Impacts of City Morphology on the Microclimatic Conditions of Consolidated Urban Areas in São Paulo During Hot Days

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IMPACTS OF CITY MORPHOLOGY ON THE MICROCLIMATIC CONDITIONS OF CONSOLIDATED URBAN AREAS IN SÃO PAULO DURING HOT DAYS

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ABSTRACT

This research evaluated the impacts that different morphological compositions of urban areas cause on the microclimatic conditions during hot days, based on simulations of the thermal conditions of open urban spaces in São Paulo. Five models representing neighborhoods with different morphological aspects were analysed using the ENVI-met software calibrated from empirical measurements of microclimatic variables in the real environment of one of the simulated models. All models were submitted to the same microclimate data and the analysis compared the main thermal variables results (air temperature, Mean Radiant Temperature, relative humidity, wind speed, direct, reflected and long wave radiation, daily hours of sunshine) over a 24-hour period.

There was a maximum difference of approximately 1.5°C in air temperature between the central points of the models. During daytime, the models with less verticalization and higher sky view factors values presented the highest air temperature, since open spaces are more exposed to direct sunlight, allowing greater surface heating, and the densest model showed the lowest air temperature, due to its urban canyon configuration. At night, the most verticalized model presented the highest air temperature, mainly due to the greater accumulation and trapping of heat by the urban canyon.

This work corroborates the results found in other researches, since it was found that different morphologies of the urban space impact on the thermal conditions of open urban spaces. They can change the received radiation, wind speed, air temperature, Mean Radiant Temperature and, consequently, the thermal comfort indexes in the open urban spaces and the demand of air conditioning in the buildings. The models with higher sky view factors presented higher air temperature during daytime, with a quicker heating due to the exposure to sunlight and, at night, the denser models showed the highest temperatures, due to the accumulation of heat in the urban canyon.

Keywords: thermal conditions, open urban spaces, urban microclimate, urban morphology

1. INTRODUCTION

This project was constituted in out an investigation of the impacts that different morphological compositions of consolidated urban areas can cause on the local microclimate conditions during hot days perceived on the pedestrian scale, based on simulations of the thermal conditions of open urban spaces in the city of São Paulo, using the ENVI-met software, calibrated from empirical measurements of microclimate variables collected in an existing environment of the city. Different models of urban planning can show how cities adapt to their growth, through horizontal expansion, densification, or both. They are relevant, among other reasons, because the bigger and more spread the urban occupation spots, the more they impact the environment, and further they intensify the effects of climate change and urban heating phenomena (GARTLAND, 2010).

In this scenario, recent researches have started looking for correlations between the formation of urban microclimates and urban morphology, which is defined by the volumetry of the urban environment and its transformation over time (LAMAS, 2004), and their results in terms of the aspects of buildings, roads, and open urban spaces (AMORIM; TANGARI, 2006). In a very simple way, by city morphology, we understand the volumetry and geometry of buildings, their heights, sizes and distributions in the city space.

The conception of urban morphology can contribute to increase or decrease the effects of urban heating phenomena (KRÜGER; MINELLA; RASIA, 2011), considering that the thermal ambience of the urban space is very sensitive to the volumetric changes of city environment (SHARMIN; STEEMERS; MATZARAKIS, 2017).

Studies have shown that urban morphology is decisive for the insolation and ventilation conditions of urban spaces and buildings (MINELLA; KRÜGER, 2015). The morphology can influence heat gain in the urban space during the day and heat loss during the night. Plus, it can change the speeds and the directions of the winds between streets and buildings (TALEGHANI et. al, 2015).

For example, urban canyons can perform thermally better during daytime than regions with lower buildings, as the shading of taller buildings helps to reduce the heat gain of urban space by direct radiation and these help to increase speed at the pedestrian level (SHARMIN; STEEMERS; MATZARAKIS, 2017), However, at night, urban morphology has a major impact on urban heat islands, as radiation is reflected diffusely in different directions by the surfaces of buildings over the other surfaces and, this way, urban canyons can help to trap radiation (OKE, 2002).

In Israel, it was found that the wide spacing has a heating effect, while the deepening of the urban canyon has a cooling effect (SHASHUA-BAR; TZAMIR; HOFFMAN, 2004), similar to a study in Sri Lanka that found more comfortable conditions on narrow streets with tall buildings (JOHANSSON; EMMANUEL, 2006).

Also, a study in Netherlands revealed that different urban geometries led to different thermal situations, with Mean Radiant Temperature and Wind Speed as the most influenced variables (TALEGHANI et. al, 2015), and studies in Bangladesh revealed Air Temperature and Mean Radiant Temperature maximum differences of up to 6°C and 10°C between irregular and regular urban forms (SHARMIN; STEEMERS; MATZARAKIS, 2017).

In this context, the objective of this research was to verify the impacts of different urban morphological compositions in thermal conditions of urban areas during hot days. The evaluation of five different models, with different occupation aspects, allowed to verify that the morphological conditions are capable of contributing to the alteration of the main thermal variables of the open urban space and pedestrian thermal comfort indexes. In the studied models, it was found that, the greater the density and the verticalization, the milder the thermal conditions of open urban spaces during the daytime (due to the shading caused by the buildings) and the higher the air temperature at night, due to the higher emission of long-wave radiation by the urban canyon at night.

2. METHODOLOGY

This work consisted in the comparative analysis of five models simulated in their thermal conditions of five models representing neighborhoods with different morphological aspects in São Paulo. The methodology used was the use simulations of thermal conditions in open urban spaces with the ENVI-met software calibrated with empirical measurements of microclimatic conditions in a real environment of São Paulo. There were five models that representing different neighborhoods of São Paulo, with different morphological aspects, from the most horizontal occupation to the densest and most verticalized.

All models were submitted to the same microclimate data and the analysis compared the main thermal variables results over a 24-hour period of evaluation from a 36-hour period of simulation.

The main thermal variables analysed were: Air Temperature (AT), Mean Radiant Temperature (MRT), Relative Humidity (RH), Wind Speed (WS), direct, reflected and long wave radiation, daily hours of sunshine. Furthermore, thermal comfort was studied through Perceived Equivalent Temperature (TEP) (MONTEIRO, 2018), a thermal comfort index for open urban spaces in São Paulo.

2.1 In loco measurements of microclimatic data

The models were calibrated from empirical measurements of microclimate variables presented on the site of one of the simulation models representing a real city environment. The measurements were made between December 6th 2018 and January 14th 2019 As shown in Figures 1A and 1B, the measurements were made in a residential neighbourhood in the southbound of São Paulo, mostly occupied by 1-floor and 2-floor houses. The meteorological station was installed in the rooftop of a 2-floor house, above the height of the surrounding buildings.

Figures 1A and 1B - Measurement location in São Paulo

Even though in São Paulo the summer is characterized by frequent rainfalls, this period was chosen as the most suitable time for measurements, reflecting greater possibilities for days with high temperatures. The 40-day measurement period, accompanied by daily records of weather conditions, made it possible to choose an evaluation hot day period after 4 consecutive days with high temperatures, low humidity, sunny conditions and stable weather. The data collected during the measurements were Wind Speed (WS) and Direction, Global Radiation (Ig), Globe Temperature (GT), Air Temperature (AT), Relative Humidity (RH), in 10-minute intervals. The measurements included the use of two Hobos and a Campbell Scientific Station.

Figures 2A, 2B, 2C and 2C - Lower measurement subpoint

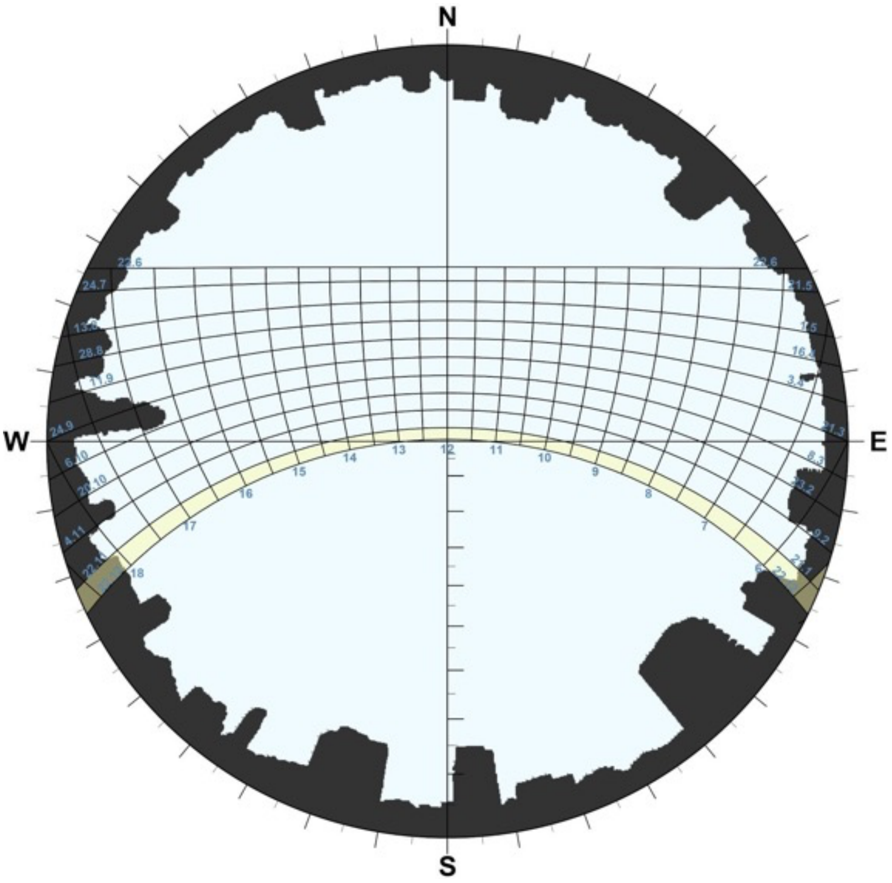
Figures 3A, 3B, 3C and 3D - Main measurement subpoint in the roof coverage

There were two fully open-sky external measuring subpoints. Figures 2A, 2B, 2C and 2C show a subpoint where control data were collected, located on the lower covering slab enclosed by sidewalls and, therefore, protected from the wind and with a partially obstructed sky view. In this case, the sensors were located approximately 4.5m above the ground, with the body of the Campbell Scientific Station and a Hobo, with 2 thermohygrometers and 2 globe thermometers.

Figures 3A, 3B, 3C and 3D show the main subpoint located on the roof slab of the two-story house, above surrounding constructions, in a location vertically and laterally unobstructed, with no sky masking, and fully exposed to sunlight and wind. With the sensors approximately 7.5m above the ground, where the data used for calibration of the simulation model were collected, the equipment of the Campbell Scientific Station and a Hobo were installed, containing 1 thermohygrometer, 1 globe thermometer, 1 pyranometer and 1 ultrasonic digital anemometer.

Figure 4 show the sky / solar mask profile of the main subpoint located on the roof slab of the two-story house, evidencing that there was no obstruction to solar direct radiation and sky view during the whole day, from 6am to 6pm during the whole 40-day measurement period.

Figure 4 - Sky / solar mask profile of the main subpoint located on the roof slab

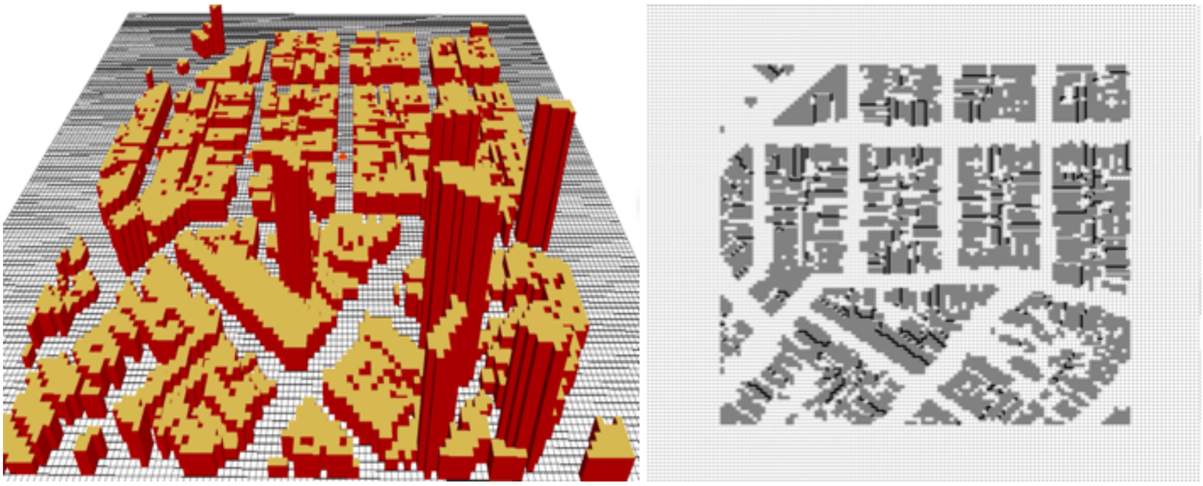


2.2 Analysis period and climatic model calibration

For the simulation and analysis, it was chosen the day that combined best high temperatures, low humidity, sunny and clear sky, stable conditions after several days with no rain. December 12th 2018 was chosen as the object day of evaluation, as it was the 4th consecutive day without precipitation, with clear and sunny skies, an AT ranged from 22°C to 35°C and RH from 20% to 68%, featuring a hot dry day with high temperatures. The predominant wind came from the Southeast (SE) direction and the weighted average wind speed was 1.5m/s. The measurements made on the roof slab were used for the calibration of the ENVI-met climatic model, while the measurements of the lower slab were used for comparative analysis. Simultaneously, measurements data were obtained for the same period from IAG/USP meteorological stations in Cidade Universitária and Água Funda.

The calibration of the ENVI-met model was carried out through successive simulations of a section of the Mirandópolis neighbourhood, with the adjustment of the software operational and input data, comparing the results obtained in the models with the data measured for the same point where the measurements were made, with volumetric and spatial characteristics modelled as in the real place. Figures 5A and 5B show the geometric model representing the Mirandópolis neighbourhood morphology surrounding the measurement point area.

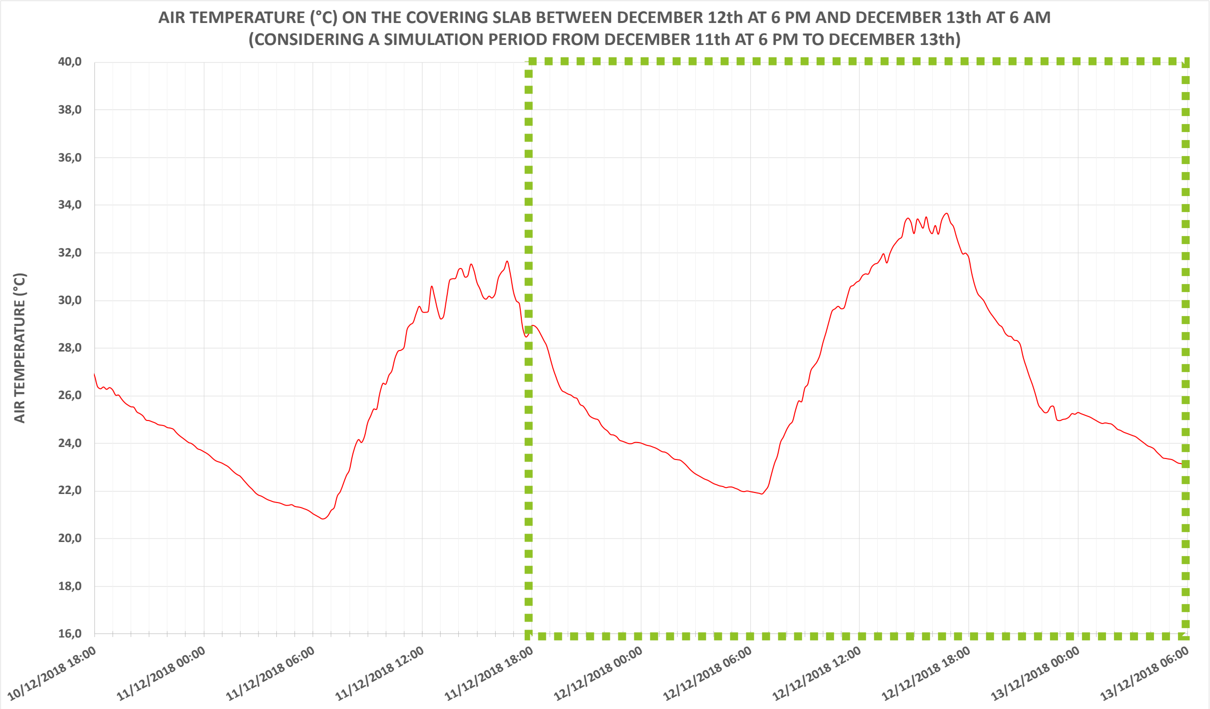
Figures 5A and 5B - Geometric model representing the Mirandópolis neighbourhood morphology surrounding the measurement point area



The period of analysis is a 24-hour cycle between December 12th 2018 at 06:00am and December 13th 2018 at 06:00am. Seeking for the adequate stabilization of the models before the analysis period and to guarantee that there are no influences on the model's initialization, the simulation time before the beginning of the analysis period was maximized and initialization during daytime period was avoided to obtain neutral atmosphere condition. This way, a 36-hour simulation period was adopted, starting at December 11th 2018 at 06:00pm (18:00), as seen in Graph 1.

Climate data was entered as full forcing in ENVI-met for the edges of the models.

Graph 1 – Air Temperature in the empirical measurements during the simulation period



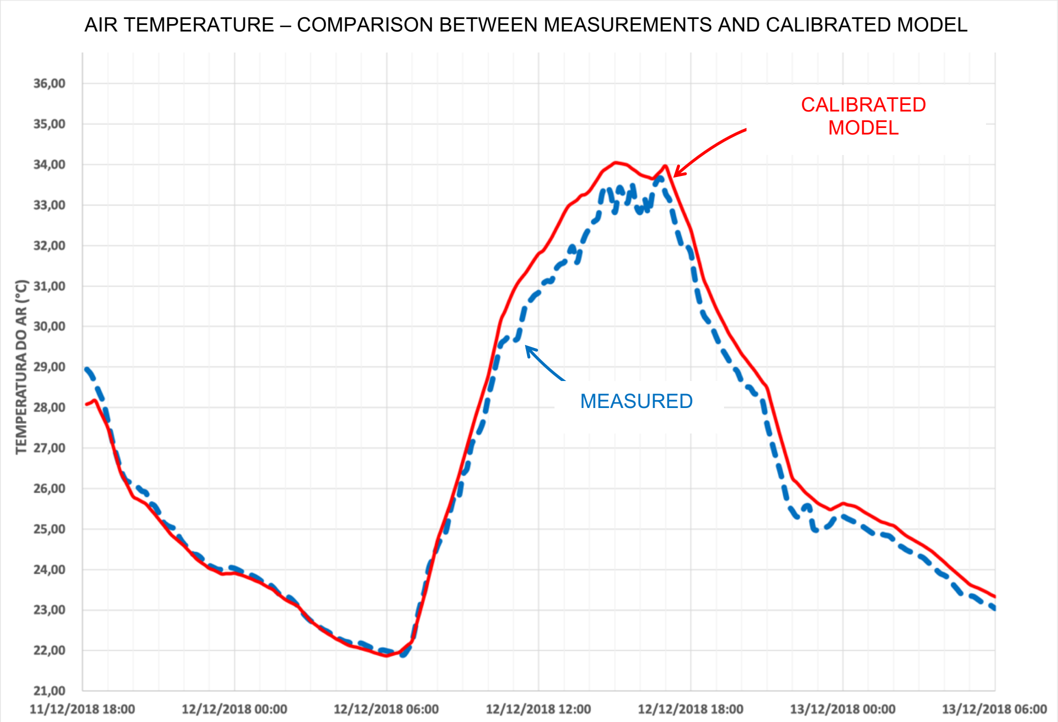
The simulation period was used to calibrate the ENVI-met climate model with a geometric model representing the place where the measurements were made. It was found as the optimum configuration for the calibrated climate model: the insertion of input data from the climate file of the Congonhas Airport for the whole year overwritten between December 9th 2018 at 00:00am and December 14th 2018 at 06:00am by the in loco measured data:

- AT and RH in 30-minute intervals from empirical measurements;
- wind direction 138.7° (Southeast) and speed 2.2m/s at the edge of the model to obtain the wind speed 1.5m/s at the measurement point, according to empirical measurements;
- and cloudiness recorded at 60-minute intervals by the IAG/USP Água Funda Meteorological Station.

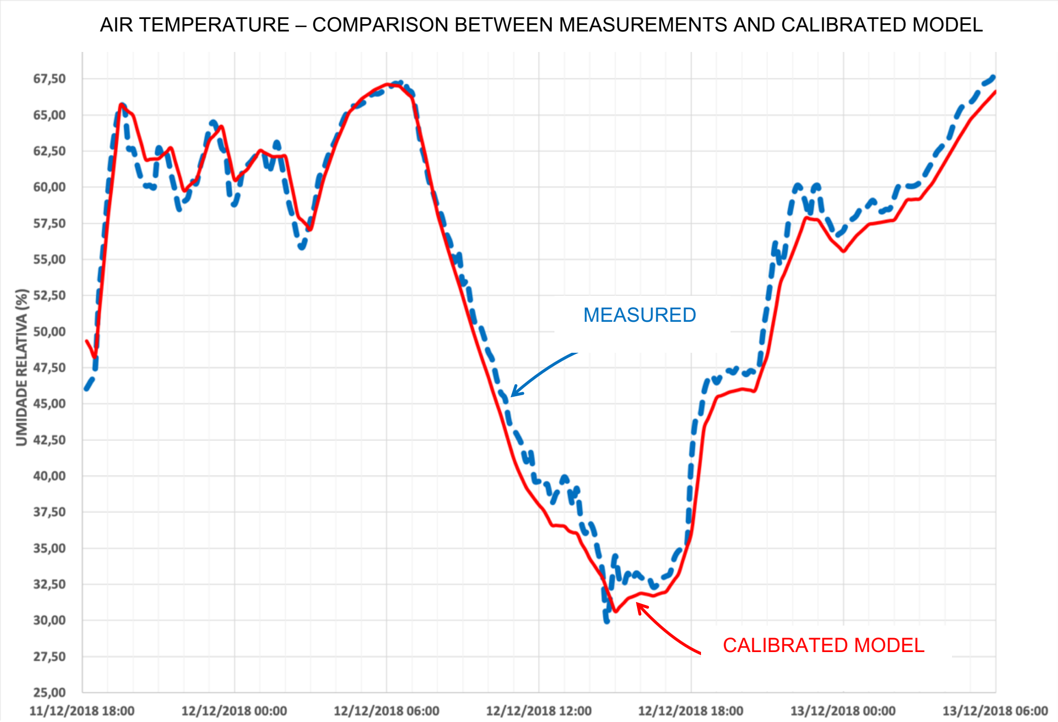
22 simulation models were made with small adjustments to achieve the optimum climate model, which presented high adherence with the real measurements made, with only minor differences. The calibrated model showed great adherence to the measurements within the established criteria, with maximum differences of:

- 1.5°C (4.9%) for AT (Graph 2),
- 5.4% (12.4%) for RH (Graph 3),
- 0.1m/s (7.7%) for the WS,
- and 0.4° (0.3%) for the wind direction.

Graph 2 - Comparison between ENVI-met calibrated model and measurements: Air Temperature (AT).



Graph 3 - Comparison between ENVI-met calibrated model and measurements: Relative Humidity (RH)



The calibrated model achieved a Mean Absolute Error (MAE) of 0.4°C in AT, 1.4% in RH, 0.1m/s in WS and 0.2° in wind direction, when compared to the measurements. Also, the Root Mean Square Error (RMSE) was evaluated comparing the calibrated model and the measurements, achieving 0.5 in AT, 1.7 in RH, 0.1 in WS and 0.2 in wind direction. A comparison was made, for the purpose of critical analysis, of the radiation records (direct, diffuse and long-wave) with the data recorded by the Meteorological Station of the IAG.

2.3 Simulated urban models and simulations

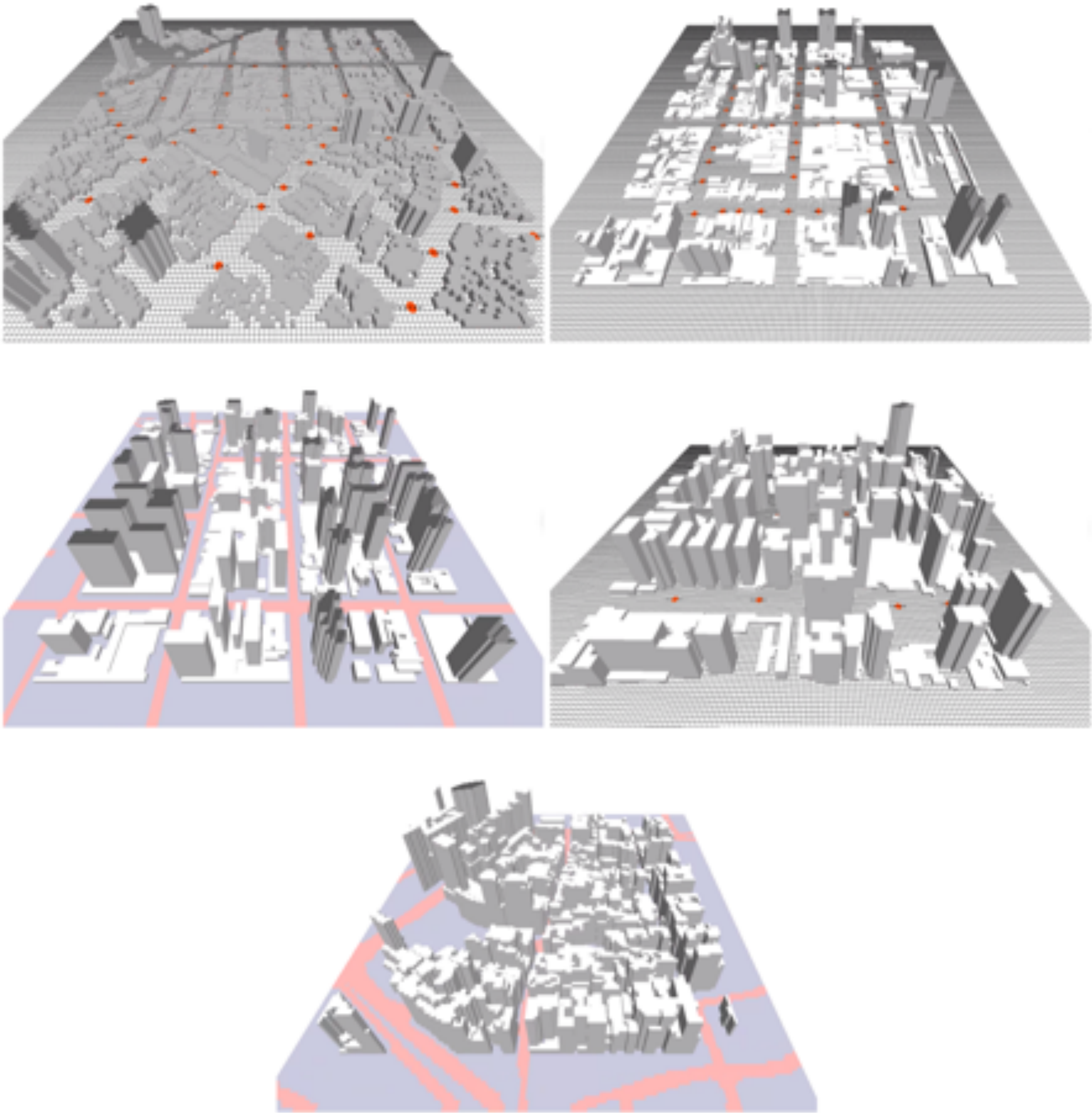
After the climate model was calibrated, the areas of the city to be analysed were chosen. Five areas were chosen to be compared, varying their morphological conditions. All areas have flat topography, little vegetations, no water bodies and similar aspects regarding the use of soil. The five models represent neighborhoods in the expanded centre of São Paulo (Mirandópolis, Ipiranga, Moema, Itaim Bibi and República), as shown in Figures 6A, 6B, 6C, 6D, 7A, 7B, 7C and 7D, with different morphological typologies, selected from consolidated urban areas of dense regular occupation, with mixed use, approximately flat topography, ranging from low to high verticalization high to low Sky View Factor (SVF), buildings spaced apart and twinned buildings, distant from water bodies, without significant vegetated areas, and with similar relationships of floor surfaces (asphalt and concrete) and similar occupancy rates (projection areas / soil area), from 54% to 67%.

Figures 6A, 6B, 6C and 6D - From left to right and top to bottom, aerial photos of the regions of the Mirandópolis, Ipiranga, Moema, Itaim Bibi and República areas

The geometries of the models, with a building area of 400x400m, wrapped in a surface area of 500x500m, and total height at least twice the height of the tallest building, were developed to reproduce the place with its streets and buildings, extracted from the digital map of the city, using QGIS. The models representing these areas have the exact same physical aspects and materials, differing only in the morphology, and all models have no vegetation. This way, we can guarantee that all different results derive specifically from the city morphology.

The volumetry of the models can be ranked as: Republic > Itaim Bibi > Moema > Ipiranga > Mirandópolis. Their variability of building heights can be ranked as: Moema > Itaim Bibi > República > Ipiranga > Mirandópolis.

Figure 7A, 7B, 7C and 7D - From left to right and from top to bottom, three-dimensional views of the models from Mirandópolis, Ipiranga, Moema, Itaim Bibi and República



To ensure the comparability between the models and that the differences in results were due exclusively to the morphological differences, all models have the same characteristics, varying only the morphological aspects of the urban typology, adopting the same materials for sidewalks, streets, soil, facades and roofs of buildings.

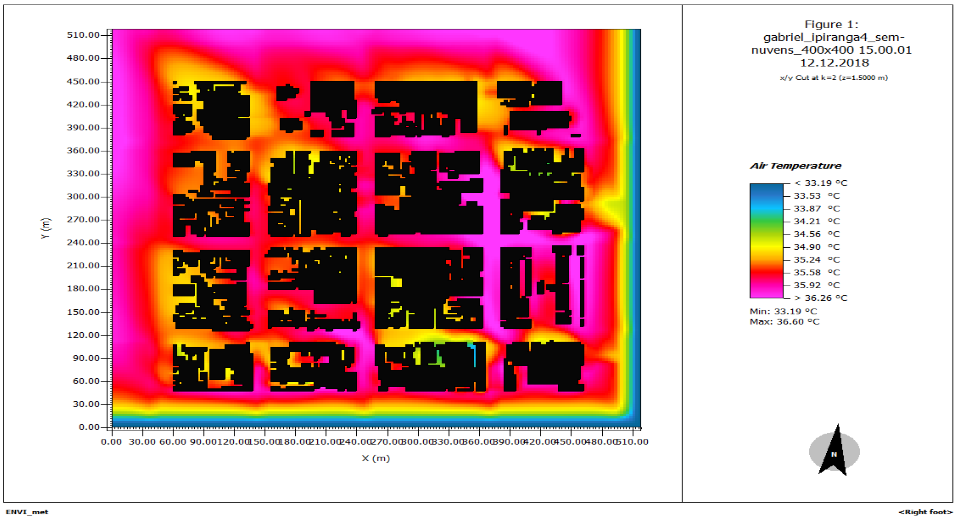
This way, all models used the same materials for the surfaces of sidewalks, streets and soil and for the facades and roofs of buildings, and they were created without topography, and, to maintain greater likelihood to reality, only approximately flat areas were selected. Also, all models were created without vegetation, thus avoiding microclimate impacts linked to soil permeability or vegetation.

The models adopted common asphalt as the surface of the roads and the "dirty" concrete pavement for the sidewalks and interior of blocks (GUSSON, 2014) and the clay and sandy soil, best representative of São Paulo (SHINZATO, 2014). For all buildings, masonry facade walls of concrete blocks and waterproofed concrete slab roofs were adopted, with normative and bibliography values for thermal and physical properties (ABNT, 2013; INMETRO, 2017).

3. RESULTS

The simulations results were analysed through maps at 1.50m height (pedestrian scale) with spatial distribution of Air Temperature (AT), Relative Humidity (RH), Wind Speed (WS), wind direction, radiation (direct, diffuse and long-wave) and Mean Radiant Temperature (MRT). Also, graphs, tables and spreadsheets of results were extracted at the central point of each model, at the most central crossing of roads, and at strategic points, at 1.50m height for the same variables and for the Perceived Equivalent Temperature (TEP). Example of a map at 1.50m height (pedestrian scale) with spatial distribution of Air Temperature (AT) in Ipiranga model can be seen in Figure 8.

Figure 8 - Example of a map at 1.50m height (pedestrian scale) with spatial distribution of Air Temperature (AT) in Ipiranga model

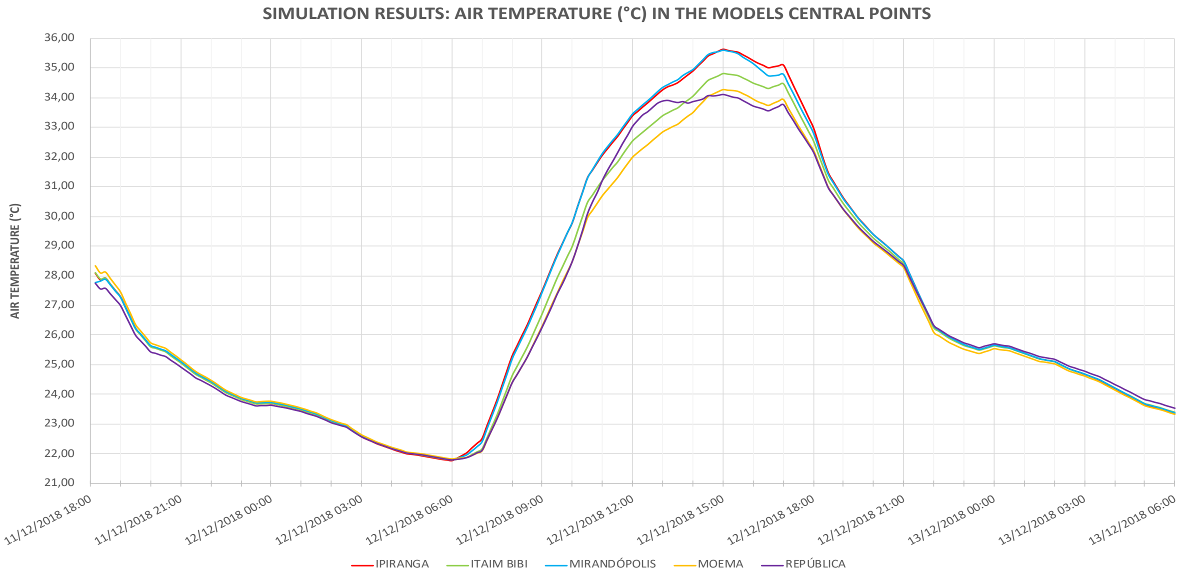


The results were analysed by comparing the models with each other in view of their different morphological characteristics. The simulations allowed to verify that the urban morphology is able to change the thermal balance of open urban spaces and the amount of radiation received by different points of space, including daytime and night-time, also changing the speed of the winds and, consequently, the thermal variables and the thermal comfort indexes.

According to Graph 4, during daytime, there was a maximum difference of Air Temperature (AT) of approximately 1.5°C between the central points of the less and more dense models. The models with less verticalization, less constructed volume and higher SVF values (Mirandópolis and Ipiranga) were the ones that presented the highest AT values during daytime period, since open spaces are more exposed to direct sunlight, allowing greater surface heating. Similarly, there was a maximum MRT difference of approximately 2.2°C between models.

On the other hand, the densest model (República) was the one with the lowest AT during the daytime, due to its urban canyon configuration, causing greater shading of open urban spaces. At night, the most verticalized models and with the highest constructive volume (Itaim Bibi and República) presented the highest AT values, which is mainly due to the greater accumulation of heat in the built masses and to the trapping of heat by the reflection of radiation in the urban canyon.

Graph 4 - Air Temperature (AT) results at the midpoints of the simulation models



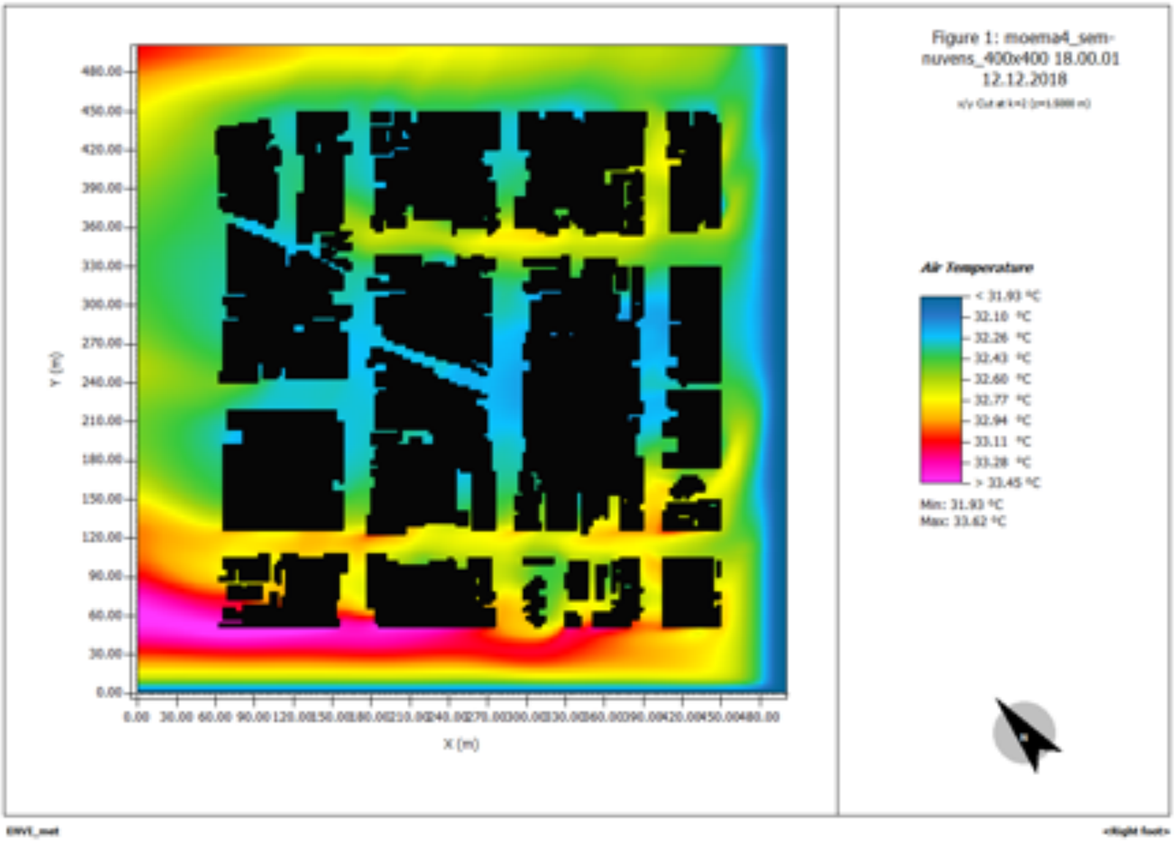
The less dense the models (Mirandópolis and Ipiranga), the more responsive they were to the daytime and night-time AT variations, with a greater and faster AT increase during the day, due to the greater exposure to direct radiation, and with a greater and faster loss of AT during the night, due to the lower emission of long-wave radiation due to the smaller amount of heat accumulated by the built masses.

Thus, the differences in response between the models also refer to the different conditions of exposure to sunlight, shading and radiation emitted by the buildings, analysed under the perspective of the Mean Radiant Temperature (MRT), whose maximum difference reaches 2.2°C between the models.

Even within the models, inside the area of one model, there were great differences between the various spaces, as the greater the building height variability (Moema and Itaim Bibi), the greater the differences between thermal conditions among the various spaces of the models. This happens mainly because the building height variability also causes different conditions of shading and exposure to the sun at different times in different spaces.

For example, in the Moema model, with greater height variability, at some times, the difference of AT between different sections of the same model reached 3.3°C (Moema), as shown in Figure 8.

Figure 8 - Air Temperature (AT) result of the Moema simulation on December 12th 2018 06:00pm (18:00)



It is also natural that the positioning and geometry of buildings can alter the directions and speeds of circulation of the winds, and in this case, the models with the greatest spacing between buildings and the greatest variability in heights were the most susceptible and permissive to the circulation of the winds.

The orientation of roads in the north-south and east-west directions forming regular blocks (Ipiranga) was the one that showed the best performance from the point of view of the permeability to the circulation of the winds coming from the southeast, which is the most common wind direction in São Paulo. This allows better distribution and greater speed of the winds in the streets.

The building height variability, besides interfering in the access to sunlight and shading, also creates differential wind conditions between the models, therefore, the models with greater spacing between buildings and with greater building height variability (Ipiranga and Moema) were the most permissive for the circulation of winds between spaces.

The good circulation of the winds made the environment more susceptible to thermal variations, which helps to remove heat and, consequently, at night, brings milder conditions. Thus, when there are mild and high AT values, the wind circulation has a positive impact on Perceived Equivalent Temperature (TEP), reducing its values, and therefore bringing better thermal comfort conditions for the pedestrians during this hot and dry period daytime. This way, the variability of building heights and the formation of urban canyons also showed a tendency of beneficial impact of reducing TEP during the day, which is associated with the shading caused by the buildings.

There are some important points to consider related to the positive impact of the wind speed in the thermal comfort of the pedestrians. First, the winds speed is beneficial to the pedestrians' thermal comfort when temperatures are mild and high but higher than the human body temperature, and wind speed can potentially reduce the effects of the radiation over the body, facilitating heat loss by the body. If this analysis were conducted in a winter cold day, or in a rainy day, with lower temperatures and lower radiation, wind speed might have had negative impacts in the pedestrians' thermal comfort index.

Secondly, the excess of wind speed might also cause discomfort, thus, creating obstacles that reduce the wind speed in the urban space, but do not integrally block wind circulation, such as buildings spaced from each other (not twinned buildings), walls, vegetation, might be a good solution. Also, we must remember that long street canyons with high twinned buildings can cause wind "corridors", helping to increase wind speed in the urban canyon direction.

To illustrate, there is a difference of up to 2.5°C in the TEP values between the central points of the models, and, with the exception of the República (most of the time with shaded roads), Ipiranga was the model that presented the best performance in terms of to TEP, which is understood to be associated mainly with the distribution of buildings and medium-to-high building height variability, which allowed alternation in the conditions of sunshine direct radiation and shading, and the regular layout of north-south and east-west roads, allowing better circulation of winds from the southeast to remove heat.

Also, during daytime, the most exposed areas of the models – which are more present in the less dense model (Mirandópolis) – showed higher values of TEP, related to the higher direct radiation in the spaces with higher SVF, contributing to reduce thermal comfort. This way, strategies to improve thermal comfort might include obstacles to sun direct radiation, mainly vegetation and also other shading tools.

4. CONCLUSION

The studies in this work corroborate results found in the referred researches, as it was found that different morphological models of the city morphology can cause great impacts on the thermal conditions of open urban spaces. This happens mainly because the morphological conditions of the urban space can change the amounts of direct, diffuse and reflected radiation received by the spaces, the wind speeds and, consequently, the Air Temperature and the Mean Radiant Temperature, and subsequently the thermal comfort indexes and the demand on the artificial air conditioning systems of buildings.

The models with less verticalization, less constructed volume and higher SVF values presented higher values of Air Temperature during the daytime, with an air heating that occurs more quickly because the open spaces are more exposed to sunlight and, at night, the more verticalizes and dense models showed the highest temperatures, due to the greater accumulation of heat in the built masses and the trapping of heat by the reflection of radiation in the urban canyon.

These results can contribute to the composition of urban planning guidelines (urban parameters, building regulations), supporting measures that can contribute to achieve better thermal conditions in urban open spaces and buildings, and a greater resilience to the scenarios of aggravation of urban heating and global climate change phenomena.

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