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

Abstract

This research carried out an evaluation of the potential 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 exemplifying neighborhoods in the city of São Paulo, using the ENVI-met software, calibrated from empirical measurements of microclimate variables collected in an existing city environment. The results of the evaluations of five different models, comparing their different occupation aspects, allowed verifying 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 index. In the studied models, it was found that, the greater density and verticalization, the milder the thermal conditions of open urban spaces during the daytime, due to the shading caused by the buildings, and the air temperature values at night are higher, due to the higher emission of long-wave radiation by the urban canyon at night.

Keywords

Thermal conditions. Open urban spaces. Urban microclimate. Urban morphology.

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IMPACTOS DA MORFOLOGIA DA CIDADE NAS CONDIÇÕES MICROCLIMÁTICAS DE ÁREAS URBANAS CONSOLIDADAS DE SÃO PAULO EM DIAS QUENTES

Resumo

Esta pesquisa realizou uma avaliação dos potenciais impactos que diferentes composições morfológicas de áreas urbanas consolidadas podem ocasionar sobre as condições microclimáticas locais em dias quentes percebidas na escala do pedestre, com base em simulações das condições térmicas de espaços urbanos abertos de exemplos de bairros da cidade de São Paulo, por meio do *software* ENVI-met, calibrado a partir de medições empíricas de variáveis microclimáticas em um ambiente existente da cidade. Os resultados das avaliações de cinco diferentes modelos, frente às suas diferentes características de ocupação, permitiram verificar que as condições morfológicas são capazes de contribuir para a alteração das principais variáveis térmicas do espaço urbano aberto e índices de conforto térmico dos pedestres. Nos modelos estudados, verificou-se que, quanto maior adensamento e a verticalização, mais amenas se mostraram as condições térmicas dos espaços urbanos abertos no período diurno, em função do sombreamento ocasionado pelos edifícios, e maiores os valores de temperatura do ar no período noturno, devido à maior emissão de radiação de onda longa pelo cânion urbano durante a noite.

Palavras-chave

Condições térmicas. Espaços urbanos abertos. Microclima urbano. Morfologia urbana.

1. Introduction and justification

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 and TANGARI, 2006).

Studies have already shown that urban morphology is decisive for the insolation and ventilation conditions of urban environments and buildings (MINELLA and KRÜGER, 2015). The morphology can influence the heat gain, reflection and accumulation by the masses built in the urban space during the day and the heat loss during the night. At the same time, it can change the speeds and the directions of the winds that permeate the voids between roads and buildings (TALEGHANI, KLEEREKOPER, *et al.*, 2015).

Thus, the conception of urban morphology can contribute to increase or decrease the effects of urban heating phenomena, helping to impact the conditions of thermal comfort of the pedestrian and the air conditioning of buildings (KRÜGER, MINELLA and RASIA, 2011), considering that the factors associated with the thermal ambience of the urban space are very sensitive to the volumetric changes of city environments (SHARMIN, STEEMERS and MATZARAKIS, 2017).

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 and 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 simulations of 60 different urban situations in Israel – a desert region with hot and dry weather –, it was found that the thermal impact due to the building configurations is significant and that the wide spacing has a heating effect, while the deepening of the urban canyon has a cooling effect (SHASHUA-BAR, TZAMIR and HOFFMAN, 2004). Similarly, a study in Colombo, Sri Lanka – a tropical climate region marked by strong winds and frequent precipitations in hot summers – found that more comfortable conditions were found on narrow streets with tall buildings. (JOHANSSON and EMMANUEL, 2006).

In another example, a comparison between 5 different models of urban geometry in urban areas of Delft, the Netherlands – a region with humid temperate climate, with cold winters and moderately hot summers – revealed that different urban geometries generated different microclimate situations, with Mean Radiant Temperature (MRT) and Wind Speed (WS) as the most influenced variables (TALEGHANI, KLEEREKOPER, *et al.*, 2015). In addition, studies in Dhaka, Bangladesh – a tropical climate region with a hot and humid summer - revealed for Air Temperature (AT) and Mean Radiant Temperature (MRT) maximum differences of up to 6.2°C and 10.0°C respectively between irregular urban forms and regular areas (SHARMIN, STEEMERS and MATZARAKIS, 2017).

In this context, resulting from a Master of Science's degree, under the guidance of the Leonardo Marques Monteiro, PhD, carried out at LABAUT, FAU USP, the objective of this research is to investigate the impacts of different solutions of urban morphological compositions in microclimatic conditions of consolidated urban areas during hot days.

2. Methodology

The work methodology consists in the comparative analysis through the simulations of the thermal conditions perceived in the pedestrian scale of open urban spaces that are representative of São Paulo districts, using the *software* ENVI-met 4.4.3 *Summer* 19, calibrated from empirical measurements of microclimate variables presented on the site of one of the simulation models representing a real city environment.

The simulated urban models represent neighborhoods with consolidated urban formations in the expanded center of São Paulo with different morphological aspects, submitted to the same microclimate data from their edges. The analysis was performed comparing the main microclimate variables (air temperature, Mean Radiant Temperature, relative humidity, wind speed, direct, reflected and long wave radiation, daily hours of sunshine) at the central points of each model and dispersed in their areas, and their variations over the 24-hour period analyzed. Furthermore, for the analysis of thermal comfort, the results obtained were studied in each model through the TEP – Perceived Equivalent Temperature (MONTEIRO, 2018) – thermal comfort index for open urban spaces in the city of São Paulo.

2.1. In loco measurements of microclimatic data

The measurements were made in a two-story house in Mirandópolis, South Zone of São Paulo, between December 6th 2018 and January 14th 2019. 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 dailys record of hot weather conditions, made it possible to choose an evaluation period after 4 consecutive days with high temperatures, low humidity, sunny conditions and stable weather.

EQUIPMENT, BRAND AND MODEL	MEASUREMENT, RESOLUTION AND ACCURACY RANGE
Nikon Coolpix 4500, 4.0Mp photo camera with "Fisheye" Hemisphere Lens Nikon Fisheye Converter FC-E8 0.21x Japan	
***Campbell* Scientific Station**	
2D Ultrasonic 2D WindSonic 4 anemometer from Campbell Scientific, Inc.	Wind direction measurement range from 0 º to 359º with a resolution of 1º and accuracy of 3º. Measuring range Air speed from 0 to 60 m / s resolution and ±2% accuracy for up to 12 m / s.
Campbell Scientific, Inc. Cr800 Type Data Logger	Data records with programmable intervals of up to 1 minute.
Campbell Scientific, Inc. CMP3-L type dome pyranometer	Measuring range up to 2000 W / m² with ±5% in the 10º to 40º of Air Temperature and imprecision of ±2% to ±7% to 1000 W / m².
Campbell Scientific, Inc. HMP45C Temperature and Relative Humidity Probe Thermohygrometer with 41003-5 Solar Radiation Thermometer Protection I 10-Plate Naturally-Aspirated Radiation Shield by Campbell Scientific, Inc.	Air temperature measurement range from -39.2º to +60º with 0.1ºC resolution and, for a working range between 0º and 40ºC, inaccuracy of ±0.3 ºC. Measurement range with variable accuracy of ±2% between 0% and 90% RH and ±3% in the range of 90% to 100%.
Campbell's Globe Thermometer with 15.2cm diameter BlackGlobe Temperature Sensor for Heat Stress from Campbell Scientific, Inc. with temperature sensor type BlackGlobe-L.	Globe temperature measurement range from -5ºC to +95ºC with 0.1ºC resolution and ±0.2ºC precision from 0ºC to 70ºC and ±0.3ºC up to 95ºC.
Hobos	
HOBO Prov v2 Loggers Data Logger	Capacity for 42,000 measurements, with periodicity programmable up to 1 second.
Protected Onset Hobo Data Loggers U23-001 thermohygrometer Protection for Thermometer against Solar Radiation model Rs1 Solar Radiation Shield	Air temperature recording range from -40ºC to +70ºC, with 0.02ºC resolution and precision of ±0.21ºC in the range of 0ºC to 50ºC. Record range of 0% to 100% relative humidity measurements with 0.03% resolution and + 2.5% accuracy in the range of 10% to 90%.
Globe thermometer composed of U23- dry bulb thermometer 004 by Onset Hobo Data Loggers inserted in a painted brass globe in light gray color with 17cm diameter	Air temperature recording range from -40ºC to + 70ºC with resolution of 0.02ºC and precision of + 0.21ºC in the range of 0ºC to 50ºC.

Table 1 – Measuring equipments used and its technical parameters
Source: NOVAES, G. B. A. Impactos da Morfologia da Cidade nas Condições Microclimáticas de Áreas Urbanas Consolidads de São Paulo em Dias Quentes. São Paulo: Dissertação de Mestrado apresentada à Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo (FAU USP), 2020.

The data collected during the measurements were Speed (Var) and Wind 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. Table 1 summarizes the equipment used and its technical aspects.

There were two fully open-spy external measuring subpoints. As shown in Figure 1, a subpoint, where control data were collected, was located on the lower covering slab of a one-story building, 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, 2 globe thermometers.

As shown in Figure 2, the other subpoint was located on the roof slab of the two-story house, above the height of the other surrounding constructions, in a vertically and laterally unobstructed location, with no sky masking between

Figure 1 – Lower subpoint with the body of the *Campbell* Scientific Station and a *Hobo*
Source: NOVAES, G. B. A. Impactos da Morfologia da Cidade nas Condições Microclimáticas de Áreas Urbanas Consolidadas de São Paulo em Dias Quentes. São Paulo: Dissertação de Mestrado apresentada à Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo (FAU USP), 2020.

Figure 2 – Subpoint of the roof slab with *Campbell* Scientific Station equipments and a *Hobo*
Source: NOVAES, G. B. A. Impactos da Morfologia da Cidade nas Condições Microclimáticas de Áreas Urbanas Consolidadas de São Paulo em Dias Quentes. São Paulo: Dissertação de Mestrado apresentada à Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo (FAU USP), 2020.

December and January, 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 (in unobstructed position ahead to the solar north in relation to the other equipments) and 1 ultrasonic digital anemometer (in an unobstructed position above all other equipments)

Among the results obtained in the measurements of the roof slab, the Air Temperature (AT) varied between 13.4°C and 37.6°C, with most days exceeding 30°C. The Relative Humidity (RH) varied between 17.0% and 96.3%, with values above 70% on most nights and below 30% on several days. The Wind Speed (WS) varied between 0.0m/s and 6.5m/s, and in about 80% of the time, it was up to 2.0m/s. In agreement with IAG/USP (2018), the predominant winds come from the Southeast (SE) direction, representing 24% of the measurement time.

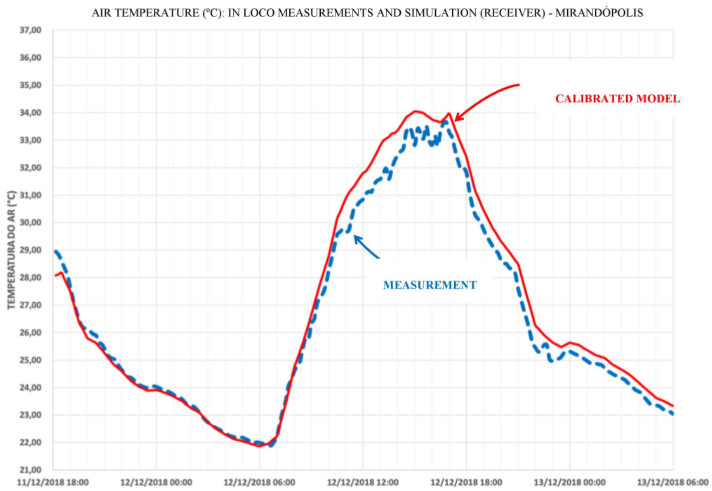
December 12th 2018 was chosen as the object day of evaluation, as it was the day that presented the most stable weather condition, being the fourth consecutive day without precipitation, with high maximum and minimum AT values, low RH throughout the day and night, clear and sunny skies. On this day, AT ranged from 22ºC to 35°C and RH from 20% to 68%, featuring a dry day with high temperatures. The predominant wind, determined by the most common value of the anemometer measurements, came from the SE direction, with 138.7° (Southeast) direction being predominant, and the weighted average wind speed was 1.5m/s.

The measurements made by the equipment 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, showing values and curves of air temperature and relative humidity measurements with low variation in relation to the roof slab. Simultaneously, data on climate measurements were obtained for this period from IAG/USP meteorological stations in Cidade Universitária (West Zone of São Paulo) and Água Funda in Parque do Estado (South Zone of São Paulo). In a comparative way, the measurements obtained in the in loco measurements were critically verified against the climatic data of the meteorological stations, to which the measurements showed adequate adherence.

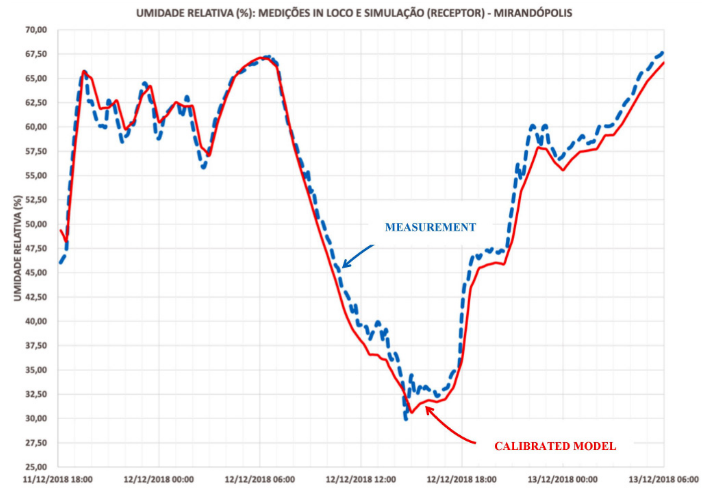
2.2. CALIBRATION OF THE CLIMATIC MODEL FOR SIMULATIONS

The calibration of the ENVI-met *software* was carried out through successive simulations of a section of the Mirandópolis neighborhood, with the adjustment of the operational data of the *software* and the input data, comparing the results obtained in the models with the data measured for the same point where the measurements were made at 7.50m high above the ground, with volumetric and spatial characteristics modeled as in the real 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 00:00 am and December 14th 2018 at 06:00 am by the in loco measured data: AT and RH in 30 minute



Graph 1 – Comparison between calibrated model and measurements: Air Temperature (AT)
Source: NOVAES, G. B. A. Impactos da Morfologia da Cidade nas Condições Microclimáticas de Áreas Urbanas Consolidads de São Paulo em Dias Quentes. São Paulo: Dissertação de Mestrado apresentada à Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo (FAU USP), 2020



Graph 2 – Comparison between calibrated model and measurements: Relative Humidity (RH)
Source: NOVAES, G. B. A. Impactos da Morfologia da Cidade nas Condições Microclimáticas de Áreas Urbanas Consolidads de São Paulo em Dias Quentes. São Paulo: Dissertação de Mestrado apresentada à Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo (FAU USP), 2020.

AIR TEMPERATURE (ºC)	MEASUREMENT	CALIBRATED MODEL	ABSOLUT DIFFERENCE (MODEL -MEASUREMENT)	RELATIVE DIFFERENCE (MODEL -MEASUREMENT)
AVERAGE	26,47	26,86	0,40	1,39%
MAXIMUM	33,65	34,04	1,53	4,86%
MINIMUM	21,89	21,87	-0,22	-0,91%
STANDARD DEVIATION	3,64	3,96	0,40	1,33%
RELATIVE HUMIDITY (%RH)	MEASUREMENT	CALIBRATED MODEL	ABSOLUT DIFFERENCE (MODEL -MEASUREMENT)	RELATIVE DIFFERENCE (MODEL -MEASUREMENT)
AVERAGE	53,80	52,80	-1,06	-2,27%
MAXIMUM	67,94	67,11	2,59	7,36%
MINIMUM	29,94	30,61	-5,42	-12,37%
STANDARD DEVIATION	10,92	11,47	1,26	2,75%
WIND SPEED (m/s)	MEASUREMENT	CALIBRATED MODEL	ABSOLUT DIFFERENCE (MODEL -MEASUREMENT)	RELATIVE DIFFERENCE (MODEL -MEASUREMENT)
AVERAGE	1,47	1,47	0,00	0,29%
MAXIMUM	1,47	1,59	0,11	7,72%
MINIMUM	1,47	1,40	-0,07	-4,55%
STANDARD DEVIATION	0,00	0,05	0,05	3,34%
WIND DIRECTION (º)	MEASUREMENT	CALIBRATED MODEL	ABSOLUT DIFFERENCE (MODEL -MEASUREMENT)	RELATIVE DIFFERENCE (MODEL -MEASUREMENT)
AVERAGE	138,70	138,74	0,05	0,04%
MAXIMUM	138,70	138,96	0,26	0,19%
MINIMUM	138,70	138,30	-0,37	-0,27%
STANDARD DEVIATION	0,00	0,19	0,18	0,13%

Table 2 – Records in the measurements and in the calibrated model
Source: NOVAES, G. B. A. Impactos da Morfologia da Cidade nas Condições Microclimáticas de Áreas Urbanas Consolidads de São Paulo em Dias Quentes. São Paulo: Dissertação de Mestrado apresentada à Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo (FAU USP), 2020.

intervals as 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 Água Funda Meteorological Station (Parque do Estado).

The period of analysis of results is a 24-hour cycle between December 12th 2018 at 06:00 am and December 13th 2018 at 06:00 am and, seeking to maximize the simulation time before the beginning of the analyzed period for the adequate stabilization of the models and to guarantee that there are no influences on the model's initialization, a simulation period of 36 hours was adopted, starting at December 11th 2018 at 06:00 pm (18:00), which means, the simulation started 12 hours before the beginning of the studied period, avoiding the daytime period to obtain neutral atmosphere condition.

The approval criteria for the calibrated model were maximum differences between measurements and simulation of 5% for air temperature and wind direction and 15% for relative humidity and wind speed. The final calibrated model showed adherence to the measurements within the established criteria, with maximum differences of 1.5°C (4.9%) for AT (Graph 1), 5.4% (12.4%) for RH (Graph 2), 0.1m/s (7.7%) for the WS, and 0.4° (0.3%) for the wind direction. Table 2 summarizes the records of AT, RH, WS and wind direction in the measurements and in the calibrated model and the respective differences.

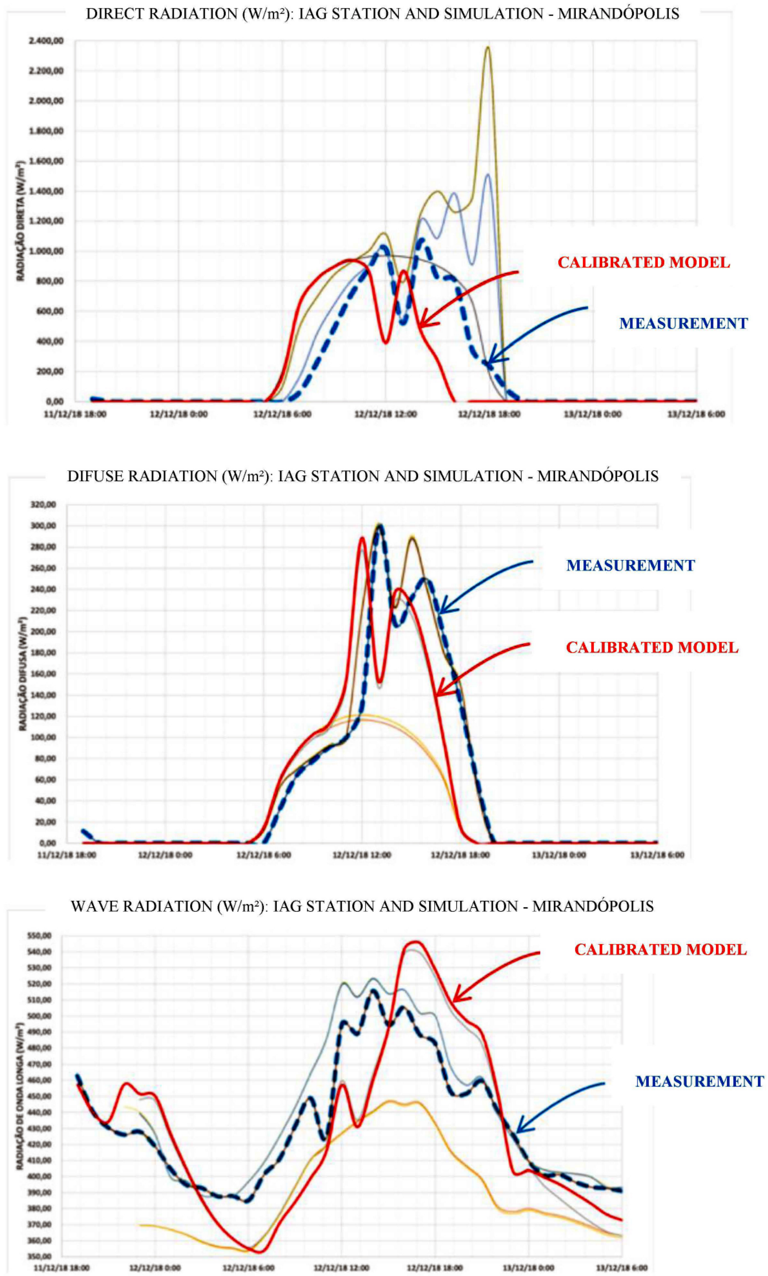
As can be seen in Graph 3, a comparison was made between the radiation records (direct, diffuse and long wave) obtained in the calibration point in the simulation model and in the data recorded by the IAG Meteorological Station for the same period. As it is not the same point, the comparison of radiation curves was done only critically. The model has been approved due to the presentation of curves with the same aspect and small differences in maximum and minimum values recorded, as shown in Table 3.

Thus, the model was considered suitable for carrying out the simulations. There was a slight tendency to overestimate the effect of daytime heating and drop in RH.

2.3. SIMULATED URBAN MODELS

With the calibrated climate model, simulations of five representative models of neighborhoods of São Paulo were performed, objects of independent simulations adopting the same climate file, that is, submitted to the same microclimate conditions in their external limits. To ensure 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 following premises:

- All models used the same materials for the surfaces of sidewalks, streets and soil and for the facades and roofs of buildings
- All models were created without topography, and, to maintain greater likelihood to reality, only approximately flat areas were selected
- All models were simulated georeferenced to the city of São Paulo



Graph 3 – Comparison between calibrated model and measurements, from top to bottom: direct radiation, diffuse radiation and long wave radiation
Source: NOVAES, G. B. A. Impactos da Morfologia da Cidade nas Condições Microclimáticas de Áreas Urbanas Consolidads de São Paulo em Dias Quentes. São Paulo: Dissertação de Mestrado apresentada à Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo (FAU USP), 2020.

	DIRECT RADIATION		DIFFUSE RADIATION		LONG WAVE RADIATION	
	IAG STATION	CALIBRATED MODEL	IAG STATION	CALIBRATED MODEL	IAG STATION	CALIBRATED MODEL
MAXIMUM	1.068,15	939,31	299,13	288,54	515,57	545,57
MINIMUM	0	0	0	0	385,08	353,95

Table 3 – Records of radiation incidence at the IAG Station and in the calibrated model
Source: NOVAES, G. B. A. Impactos da Morfologia da Cidade nas Condições Microclimáticas de Áreas Urbanas Consolidads de São Paulo em Dias Quentes. São Paulo: Dissertação de Mestrado apresentada à Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo (FAU USP), 2020.

• All models were created without vegetation, thus avoiding microclimate impacts linked to soil permeability or vegetation

• All models were simulated with minimum cloud conditions, according to the day chosen for analysis, which presented clear skies

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 layout and masses built. The locations of the buildings and their geometries and the maps of streets and sidewalks were extracted from the Digital Map of the City (MUNICIPALITY OF SÃO PAULO, 2019) using the QGIS *software* and inserted in ENVI-met. The models followed examples of similar studies in São Paulo, with the adoption of common asphalt as the surface of the carriage bed of the roads, the "dirty" concrete pavement for the sidewalk areas and interior of blocks (GUSSON, 2014) and the clay and sandy soil, best representative of the São Paulo city (SHINZATO, 2014). For all buildings, masonry facade walls of concrete blocks and waterproofed concrete slab roofs were adopted, with normative (ABNT, 2013) and bibliography (INMETRO, 2017) values for thermal and physical properties.

The areas chosen are regions in the expanded center of São Paulo (Ipiranga, Itaim Bibi, Mirandópolis, Moema and República), as shown in Figure 3, with

Figure 3 – From left to right and top to bottom, aerial photos of the regions of the Mirandópolis, Ipiranga, Moema, Itaim Bibi and República models
Photos extracted by Google Earth . In: NOVAES, G. B. A. Impactos da Morfologia da Cidade nas Condições Microclimáticas de Áreas Urbanas Consolidads de São Paulo em Dias Quentes. São Paulo: Dissertação de Mestrado apresentada à Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo (FAU USP), 2020.

different morphological typologies, selected from consolidated urban areas of densely built regular occupation, with mixed use, approximately flat topography, ranging from low verticalization to large verticalization and between buildings spaced apart and twinned buildings, distant from water bodies, without significant vegetated areas, and with similar relationships of floor surfaces (asphalt and concrete).

Urban parameters and statistical data of the models were used to characterize the geometries of the models, such as the average height of the buildings and the statistical distribution of the built area by height ranges and projection area, the standard deviation of the heights of the buildings, Occupancy Rate (OR), constructed volume, estimated Utilization Coefficient (UC). The H/W factor (ratio between the height of buildings and the width of the urban canyon roads) and the Sky View Factor (SVF) are used to characterize the geometry of the urban space, and the H/Aproj index (ratio between height and projection area of the building) to characterize the occupation in terms of more vertical or horizontal buildings. There is also the verification of the orientation of the roads, which has an impact on the conduction of the winds, and access to sunlight on the roads at the pedestrian height.

The model with the lowest building density was an area in the Mirandópolis neighborhood, with predominantly residential use. Without significant verticalization, there are few residential towers in the middle of the one and two-story houses, forming a neighborhood with many low and small buildings. It is a reasonably flat area, with irregular street layout, forming rectangular, trapezoidal and triangular blocks. The streets are oriented approximately in the Southwest-Northeast and Southeast-Northeast directions.

With an OR of 56.7%, the buildings have a projection area of up to 941.6m², the majority of which are between 100m² and 200m². Its heights reach 52.6m and, with an average of 5.2m and standard deviation of 4.3m, there is little variability. These are mostly one and two-story houses, and small commercial establishments. With an estimated UC of 1.4, 63.3% of the occupied area corresponds to buildings with an H/Aproj ratio of up to 0.05 (low buildings) and the H/W values vary between 0.1 and 1.0 in the frontal and up to 1.7 in the lateral direction, which results in SVF between 0.5 and 0.9 on the roads.

The second model, with a light building density and progressive verticalization in the last decades, is an area of Ipiranga, with a predominantly mixed use, marked by neighborhood commerce, with a few industrial warehouses, wholesale markets and factory stores. It is a neighborhood with many low buildings, such as one and two-story houses, permeated by several new medium and high residential towers with lateral and frontal setbacks. It is a flat region, with a reticulated and quadrangular road layout, and streets oriented in the North-South and East-West direction.

With an OR of 64.1%, the projection areas of the buildings reach 4,186.6m² (warehouses and large stores) and the heights reach 76m, with an average height of 10m and standard deviation of 13.7m, that is, with median variability in building heights. There are many buildings with heights of up to 10m and projection areas of up to 200m² (one and two-story houses), but also several buildings with 30m to 70m of height and projection area of up to 300m² (residential towers). With an estimated UC of 2.5, 69.6% of the occupied area has an H/Aproj index of up to 0.05 (houses, two-story houses, warehouses), with a significant share of 11.4% with more than 2000m² of projection area (warehouses and large stores). The distance between the buildings brings H/W values between 0.1 and 5.1 in the frontal direction and from 5.1 in the lateral direction. This geometry results in SVF between 0.3 and 0.8 on the roads.

The third model on the scale of construction density is the area in Moema, a neighborhood marked by mixed use, mixing intense verticalization but still very relevant presence of lower buildings such as one and two-story houses and commercial establishments. It is a very flat region, with regular road layout, forming rectangular blocks, but also, due to some diagonal paths, some few trapezoidal and triangular blocks. In this section of the neighborhood, the streets are mostly oriented approximately in the Southwest-Northeast and Southeast-Northeast directions.

With an OR of 66.7%, the projection areas of the buildings reach 2,853.6m² (large buildings, basements of towers and commercial establishments), with an average of 356.7m² (residential tower), and the heights reach 74m, with an average of 17m and standard deviation of 21m, that is, with great variability of heights. There is a concentration of buildings up to 10m high with various projection areas, such as houses, two-story houses, commercial establishments, etc., and of buildings between 30 and 60m high with projection areas between 200 and 500m², such as medium-sized towers. With an estimated UC of 3.9, 66.2% of the projection area is up to 6m high and 26.4% between 6m and 70m high. The frontal distance between the buildings brings H/W values between 0.1 and 3.7 in the frontal direction and between 0.1 and 7.4 in the lateral direction, which results in SVF varying between 0.3 and 0.8 on the roads.

As the second most densified model, Itaim Bibi has undergone an intense verticalization and densification process in the most recent decades. It is an area of mixed use, almost entirely verticalized, with towers marked by great lateral proximity and frontal alignment, forming urban canyons. With many tall residential and commercial towers arranged independently on their lands, mostly small, permeated by some of the lower remaining buildings and the lower and wider basements of the towers. There is a relative standardization of the heights of the towers. In addition, it is a region with a reticulated road layout, with mostly rectangular blocks. In this section, the streets are oriented in the Southwest-Northeast direction.

With an OR of 54.3%, the projection areas of the buildings reach 1,589.8m² (basements of towers and commercial establishments), with an average of 313.5m² (tower), and the buildings have a height that reaches 89m, with an average height of 19m and standard deviation of 20.4m, that is, there is a relative variability of heights marked by the differences between the towers and their bases. There are several buildings up to 10m high and up to 500m² of projection area (commercial establishments, towers basements, etc.) and many buildings from 30m to 70m in height with a projection area of 200m² to 800m² (towers). With an estimated UC of 4, 52.9% of the building projection area is up to 6m high, but 35.9% have heights greater than 30m. 40.5% of the occupied area has H/Aproj of 0.05 to 0.25 (most of the residential and commercial towers). The distances between the towers bring H/W values between 0.1 and

5.0 in the frontal direction and between 0.3 and 8.9 in the lateral direction, which results in SVF values between 0.2 and 0.6 in the tracks, being between 0.2 and 0.3 in the central track of the model.

The most densely constructed model is the area in the República neighborhood, an area of old urbanization, with densification in the first half of the 20th century. It is a predominantly commercial area, with mixed use, very vertical, with several tall buildings, most of them without frontal or lateral setbacks, creating urban canyons. Over time, some high-rise residential and commercial buildings and towers have emerged, such as the Copan Building and the Itália Building. In addition, it is a very flat region, with a very irregular road layout, forming blocks of varied shapes with streets of different sizes, oriented approximately in the Southwest-Northeast and Southeast-Northwest directions.

With an OR of 59.8%, the projection areas of the buildings reach 2,709.7m^2 (larger buildings and commercial establishments), with an average of 213.7m^2, and the buildings have a height that reaches 125m, with an average height of 37m and standard deviation of 18.4m, that is, there is reasonable variability of the heights of the built masses. There are many buildings with heights of up to 20m and projection areas of up to 200m^2 and several between 30 and 60m in height with projection areas of up to 200m^2, corresponding to the typical profile of the region of medium height buildings with small dimensions in plan. With an estimated UC of 7.7, 88.0% of the occupied area is marked by small, medium and large buildings over 12m high. 56.8% of the occupied area presents H/Aproj from 0.05 to 0.25 (marked presence of medium height buildings) and 16.2% above 0.25 (towers). The frontal distances between the buildings and the null lateral distances (twinned buildings) bring H/W values between 0.1 and 4.7 in the frontal direction, which results in SVF varying between 0.1 and 0.6, being between 0.1 and 0.3 on most roads.

Figure 4 presents the geometric models built for the simulations of the studied regions.

The Occupancy Rate is very similar between the models, varying from 54% (Itaim Bibi) to 67% (Moema), as well as the area ratio of asphalt roads and concrete pavements (sidewalks and interior of blocks), being approximately 15% asphalt surface and 85% concrete pavement surface on all models. The average height of the buildings and the statistical analysis of the heights allow verifying the verticalization and the variability of the heights of buildings in the same region. The average height of the buildings exposed the gradation of built volumetry: República > Itaim Bibi > Moema > Ipiranga > Mirandópolis. And the standard deviation of heights expressed the variability of the heights of buildings: the greater the standard deviation, the greater the variability of heights, with the following gradation: Moema > Itaim Bibi > República > Ipiranga > Mirandópolis.

It became clear that it is necessary to critically analyze the effect of urban morphology, characterized by a set of different aspects. For example, the models are similar to each other in terms of soil occupancy rate (OR) and road area, but differ essentially in volume built, quantities, types, dimensions and distributions of buildings.

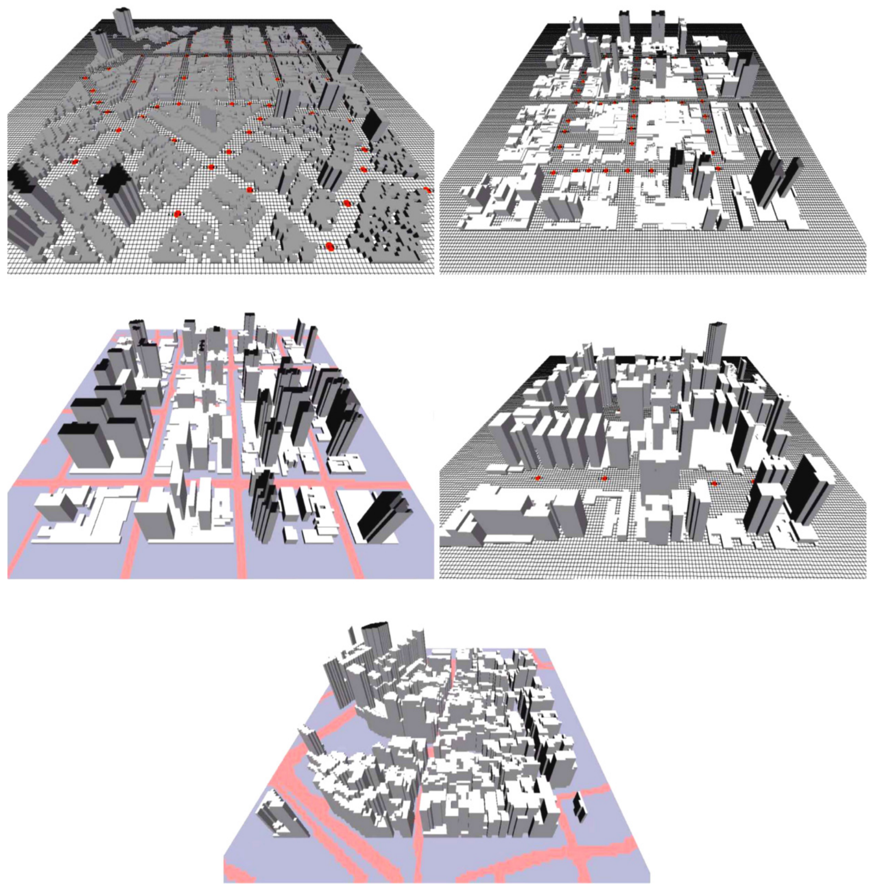


Figure 4 – From left to right and from top to bottom, three-dimensional views of the models from Mirandópolis, Ipiranga, Moema, Itaim Bibi and República
Source: NOVAES, G. B. A. Impactos da Morfologia da Cidade nas Condições Microclimáticas de Áreas Urbanas Consolidads de São Paulo em Dias Quentes. São Paulo: Dissertação de Mestrado apresentada à Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo (FAU USP), 2020.

In this sense, the study of the factors H/W, H/Aproj and SVF allows to characterize the models in a qualitative way and in terms of exposure to the sky and access to sunlight. The H/W marked the Mirandópolis model very clearly for its low verticalization, while the SVF denoted how the Mirandópolis and Ipiranga models offer much greater exposure to the sky in their various points, while the República model offers great sky view obstruction and masking and, in a median way, Itaim Bibi and Moema show great variability between exposed and shaded areas in the roads.

3. Results and conclusions

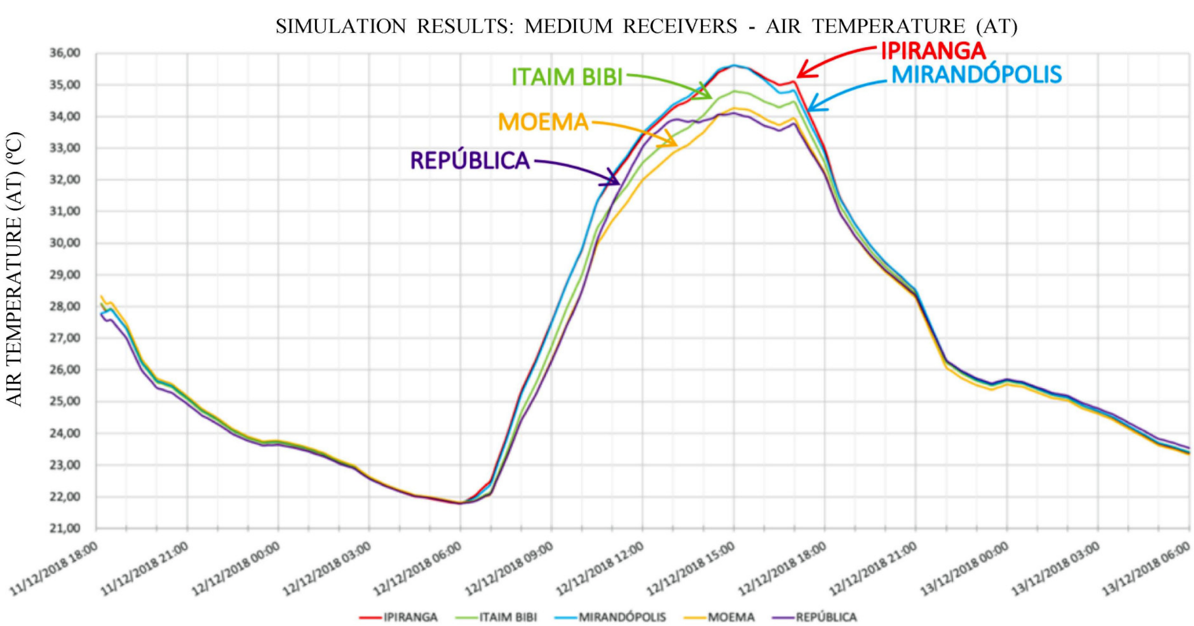
Maps with spatial distribution at 1.50m height (pedestrian scale) were extracted for Air Temperature (AT), Relative Humidity (RH), Wind Speed (WS), wind direction, radiation (direct, diffuse and long wave) and Mean Radiant Temperature (MRT). Graphs of results were also extracted at the central point of each model, always at the most central crossing of roads, also at 1.50 m in height for the same variables and for the Perceived Equivalent Temperature (TEP). The results were analyzed by comparing the models with each other in view of their different morphological characteristics.

Thus, in accordance with the results of the studies presented, 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 at night, also changing the speed of the winds and, consequently, the thermal variables and the thermal comfort indexes.

According to Graph 3, during the day, there was a maximum difference of 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.

At the same time, the densest model (República) was the one with the lowest AT during the day, 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.

The less dense the models (Mirandópolis and Ipiranga), the more responsive they were to the daytime and nighttime AT variations, with a greater and faster



Graph 3 – AT results at the midpoints of the simulation models
Source: NOVAES, G. B. A. Impactos da Morfologia da Cidade nas Condições Microclimáticas de Áreas Urbanas Consolidadas de São Paulo em Dias Quentes. São Paulo: Dissertação de Mestrado apresentada à Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo (FAU USP), 2020.

AT increase during the day, due to the greater exposure to direct radiation, and also, during the night, with greater and faster loss of AT, 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, analyzed under the perspective of the MRT, whose maximum difference reaches 2.2 ° C between the models.

Even within the models, there were great differences between the different spaces, as the greater height variability (Moema and Itaim Bibi) also caused different conditions of shading and exposure to the sun at different times in different spaces. 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 5.

It is also natural that the positioning and geometry of buildings 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

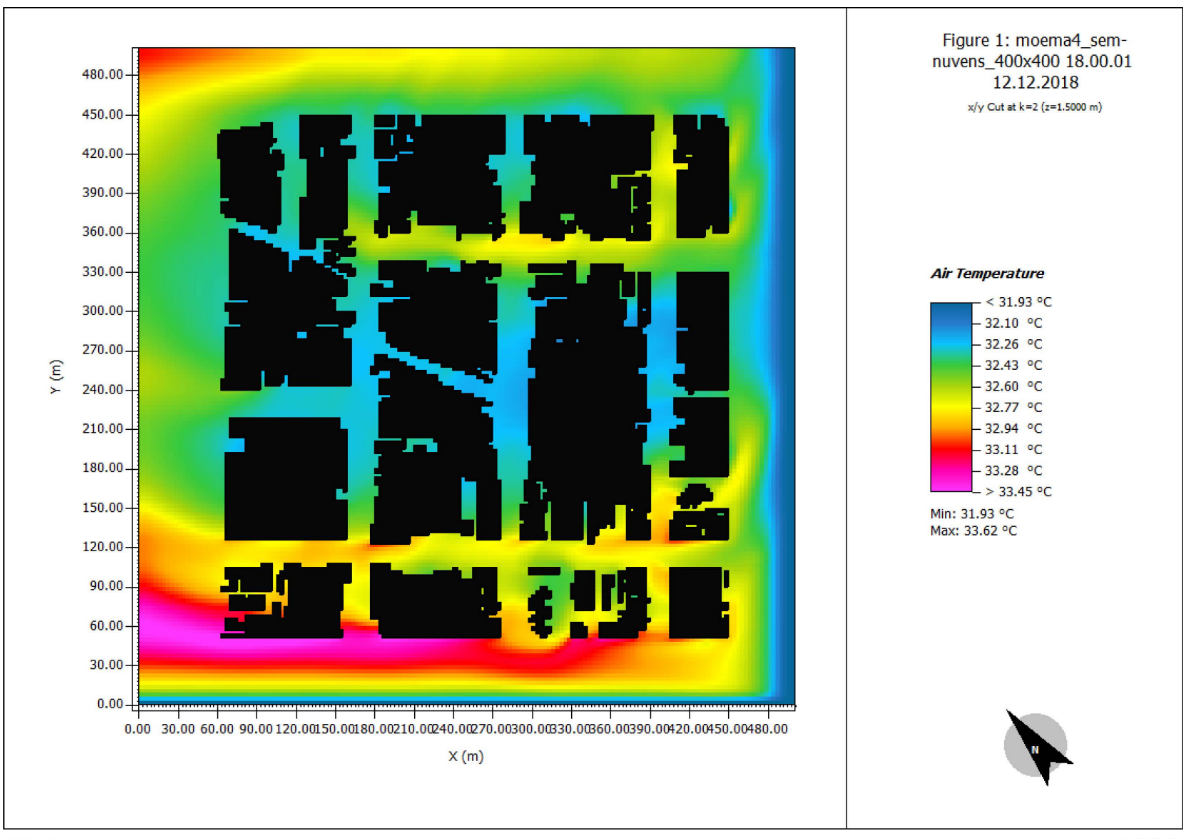


Figure 5 – Air Temperature (AT) result of the Moema simulation on December 12th 2018 06:00pm
Source: NOVAES, G. B. A. Impactos da Morfologia da Cidade nas Condições Microclimáticas de Áreas Urbanas Consolidadas de São Paulo em Dias Quentes. São Paulo: Dissertação de Mestrado apresentada à Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo (FAU USP), 2020.

MORPHOLOGICAL ASPECT	INCREASE OR DECREASE	ASSOCIATED URBAN PARAMETERS	IDENTIFIED EFFECTS
VOLUMETRY AND BUILT DENSITY	↑	Build area (↑) UC (↑) OR (↑) Built volume (↑) SVF (↓) H/W factor (↓)	Less susceptibility to daily thermal variations, less thermal
			More shaded spaces, less direct solar radiation in spaces
			Higher amount of radiation emitted by surfaces and buildings (long wave) at night, greater accumulation of heat by the built masses
			Less permeability to the passage of winds, lower speed
			Lower values of AT, MRT, radiation and TEP in the daytime
			Higher AT, MRT and TEP values at night
	↓	SVF (↑) H/W factor (↑) Build area (↓) UC (↓) OR (↓) Built volume(↓)	Greater susceptibility to daily thermal variations, with greater thermal amplitude
			Greater amount of spaces exposed to the sky and the sun with greater amount of direct solar radiation in the spaces
			Less radiation emitted by surfaces and buildings (long wave) at night
			Greater permeability to the passage of winds, with higher speeds
			Higher values of AT, MRT, radiation and TEP in the daytime
			Lower values of AT, MRT, radiation and TEP at night
VERTICALIZATION	↑	Maximum height of buildings (↑) Averag building height (↑) H/Aproj Factor Factor (↑) H/W factor (↑) Projection areas profile (↓)	Increased shading over open urban spaces
			Greater heterogeneity of AT, heat and radiation conditions
			Greater urban canyon effect, with effects of channeling winds, trapping value, etc
			Creation of high and low pressure zones that benefit the differential wind circulation between spaces, which helps heat removal
			Shading of buildings over each other
	↓	Projection areas profile (↑) Maximum height of buildings (↓) Average building height (↓) H/Aproj Factor (↓) H/W factor (↓)	Increase in areas with unobstructed access to the sun and sky
			Greater homogeneity of AT, heat and radiation conditions
			Higher wind speeds and lower heights
			Less obstacles to the passage of winds and access to the sun
			Greater widespread insolation of open spaces, roofs and façades of buildings
HEIGHT VARIABILITY IN BUILDINGS	↑	Standard deviation of heights (↑) Building heights profile (-)	Creation of insolation areas and shading areas in different urban spaces
			Greater heterogeneity of AT, heat stroke and radiation conditions
			Reduction of the effects of urban canyons, reducing the effects of channeling winds, trapping heat, etc.
			Creation of high and low pressure zones that benefit the differential wind circulation between spaces, which helps heat removal
	↓	Building heights profile (-) Standard deviation of heights (↓)	Standardization of the condition of sunstroke and shading of spaces, either for sunstroke or shading
			Greater homogeneity of AT, heat and radiation conditions
			In case of tall buildings, maximizing the effects of urban canyons
			Faster circulation of winds, which vary little in direction, height and speed, passing over or between buildings, reducing the thermal load capacity
STREET WIDTHS AND DISTANCE BETWEEN BUILDINGS	↑	SVF (↑) Setbacks (↑) H/W Factor (↓) Front alignment (↓)	Creation of insolation areas and shading areas in different urban spaces
			Greater heterogeneity of AT, heat stroke and radiation conditions, mostly higher in the daytime and lower in the nighttime
			Reduction of the effects of urban canyon, reducing effects of channeling winds, heat trapping, etc.
			Greater permissiveness for the circulation of winds from any direction, maximizing the removal of thermal load
			Creation of high and low pressure zones that benefit the differential wind circulation between spaces, which helps heat removal
	↓	H/W factor (↑) front alignment (↑) SVF (↓) Setbacks (↓)	Greater shading of open urban spaces
			Greater homogeneity of AT, sunstroke and radiation conditions, mostly lower in the daytime and higher in the nighttime
			In case of tall buildings, maximizing the effects of urban canyons
			Faster circulation of winds, few of which vary in direction, channeled into urban canyons, more likely to generate wind speeds that cause discomfort

Table 4 – Summary of urban morphological aspects and their microclimate effects
Source: NOVAES, G. B. A. Impactos da Morfologia da Cidade nas Condições Microclimáticas de Áreas Urbanas Consolidadas de São Paulo em Dias Quentes. São Paulo: Dissertação de Mestrado apresentada à Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo (FAU USP), 2020.

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 permeability to the circulation of the winds coming from the southeast, allowing better distribution and greater speed of the winds in the routes. The height variability also creates differential wind conditions between the models, therefore, the models with greater spacing between buildings and with greater height variability were the most permissive for the circulation of winds between spaces (Ipiranga and Moema).

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 AT values, the wind circulation has a positive impact on TEP, reducing its values. The variability of 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 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 reasonable height variability, which allowed alternation in the conditions of sunshine and shading, and the regular layout of north-south and east-west roads, allowing better circulation of winds from the southeast to remove heat.

Table 4 qualitatively summarizes the results found, with a synthesis of studied urban morphological aspects and their microclimate effects evidenced by the simulations.

4. Final considerations

The studies in this work corroborate results found in researches in the area, since, as identified by TALEGHANI, KLEEREKOPER, et al. (2015), KRÜGER, MINELLA and RASIA (2011) and SHARMIN, STEEMERS and MATZARAKIS (2017), it was found that different morphological models of the city can impact in different ways on the thermal conditions of open urban spaces.

The morphological conditions of the urban space can change the amounts of direct, diffuse and reflected radiation received by the spaces, the speed of passage of the winds in the spaces and, consequently, the Air Temperature, the Mean Radiant Temperature, the Relative Humidity 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 in the daytime, with a heating that occurs more quickly because the open spaces are more exposed to sunlight and, at night, the more upright 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.

With the continuation of the work, analyzing more models of urban typologies and studying in depth the impacts of the height and shape variability of buildings and verticalization of the urban environment, the conclusions found can assist in the composition of urban planning guidelines (urban parameters, building regulations), supporting measures that can contribute to cities with better thermal conditions for open spaces and buildings, and more resilient to the scenarios of aggravation of urban heating and global climate change phenomena.

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