Impact of extreme weather events on the thermal comfort of vulnerable populations in the city of Sao Paulo

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Abstract

In a context of global warming, heatwaves are predicted to become more frequent and intense over the next decades. The elderly are among the most vulnerable groups to extreme heat due to their dysfunctional thermoregulatory mechanisms and propensity to illnesses. This research aims to assess impacts of urban heating on this demographic group, using the ENVI-met V.5 model to simulate microclimatic conditions at a representative neighborhood in the city of Sao Paulo, adopting the PET Index as a comparative variable. Results obtained from historical climate data are compared to those of projections according to the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathways (RCP) 8.5 scenario. After the realization of impacts, urban surfaces albedo modifications were tested, in search for the most effective mitigating adaptations. Results obtained until now show that increasing the average albedo of built surfaces can help moderate rising temperatures, but would not be enough to compensate for the increase predicted for the coming decades.

Keywords - Heatwaves, Urban Adaptation, ENVI-met, PET Index, Outdoor Thermal Comfort.

1. Introduction

Climate change effects are already being felt worldwide, bringing significant increase in frequency, intensity, and duration of extreme weather events, such as heatwaves. People living in urban environments will be even more vulnerable to heat extreme events because of the Urban Heat Island (UHI) phenomenon and the high population density, with Asia, Africa, North America and parts of South America affected most [1]. According to the IPCC Sixth Assessment Report (AR6), published in 2021, global average temperature will probably rise by 1.5°C over the next decades, even if the emission of greenhouse gases were halt immediately. As they keep being emitted, global averages may rise up to 4°C until 2100. [2]

Since the elderly are more susceptible to heat, global population ageing trends will magnify risks from excess heat exposure. It is predicted that heat waves will cause higher mortality under conditions aggravated by greenhouse gas emissions [3,4]. In Brazil, maximum temperatures are expected to rise up to 5.8°C, while relative humidity may lower to about -11% until 2099, in case the IPCC RCP 8.5 scenario becomes true. A huge metropolis like Sao Paulo may experience a heatwave increase of around 1200% until the end of the century under that pessimistic scenario, causing mortality rates of the elderly to rise above 1000% if no adaptation measures are taken [5,6].

Therefore, without provision of structural adaptation of the current urban environment, outdoor comfort levels will be seriously degraded by the rising temperatures, and physiological stress will result in increased mortality during extreme events. Older people will be among the most severely affected groups, with additional risk from urban heat if already chronically ill, socially deprived or inner-city residents [1].

1.1 Context

Literature mentions the scarcity of studies on the impacts of climate change specific to cities in tropical climates, and the need for further investigation into the potential of planning measures to reduce thermal stress in outdoor environments, under constantly changing climatic conditions. A few recent works downscale projected climate data to assess microclimatic effects in urban outdoor areas. One of these articles compares measurements taken in loco with simulated projections in ENVI-met for an urban canyon in the city of Sydney, testing the effects of different measures of urban adaptation [7]. Guerreiro [8] used projected data, obtained from Meteonorm, to simulate the effect of future scenarios on thermal comfort using ENVI-met, in search of effective mitigation measures for the UHI in the city of Lisbon. Yoshida [9] uses climate data projections obtained in the Projeta Platform (Eta-HADGEM2), simulating with ENVI-met future conditions in the city of Sao Paulo, the same method and instruments of the present work, but with the objective of assessing effects of higher temperatures on the health of trees, not of human beings. Another important reference was the article [5] which estimates the evolution of the elderly population in Sao Paulo, its exposure and increased thermal risk over the next decades. The 2022 doctoral thesis by the same author [6] deepens that investigation by studying future climate scenarios for Brazilian capitals, associating them with exposure and health risks.

When the external environment is hot, the human body maintains core temperature by losing heat via radiant, convective, and evaporative heat loss, with vasodilatation and perspiration. When the surrounding temperature is the same or higher than the body, the effectiveness of this mechanism is remarkably reduced, leading to a clinical condition called heat stress, ranging from cramps to heat exhaustion. When the core temperature rises above 40.5°C, it can lead to heatstroke and multiple organ dysfunction. The hypothalamus is the region of the brain that coordinates physiological response to excessive heat. In extremely hot environments, irreversible brain damage can occur with neurological signs such as lack of coordination, consciousness and seizures. [1]

Diniz [6] elaborated tables identifying heatwave periods and its temperature thresholds in Brazilian capital cities. They show an average of maximum temperatures (°C) percentiles P90, P95 e P98 for the hot period in São Paulo, based on climate projections for the distant future (2079- 2099) of the Eta-HADGEM2-ES model. Table 1 was extracted from that study and summarizes these values for Sao Paulo.

Table 1: Heatwave threshold temperatures (°C)

RCP 4.5			RCP 8.5		
P90	P95	P98	P90	P95	P98
33.9	34.9	36.0	37.5	38.5	39.6

1.2 Objectives

The work presented here is part of a broader research, with the ultimate aim of proposing urban adaptation measures, in order to counterbalance the projected increase in environmental temperatures, and to mitigate physiological thermal stress that might lead to higher morbidity and mortality rates. The general objective of the research is to verify the impact of extreme climatic events on the thermal comfort of the vulnerable population in the city of São Paulo, especially the elderly. Its secondary objectives are: (1) Simulation of future scenarios, using the ENVI-met computational model, to assess the influence of high temperatures in representative areas of the city of São Paulo, on the elderly population (2) Analysis of thermal comfort based on thermal sensation calculations, using PET indices; (3) Contribution with practical proposals for urban adaptation for the Municipality's action plans.

The main hypothesis is that, without any structural adaptation of the current urban environment, outdoor comfort levels will be seriously degraded by increasing global temperatures, and during extreme events, physiological stress will result in increased morbidity and mortality.

1.3 Urban Adaptation

The main characteristics causing urban overheating are: thermal properties of building materials, urban canyons radiative distribution, urban greenhouse effect, diminished evaporative surfaces and turbulent transfer. Planned urban adaptation is an important strategy to control the negative effects of climate change on health. Passive solutions such as shading; waterbodies; increasing the surfaces albedo - can considerably reduce the air temperature [1]. Usual ranges of urban albedo vary between 0.1 and 0.7, with an average value close to 0.5. Cities with high levels of green infrastructure benefit from a higher temperature drop when reflective materials are implemented at the city scale. Correlations can be found between these variables, e.g., in average an increase of the albedo by 0.1 decreases in average the initial mortality by 1.8. This is a very serious contribution of reflective materials on urban public health. Increase in the vegetation fraction in cities offers serious benefits to the urban climate, pollution control and health [1].

Considering the whole of this research, a full set of simulations should include the following factors, based on the parameters suggested by the bibliography:

- Increase in surface albedo: with more reflective materials and coatings in lighter colors, causing buildings to absorb less energy, consequently reducing average radiant temperatures in the urban environment. [10, 11]

- Vegetation on the roofs and buildings facades: layers of vegetation applied to the envelope of buildings can absorb a significant part of the incident solar radiation, in addition to raising the humidity of the air in the immediate surroundings and providing cooling effects thanks to evapotranspiration in the leaves. [11 - 14]

- Vegetation cover on roads, squares and parks: it consists of several resources, from the traditional afforestation to the use of devices such as pergolas, shelters or shaded paths. In addition to the shading effect, the evapotranspiration of the leaves produces a cooling of the surrounding air. [15 - 18]

- Water bodies and sprinklers: while vegetation allows the reduction of air temperatures by increasing the moisture content in a natural way, artificial strategies can strongly increase the humidity in certain areas, providing localized relief from high temperatures. [7, 19, 20]

- Urban morphology: orientation of the road system along predominant wind direction; the adequate proportion between built and empty volumes regulate exposure to direct radiation. [21 - 24]

2. Methods

This research is based on a computational analytical method, using the ENVI-met model to simulate microclimatic conditions at a representative neighborhood in a central area of the city. The existing urban environment, under historical climatic data, is compared with projected scenarios, estimated with IPPC RCP 8.5. Among many variables, PET Index is used as a measure of the human body response, in several microclimatic conditions, ages and physiological variables.

The comparative analysis of physical, objective outputs with the physiological, subjective outputs allows us to distinguish how the variables will affect human comfort and eventually cause physiological stress conditions within the urban environment over the next decades.

ENVI-met is a three-dimensional model, designed to simulate complex surface-vegetation-atmosphere interactions for urban environments. It allows analyzing, on a microscale, the interaction between urban design and microclimate, using a high-resolution orthogonal mesh. It is a prognostic model based on the laws of fluid dynamics and thermodynamics, widely validated and used as a computer fluid dynamic (CFD) tool, able to simulate and evaluate the effectiveness of urban heat mitigation strategies including surface materials, greenery, water systems, and building geometry, with reasonable accuracy [25 - 27]

The ENVI-met model is widely used in urban outdoor simulations, with validation in different regions and climates. Studies using the ENVI-met with future projections data are rather scarce, though. Therefore, this work proposes bringing the mesoclimatic projections of the Eta-HADGEM2-ES model to feed microclimatic simulations, in the urban environment of the city of São Paulo.

Due to temporary unavailability and absence of intended sets of data, CORDEX was preferred over Plataforma Projeta as a source for climate data. Therefore, historical and projected climate data were obtained in the CORDEX platform . For the most accurate and recent data, the chosen Domain was the SAM 22 (South America, grid resolution around 25 x 25 km). For the sake of comparison with studies by local authors [4, 5, 8], the adopted Driving Model was the MOHC-HadGEM2-ES.

CORDEX is part of The World Climate Research Programme (WCRP) framework, intended to evaluate regional climate model performance through a set of experiments, by producing regional climate projections. Regional Climate Downscaling (RCD) has an important role to play by providing projections with much greater detail and more accurate representation of local extreme events. For the South America Domain, the Dynamical downscaling experiments and validation studies are led by Professor Rosmeri Porfirio da Rocha, from IAGUniversity of Sao Paulo [28 – 30].

Experiments used in the present work were: historical data from 1970 to 2005; projected data from 2006 to 2099, RCP 8.5. The highest available resolution was a time frequency of 3 hours, and the main variables were near-surface air temperature and near-surface air relative humidity, which are enough as inputs for ENVI-met Simple Forcing feature simulations, using the Indexed View Sphere – IVS tool. Extraction of the climate data was streamlined by the computer software CORDEX Data Extractor .

Simulations were performed using period average data (typical years for air temperature and relative humidity), as well as extreme events (heatwaves, with temperature above the 95th percentile, spanning at least 3 days). After the compilation of the simulation results, the base case scenario (under historical climatic data) was compared to projected scenarios, estimated with IPPC concentration path RCP 8.5.

The Bom Retiro neighbourhood (coordinates 23°53' S; 46°64' W) was chosen as a first object of simulation due to its historical relevance; geographical centrality as a metropolitan rail system hub; mixed use; walkability; high proportion of elderly population; high densification potential for the next decades.

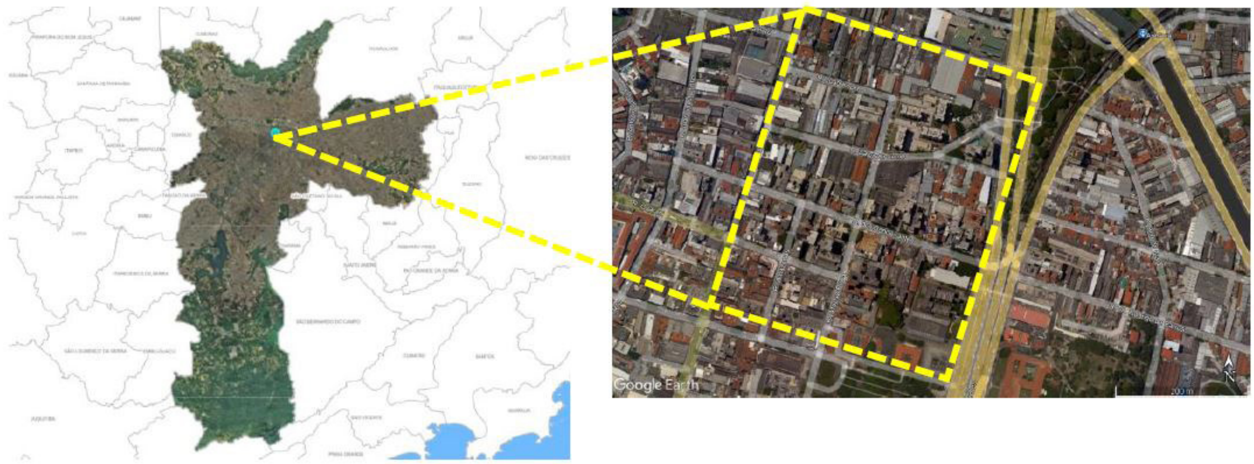

Figure 1: Area of study location in the map of Sao Paulo.

The base scenario consists of a rectangular section of the neighborhood with 558 x 426 m, covering 10 urban blocks. The 3D model was built with a 3x3 m grid resolution, reaching a 120 m height for simulation. Building materials properties data was extracted from local constructive usual practice sources [31].

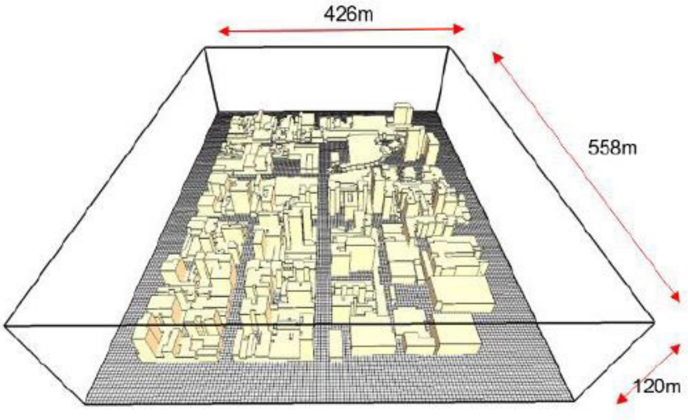

Figure 2: 3D model for the basecase

Among many output variables, PET Index was calculated using the BIO-met tool in ENVI-met, for 4 types of subjects: adult male and female, both 35 years old; 8 years old male child; and 80 years old male. All categories are supposed to wear light summer clothes (0.5 clo) and perform light levels of physical activity (walk at 0.9 to 1.34 m/s speed).

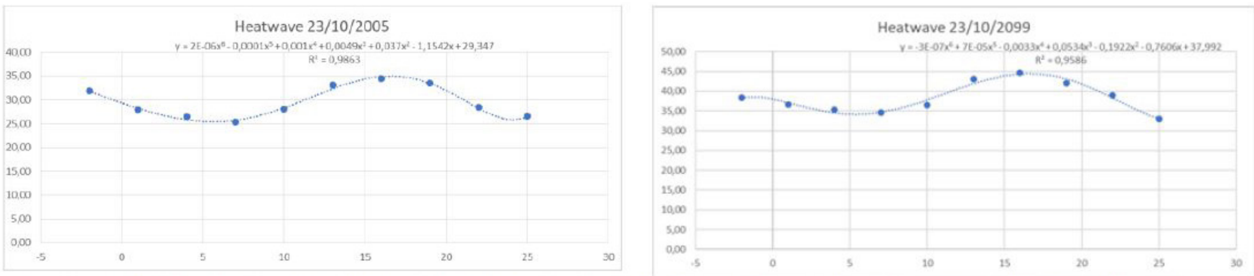

Figure 3: Graphics for air temperature extracted from CORDEX files, with intervals every 3 hours. Intermediary values for every hour were obtained by interpolation, using polynomial equations.

Analysis of climate data offers a preview of the projected climate changes. Fig. 3 shows a comparison between a heatwave (according to the definition adopted by [6]) occurring in 2005, and an equivalent event happening in 2099 under a RCP 8.5 scenario. Although the curves behave similarly, values are displaced from about 25 – 35°C to around 35 – 45°C. Therefore, in a pessimistic scenario, extreme heat events may elevate maximum temperatures to about 10°C within a single century. Another significant finding is that nighttime temperatures may reach above 30°C Celsius, which is absolutely unusual for the subtropical climate of Sao Paulo.

As for the average reflectivity of urban surfaces used for simulations, Table 2 shows the adopted values:

Table 2: Albedo values used in simulations

Material	Basecase	Future Adaptation
Asphalt Floor	0.10	0.40
Concrete Floor	0.20	0.50
Vertical Surfaces	0.20	0.70
Horizontal Surfaces	0.15	0.85

Sky View Factor used in the first simulations ranges from 2.00 to 3.50. For Sao Paulo conditions, PET values between 31- 43°C are considered hot, above 43°C are very hot, on the verge of thermal stress conditions [32].

3. Results

A sample of ENVI-met simulation outputs is shown below, with data from a heatwave occurring in 2005, compared to another in 2099 (RCP 8.5). Fig. 4 presents results for air temperature, comparing values at 3 p.m. Values on the right face of the rectangle tend to be higher, due to openness and proximity to a large avenue.

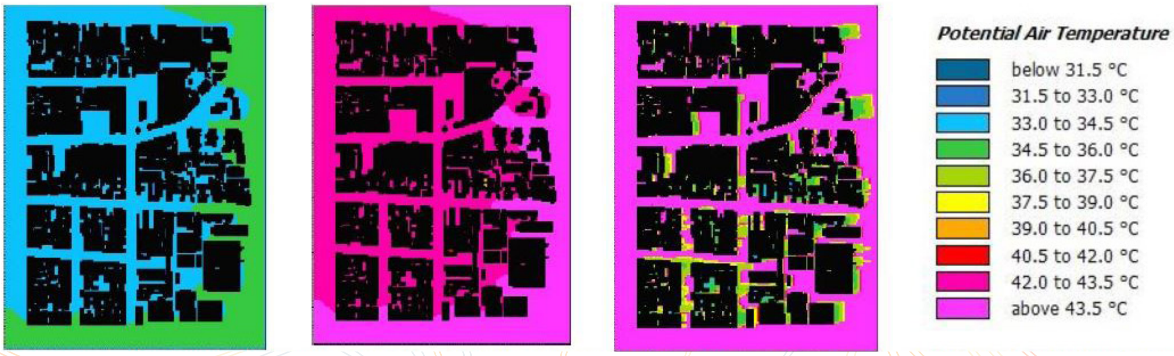

Figure 4: Results for Air Temperature at 3PM for current heatwave (left), future projection RCP 8.5 without adaptation (middle) and future projection RCP 8.5 with albedo adaptation (right).

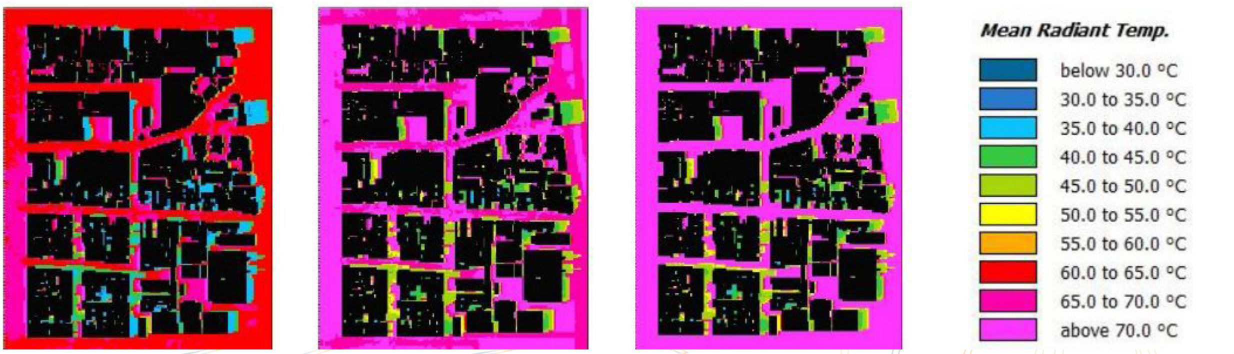

Figure 5: Results for MRT at 3PM for current heatwave (left), future projection RCP 8.5 without adaptation (middle) and future projection RCP 8.5 with albedo adaptation (right).

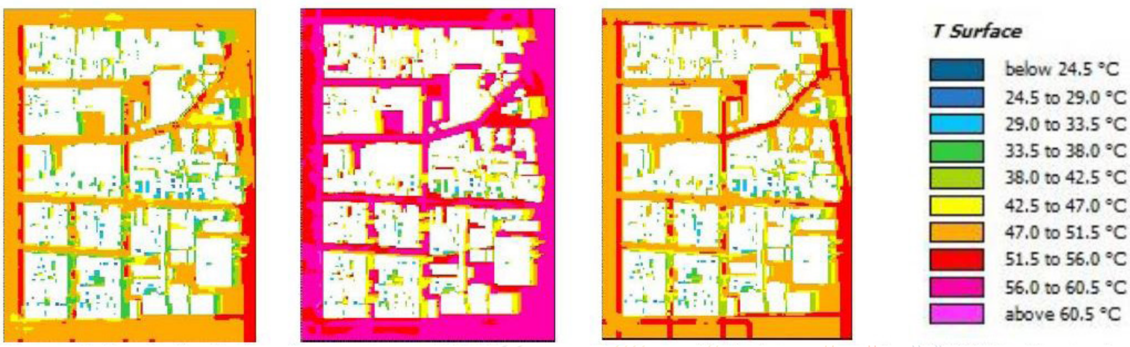

Figure 6: Results for Surface Temperature at 3PM for current heatwave (left), future projection RCP 8.5 without adaptation (middle) and future projection RCP 8.5 with albedo adaptation (right).

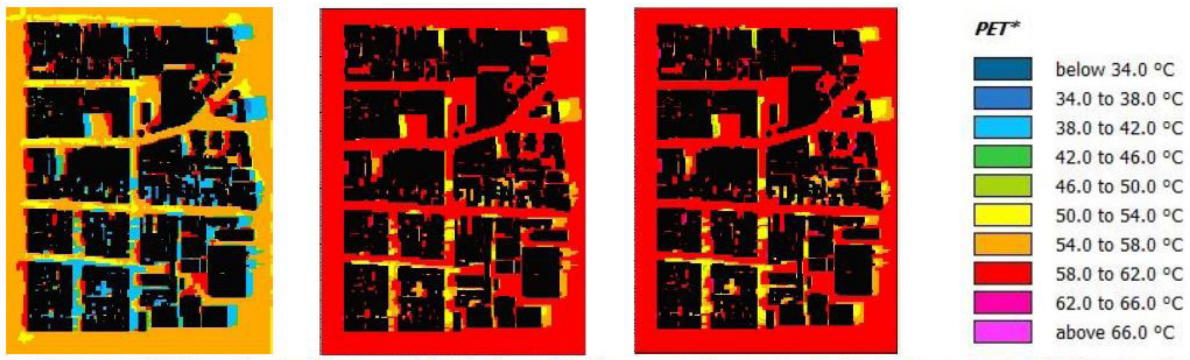

Figure 7: PET Results for 80 years old elderly at 3PM for current heatwave (left), future projection RCP 8.5 without adaptation (middle) and future projection RCP 8.5 with albedo adaptation (right).

4. Discussion

ENVI-met simulations allow a plethora of outputs. By comparing the different subjects in BIO-met calculations, it is possible to verify how sensitive to heat each group of the population is. Comparison among scenarios offer a notion of the evolution of urban heating over decades, allowing to test intervention hypotheses and its effects on each microclimatic variable. For the sake of concision of this article, only extreme results were shown, with the effects of heatwave events in a pessimistic RCP 8.5 scenario, comparing the business as usual with a general elevation of surfaces albedo.

The array of images show how the air temperatures would rise around 10°C in the whole area in the case of no mitigation, and how increasing albedo could benefit narrower streets with cooler pockets (Fig.4). As for the mean radiant temperatures, Fig. 5 shows that increasing albedo will make little difference in the future, but could have a very positive effect in reducing surface temperatures (Fig. 6), keeping them very close to the historical climate record.

PET results (Fig. 7) show that values are very uncomfortable for the elderly since the initial scenario, considering the heatwave data of 2005. That is worsened in the 2099 scenarios, and the change in urban surfaces albedo will have no noticeable mitigation effect.
The next round of simulations of this research will test the effect of increasing the Sky View Factor and offering shading devices on the sidewalks.

5. Conclusion

This is an ongoing research that is still exploring variables with the aim of proposing urban adaptation measures.

Results obtained until now confirm the hypothesis that increasing average albedo of built surfaces help mitigate rising temperatures, having a very favourable effect on superficial temperatures, and significant positive results on air temperatures. They also make clear that no single measure will be able to cope with the magnitude of the projected rising temperatures, but only a combination of factors will be effective in alleviating thermal discomfort. Increasing reflectivity of building surfaces, providing adequate urban morphology and wise inclusion of shading devices are some of the adaptation measures to be investigated.

Further developments of this research intend to contribute with effective guidelines for construction and urban planning for Sao Paulo, proposing urban adaptation measures for the Municipality's action plans.

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