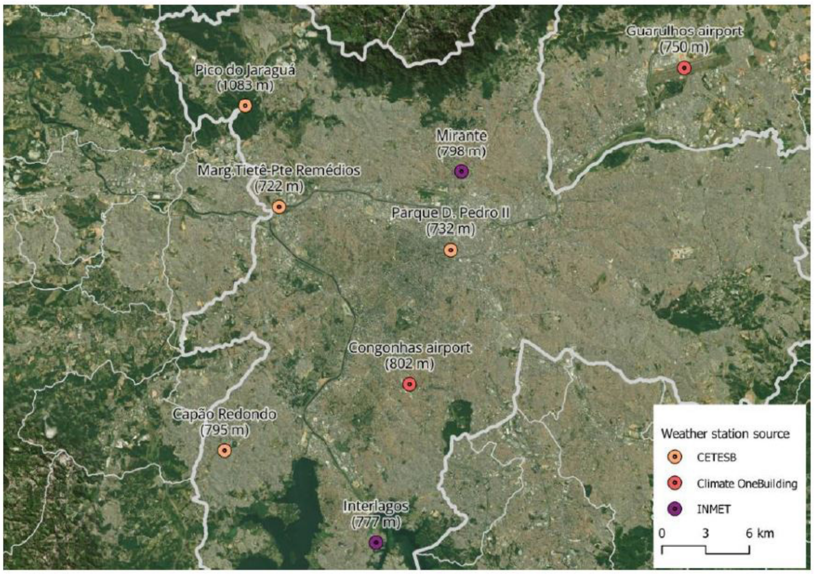

Figure 1: Weather station location, elevation, and data source.

CETESB is the state of São Paulo government agency responsible for controlling, inspecting, monitoring, and licensing activities generating pollution. The data is available for download on [8]. Regarding CETESB stations, the one in Pico do Jaraguá did not provide data for relative humidity, atmospheric pressure, and horizontal global irradiation. The other stations had a data completeness of around 90%. INMET, the Brazilian National Institute of Meteorology, offers access to data from all stations at [9]. For 2021, INMET stations' weather data were complete. Climate.OneBuilding [10] is a website with various weather files for building energy simulations maintained by Dru Crawley and Linda Lawrie. The website maintainers provided the historical time series used to develop the TMYx (Typical Meteorological Year) weather files. These files utilize data derived from hourly weather data in the ISD (US NOAA's Integrated Surface Database), supplemented with solar irradiation data from the ERA5 reanalysis dataset. The weather data is provided in the EPW (EnergyPlus Weather file) format, a simple ASCII format commonly used in EnergyPlus inputs. Therefore, these files were ready for use in the selected simulation tool for building performance analysis.

The other data sources require the development of EPW files to proceed with the building simulation phase. For this purpose, we utilized the Weather Converter program bundled with EnergyPlus to create the necessary weather files for building simulation. This tool converts and extends weather data into the EPW format. It performs calculations to fill in missing data and generates a statistical summary of the weather dataset during the processing [11]. The relative humidity and global horizontal irradiation values from the station located at Congonhas Airport were used to complete the missing values for the Pico do Jaraguá location.

In addition to using the EPW files for the simulation, we conducted an exploratory analysis of climate variables (specifically Dry Bulb Temperature, Wind Speed, Relative Humidity, and Global Horizontal Irradiation) to assess the overall behavior of the generated files. We also employed the Cooling Degree Hours (CDH) indicator to characterize different locations. CDH measures the accumulated amount (in degrees Celsius) and duration (in hours) that the dry-bulb temperature exceeds a specific base temperature. This study adopted a base temperature of 26°C for CDH calculations. From now on, we will use the abbreviation CDH26 for ease of understanding.

3.2 Surrounding indexes evaluation

The microclimates of each location are significantly influenced by their respective surroundings. To comprehensively characterize the weather station areas, a set of indices was employed. Natural coverage indexes included vegetation and water body cover, measured by the proportion of such coverages relative to the total site area.

The urban indexes comprised average building height, site coverage ratio, and façade-to-site ratio. The average height is derived from the mean of the building's height weighted by the building footprint. The site coverage ratio indicates the percentage of the total area taken up by the building's footprint. The relationship between façade areas (perimeter multiplied by height) and the site area determines the façade-to-site ratio.

The data collection consisted of a GIS (Geographical Information System)-based approach of a footprint area with a 500 m radius around the station. Table 1 presents the surrounding characterization for each weather station evaluated. The source of GIS information was OSM Buildings and the project SIG-SP [12].

Table 1: Weather station surrounding characterization.

Location (Weather station)	Average building height (m)	Site coverage	Façade-to-site ratio	Vegetation cover	Water body cover
Capão Redondo	5.73	0.21	0.42	0.32	0.01
Marg.Tietê-Pte Remédios	5.12	0.31	0.32	0.16	0.09
Parque D.Pedro II	9.40	0.31	0.74	0.14	0.03
Pico do Jaraguá	4.18	0	0.01	0.80	0
Interlagos	4.26	0.14	0.27	0.49	0.05
Mirante	7.50	0.36	0.16	0.13	0
Congonhas airport	6.16	0.09	0.16	0.33	0
Guarulhos airport	0	0	0	0.52	0

Figure 2 shows the evaluated areas, with marked natural elements (vegetation and water bodies) and buildings colored based on their respective heights. Each circle represents the area of 500 m around the weather station (the center).

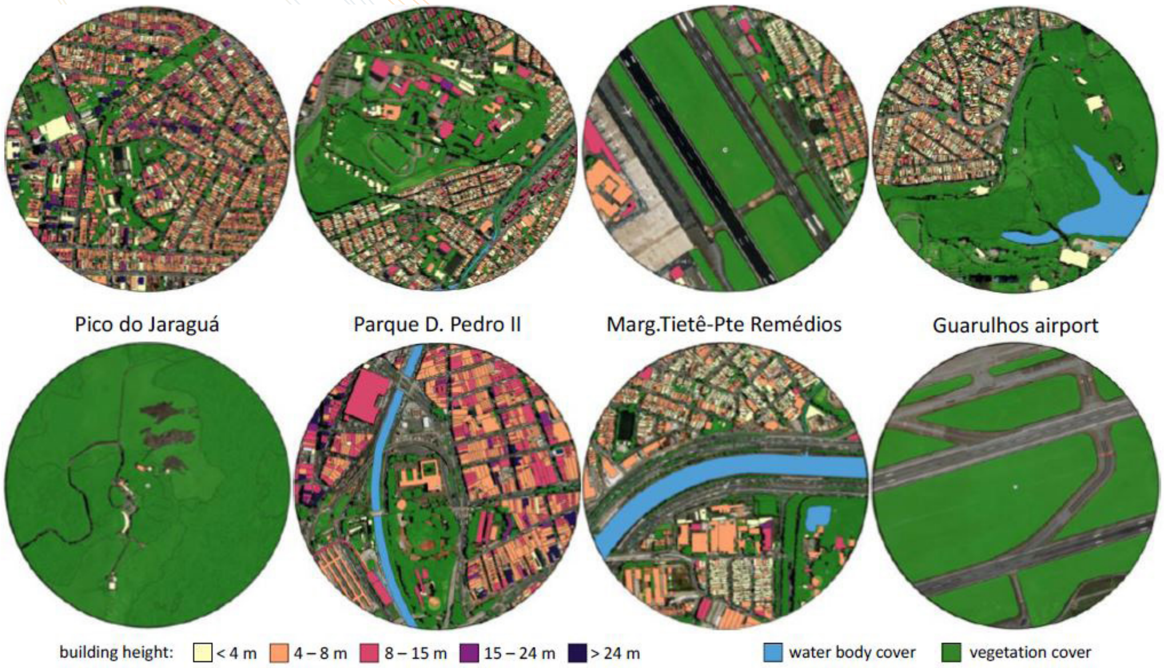

Figure 2: Process of GIS interpretation of the surroundings of each weather station.

3.3 Simulation method

A simulation model based on EnergyPlus version 22.2 was developed based on the requirements of the Brazilian Standard for the performance of residential buildings (NBR 15.575-1:2021) [13]. This way, the occupancy, lighting, and equipment loads were adopted per the standard (Figure 3). The thermal properties of the walls were chosen based on the reference model provided by the standard (equivalent to a 10 cm wall with a thermal conductivity of 1.75 W/m.K, specific heat of 1000 J/kg.K, solar absorptance of 0.58, and density of 2,200 kg/m^3). The GroundDomain:Slab object was used to model the contact with the ground, with the properties of the floor following the standard (equivalent to a 10 cm slab with a thermal conductivity of 1.75 W/m.K, specific heat of 1000 J/kg.K, solar absorptance of 0.65, and density of 2,200 kg/m^3).

The building model used in the simulations is a single-family house comprising two bedrooms, a living room with an integrated kitchen, and a bathroom, with a total area of 44.99 m^2 and a ceiling height of 2.50 m. Its geometric features were based on Triana et al.'s representative Brazilian building characterization [14].

Internal load	Living room	Bedroom
Number of people	Four people	Two people
Lights	5 W/m²	5 W/m²
Equipment	120 W	0 W
Activity Level	108 W	81 W
Occupation period	14h-18h: 2 people 18h-22h: 4 people	22h-8h: 2 people

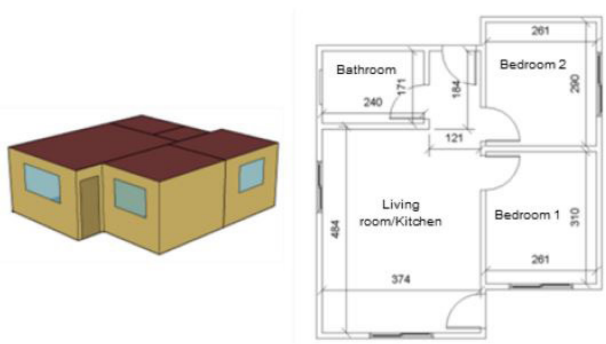

Figure 3: Simulation model and floor plan of the considered typology and Internal loads and schedules configuration.

The model was simulated in naturally ventilated and artificially conditioned states. The naturally ventilated model was designed with open windows and a ventilation factor of 45%, except for the bathroom window, which has an opening factor of 90%. The windows are allowed to be opened when the space is occupied for (1) indoor temperature higher than 19°C and (2) indoor temperature higher than the outdoor temperature. The artificially conditioned model was simulated with closed windows and utilized the HVACTemplate:

Zone:IdealLoadsAirSystem object. An infiltration rate of 0.5 air changes per hour was always considered. Two performance indicators for the naturally ventilated simulation were considered: (1) Thermal autonomy (%): it measures the percentage of occupied hours within an acceptable temperature range. We set an upper operative temperature limit of 26°C and a lower limit of 18°C for all locations; (2) Maximum and minimum operative temperatures (°C): these indicators represent the highest and lowest operative temperatures during occupied hours.

Two additional performance indicators were considered for the artificially conditioned mode: Cooling and Heating loads (kWh/year). In the artificially conditioned mode, the thermal load was considered only when the naturally ventilated mode's operative temperature fell outside the acceptable range during the same time frame.

3.4 Analysis of results

A first exploratory analysis of the simulation results (building performance indicators) and the characterization of the climatic variables were performed. Afterward, a dispersion analysis associated the simulation results with the surrounding indexes (Table 1). The linear general model was applied to obtain a statistical fit considering the association of Thermal Autonomy and Cooling thermal load to each surroundings index. In this sense, the coefficient of determination (R^2) expresses the level of association (influence) of each surroundings index on the simulation result and, consequently, on the building performance.

4. Results

Table 2 presents the maximum, mean, and minimum values of dry-bulb temperature, mean and maximum wind speed, mean relative humidity (RH), CDH26, and Global Horizontal Irradiation (GHI) for each weather station (location).

Table 2: Characterization of the climatic variables for each location.

Location (Weather station)	Dry-bulb temperature (°C)			Wind speed (m/s)		RH (%)	CDH_{26} (°C.h)	GHI (Wh/m². day)
	Max.	Mean	Min	Max.	Mean	Mean		
Capão Redondo	35.3	19.6	3.3	7.0	2.5	78.13	2593.3	*4045.7*
Marg.Tietê-Pte Remédios	35.3	20.6	**5.1**	5.9	2.1	*67.09*	4306.4	4685.8
Parque D.Pedro II	**35.5**	**21.0**	4.6	*4.0*	1.3	69.76	**5724.0**	4414.5
Pico do Jaraguá	*33.1*	*18.1*	1.7	7.0	1.8	73.58	*1082.6*	4762.8
Interlagos	34.1	19.0	3.7	6.4	2.0	**84.91**	1702.5	4443.9
Mirante	35.4	20.1	4.4	7.2	*1.2*	68.35	2495.6	**4892.8**
Congonhas airport	35.0	19.6	4.0	**14.9**	**3.4**	73.58	1848.3	4762.8
Guarulhos airport	35.0	19.6	*1.0*	12.4	2.7	77.95	2441.9	4790.0

* The highest values are highlighted in **red bold** and the lowest in *blue italic*.

The Pico do Jaraguá weather file exhibited the lowest maximum and mean temperatures, 33.1°C and 18.1°C, respectively, along with the lowest CDH26 value (1082.6°C.h). This location is within a large preservation area and is 300 meters higher than the others. It presents the highest vegetation cover index (0.80). On the other hand, the highest maximum and mean temperatures (35.5°C and 21.0°C, respectively) were found in the Parque D.Pedro II location, near the central region of São Paulo with the highest façade-to-site ratio of 0.74. Similarly, the highest CDH26 value was observed in this area (5724.0°C.h).

The weather stations located at Congonhas and Guarulhos airports showed intermediate values for the analyzed variables, except for mean and maximum wind speed, where these stations presented higher values compared to the others since these locations present more open spaces (site coverage index of 0.09 and 0, respectively).

Regarding relative humidity, the highest mean value was recorded for the Interlagos location, with 84.91%. The weather station is near large bodies of water (water body cover of 0.05) and is surrounded by a dense tree cover (vegetation cover of 0.49). Conversely, the lowest value occurred in the Marg.Tietê-Pte Remédios location with 67.09%. This area is adjacent to a major freeway in a highly urbanized part of São Paulo, presenting the second highest site coverage index of 0.31. It also presents the second-highest value of CDH26 (4306.4°C.h).

The simulation results are presented as performance indicators in Table 3 for each location.

Table 3: Building performance indicators for each location.

Location (Weather station)	Thermal autonomy (%)	Cooling load (kWh/year)	Heating load (kWh/year)	Max. op. temp. (°C)	Min. op. temp. (°C)
Capão Redondo	76.4	2110.2	167.1	34.8	13.6
Marg.Tietê-Pte Remédios	*62.7*	3852.3	188.1	38.2	*11.9*
Parque D.Pedro II	64.8	**3930.8**	48.6	**39.2**	15.3
Pico do Jaraguá	75.2	*1823.5*	**289.2**	*33.5*	12.7
Interlagos	76.3	2202.2	169.0	34.8	13.6
Mirante	65.7	3884.6	*30.2*	35.5	**15.4**
Congonhas airport	**77.4**	1994.2	142.1	34.0	12.4
Guarulhos airport	74.9	2453.9	146.9	34.0	12.0

* The highest values are highlighted in **red bold** and the lowest in *blue italic*.

The simulation using the weather file of Parque D.Pedro II again showed the highest cooling thermal load value (3930.8 kWh/year), while Pico do Jaraguá presented the lowest value (1823.5 kWh/year). As for the heating load, the simulation considering the Pico do Jaraguá location exhibited the highest value (289.2 kWh/year). The Mirante location presented the lowest value (30.2 kWh/year).

Parque D.Pedro II also showed the highest results for maximum operative temperature, reaching 39.2°C, 5.2°C hotter than the values simulated using the airport weather files – traditionally used for building energy simulation. The lowest value was found for Pico do Jaraguá at 33.5°C. Interestingly, the minimum operative temperature was found when considering the weather file of Marg.Tietê-Pte Remédios, with 11.9°C. The highest minimum operative temperature occurred in the Mirante location at 15.4°C. Regarding thermal autonomy, Congonhas Airport presented the highest value, 77.4%. Higher values of this indicator indicate that the building maintains mild temperatures for longer throughout the year. As for this indicator, the lowest value was found for Marg.TietêPte Remédios, with only 62.7%.

Figure 4 shows the association of the simulation results (Table 5) with the urban indexes (Table 3). The coefficient of determination (R^2) was higher for the association of site coverage with thermal autonomy (R^2=0.6634) and cooling load (R^2=0.7359). Also, the vegetation cover with the cooling load was relevant (R^2=0.6416). The other surrounding indexes were less meaningful. Despite testing other statistical models, the linear model represented the best fit. It is important to consider that the sample comprises a few cases (eight), making the correlations only indicative of a behavior.

5. Discussion

Several studies highlight the inadequacy of traditional weather station data, usually from airports, to assess the thermal energy of buildings, especially in urban contexts. In this context, relating the surrounding indexes and the weather data proved that the more densely built-up areas presented the warmest climates. Pico do Jaraguá was more naturally covered, with vegetation covering 0.8 of the 500 m radius area. This location showed the lowest mean and maximum air temperatures and CDH26. On the other hand, Parque D. Pedro II displayed the highest vertical density (façade-to-site ratio and average building height) and the second highest horizontal density (site coverage) between the locations, and CDH26 five times greater than Pico do Jaraguá.

The warmer climates consequently had a significant impact on the building simulation results. Much higher values of cooling loads and maximum operative temperatures were found for the more urbanized regions of the metropolis compared to the weather data from the airports in the region. Furthermore, if we consider that simulation users often utilize TMY files from a few years ago, there is a significant likelihood that overheating effects are underestimated in the performance analysis results.

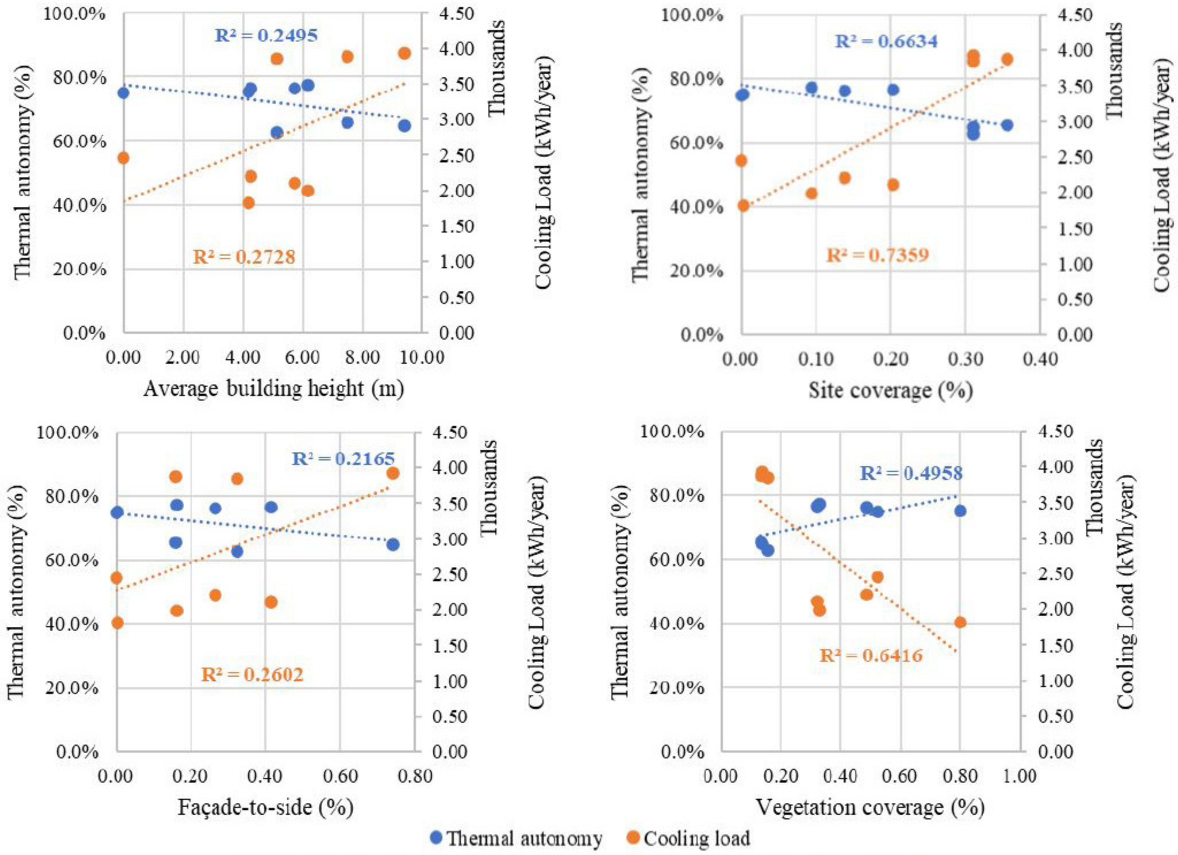

Figure 4: Simulation results associated with the surroundings indexes.

Salvati et al. [15] found that the three urban indexes exert a significant influence on the temperatures by parametric simulations on the Urban Weather Generator (UWG) model. Considering the cooling load and the thermal autonomy of the simulated building for each weather data, the relationship between the urban indexes was more significant for site coverage.

Regarding the vegetation's role in the climate, some studies assess their positive impact on decreasing air temperatures [16], [17]. Even though the linear correlation's R^2 value was not high (just 0.5 for thermal autonomy and 0.64 for cooling load), it showed the tendency of warmer air temperatures with less vegetation cover. Also, it is important to acknowledge that the specific vegetation types, like grass and trees, could have influenced the outcomes. This distinction should be considered in future research.

As limitations of this study, we address the following: assess monthly variations, determine the type of vegetation, explore filling missing data from weather files, expand the number of simulations for different typologies and building envelopes, consider surrounding shadows and explore future climate scenarios.

6. Conclusion

This study aimed to evaluate the spatial variability of the climate within the urban zone of São Paulo, Brazil, and its impact on the thermal energy simulation of buildings. To do so, eight weather data from different weather stations were used to run building performance simulations. Their surroundings indexes were evaluated, which were used to assess cause-effect inferences on building performance. In this sense, the following conclusions can be drawn:

- The different weather data locations considerably affect the simulation results. The maximum operative temperatures reach 5°C above the typical airport station data. In densely built-up areas, the cooling load was double that of the airports.

- Regarding the surrounding indexes, the site coverage presented a higher correlation with thermal autonomy and cooling load. Meanwhile, vegetation linear regression reasonably correlated to the building cooling load.

Future work will focus on expanding the cases considered for simulation and comparing tools like the UWG for developing weather data files considering the urban context.

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