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EVALUATION OF THE IMPACTS OF URBAN FORM ON THE MICROCLIMATE OF NEIGHBOURHOODS IN RIO DE JANEIRO, BRAZIL

AVALIAÇÃO DOS IMPACTOS DA FORMA URBANA NO MICROCLIMA DE BAIRROS DA CIDADE DO RIO DE JANEIRO, BRASIL

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Abstract

Accelerated and disorganized urbanization process coupled with rapid population growth leads to microclimate changes in the urban spaces. In tropical climate regions, excessive city densification and vegetation suppression can induce the urban heat islands formation and create thermal discomfort situations. Knowing thermal comfort variables, urban design and interactions between built and natural spaces is crucial for shaping and altering these spaces to make them more pleasant. This work aims to evaluate the urban form influence on the microclimate in the neighbourhoods of Copacabana, Ipanema and Ramos in the Rio de Janeiro city, Brazil. For this purpose, the results of microclimatic simulations with ENVI-met were analyzed. Furthermore, the computational data were still used as inputs for the comfort index Physiological Equivalent Temperature (PET) calculation. The results indicate that the urban design can modify the local microclimate.

Keywords: *microclimate, urban form, thermal comfort, urban densification, ENVI-met.*

Resumo

O processo de urbanização acelerado e desordenado aliado ao rápido crescimento populacional pode contribuir para mudanças microclimáticas nos espaços urbanos. Em regiões de clima tropical, o adensamento excessivo da cidade e a supressão da vegetação podem induzir a formação de ilhas de calor urbanas e criar situações de desconforto térmico. O conhecimento das variáveis de conforto térmico, desenho urbano e interações entre os espaços construídos e naturais é fundamental para a modelagem e alteração desses espaços para torná-los mais agradáveis. Este trabalho tem como objetivo analisar a influência da forma urbana sobre o microclima nos bairros de Copacabana, Ipanema e Ramos, na cidade do Rio de Janeiro, Brasil. Para tanto, foram analisados os resultados de simulações microclimáticas, realizadas com ENVI-met. Além disso, os dados computacionais ainda foram utilizados como insumos para o cálculo do índice de conforto Physiological Equivalent Temperature (PET). Os resultados indicaram que o desenho urbano pode influenciar no microclima local.

Palavras chave: *microclima, forma urbana, conforto térmico, densificação urbana, ENVI-met.*

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Introduction

According to World Urbanization Prospects (UN, 2018), between 2015 and 2020, almost 82% of the world's population lived in urban areas. Dynamics projections of the urban and rural population up to 2050 show an urban occupation superior to the rural one over the years. In Brazil, the Brazilian Institute of Geography and Statistics - IBGE estimates

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show the urban population grew from 31 per cent in 1940 to 84 per cent in 2010 (IBGE, 2010). The United Nations (UN, 2018) confirmed these values, indicating that current rates are near 87,1 %, with a forecast to reach 92,4 % in 2050.

Due to the urbanization process, it is possible to note significant environmental changes, such as the enlargement of the built space at the expense of the natural environment. The urban expansion, even when coupled with efficient infrastructure, changes the cities dynamics. One of the observed alterations is on the microclimate (BARBOSA; DRACH; CORBELLA, 2010).

Microclimates correspond to climatic characteristics in the space of reduced proportions within cities. Alterations of these conditions might worsen urban quality, with temperature increases, wind channeling, and higher sun exposure, among other phenomena. Urban heat islands are typical climatic anomalies, which commonly occur in densely urbanized cities that could be provoked by, for example, the buildings' heights and other factors. The consequences of this phenomenon are, especially in tropical climate regions, thermal discomfort, increased energy consumption and pollution.

According to the last International Panel on Climate Change (IPCC) report, the anthropogenic influence on the climate is evident, with greenhouse gas emissions reaching unprecedented levels, intensified by the economic and population growth resulting from the Industrial Revolution (IPCC, 2015).

One of the main consequences of these changes is the more frequent occurrences of extreme climate events. Recent research points to the increased frequency and intensity of rainfalls in the south and southeast of Brazil. This situation makes floods and landslides more constant (MAGRIN *et al.*, 2014). Therefore, understanding the urban design, comfort conditions, and the human, space, and climate interactions are fundamental to proposing sustainable projects, both in the scale of cities and buildings. Determining the principles of urban layouts that guide the constructive and spatial adaptations to the climate, activities and needs of the population is the responsibility of the architects and engineers. Therefore, it should be done scientifically and in an integrated form.

In this sense, this work has the objective of analyzing which aspects of the urban design, such as urban densification degree, vegetation and characteristics of edifications and pathways, could influence the microclimate conditions and the thermal comfort of three neighbourhoods (Copacabana, Ipanema and Ramos) in Rio de Janeiro, Brazil.

Three neighbourhoods were chosen due to their proximity to water bodies and differences in the urban configurations, geographic locations and occupational densities. Each region was modelled with the ENVI-met software, and microclimatic simulations were performed using 2017 summer's climatic data as inputs. This data was provided by the meteorological station of the Copacabana Fort (INMET, 2018). This input data comprises the average air temperature, relative humidity, wind direction and speed, so the simulation was not done on a typical day.

Several parameters, including air temperature at the pedestrian level, average radiant temperature, humidity, direct and diffuse radiation, ventilation, and sky view factor (SVF) (AL-SUDANI; HUSSEIN; SHARPLES, 2017), were obtained with these simulations. Furthermore, the results were compared with the local measurements to verify the validity of the computational method.

Also, Physiological Equivalent Temperature (PET) index (HÖPPE, 1999) was calculated for the three neighbourhoods using the Rayman software (MATZARAKIS; RUTZ;

MAYER, 2010). Input parameters were some climate data of specific points extracted from the microclimatic simulations, geographic information of Rio de Janeiro and human characteristics.

Urban design and microclimate

Urban population accelerated growth, and the climate alterations, on a global scale, have provoked several socio-environmental problems and negatively affected the quality of life in the cities. Transport systems' inefficiency, high pollution levels, and catastrophic climate events show the necessity of actions that promote more efficient and resilient cities. However, due to other aspects, such as real estate speculation and the inadequacy of urban legislation, changes in the city's physical configuration have gone against the interests and needs of the population.

The urban form is defined by the way the elements that compose the city are organized, such as the layout and size of the roads, the size of the blocks and sidewalks, buildings volumetry and geometry, the existence of free spaces, the presence of vegetation, among others (ROCHA, 2018; XIMENES, 2016). These urban design elements present particularities on a scale smaller than a city. When walking a route, it is possible to perceive them in each neighbourhoods, block, or street through buildings with different architectural expressions and ends or pathways with different dimensions, afforestation levels, and shading (BARBOSA; ROSSI; DRACH, 2014).

These features can influence energetic consumption, air quality, land use and microclimate. Drach and Barbosa (2016) give some successful urban examples of climate-sensitive design concerning the latter. Some of the effects of an urban design that does not consider the local climatic characteristics can be related to the waste of energy and the presence of thermal discomfort.

Studies developed by Futcher and Mills (2013) in London, United Kingdom, point to the ability to alter the thermal load on buildings from changes in street geometry. In the Rio de Janeiro city, intra-urban temperature variations were observed as an influence of morphology and vegetation (DRACH; BARBOSA, 2016), and the impacts on microclimate related to urban density are addressed in the studies by Wei et al. (2016) and Park, Oh and Hong (2018). In cities such as Rio de Janeiro, where the humid tropical climate predominates, some general urban design guidelines might be observed to adequate the spaces for climatic conditions and provide comfort to the inhabitants' uses. The higher temperature values and air humidity, typical for these climates, linked by lower ventilation and changes in soil cover, which allow the accumulation of heat, are the main causes of the formation of the urban heat islands. This microclimate phenomenon is common in urban areas and is characterized by verifying higher temperatures in a particular location compared to nearby regions. As a result, an energetic consumption increase for cooling systems and the deterioration of air quality are verified, in addition to thermal discomfort (BARBOSA; ROSSI; DRACH, 2014).

It is important to mention that multiple reflections, besides thermal discomfort, may cause glare and visual discomfort (EMMANUEL; ROSELUND; JOHANSSON, 2007; DUARTE, 2015). Some architectural and urban project resources, such as irregular building facades, can reflect the radiation diffusely, thereby attenuating these consequences efficiently. Vegetation introduction allows for an even broader understanding (DUARTE, 2015; ROMERO, 2013) since this interferes directly with the microclimate, increasing the evaporative cooling and blocking the passage of the solar radiation promoting shading (DUARTE, 2015; TALEGHANI, 2018). Vegetation helps the microclimate balance by absorbing part of the solar radiation used in the photosynthetic process without temperature increase.

According to Hwang, Lum and Chan (2015), shading is the most important factor for temperature reduction and, consequently, creating thermally comfortable locations in tropical zones. However, it should be emphasized that it must be present continuously and in larger volumes to potentialize its effects (HWANG; LUM; CHAN, 2015; DIMOUDI; NIKOLOPOULOU, 2003).

In contrast with the verified benefits, it must be mentioned that the vegetation can also harm the comfort conditions. A high concentration of tall trees with dense canopies increases humidity. It blocks the winding passage, which hampers heat exchanges by evaporation and convection, whereas trees with sparse tops, besides these effects, do not provide shading enough (GIVONI,1994; DUARTE, 2015; HWANG; LUM; CHAN, 2015). So, these tree species must be avoided in hot and humid regions. Afforestation in humid tropical climates should be done with medium-sized, low-rooted, evergreen trees. The crowns should not be too dense (GONÇALVES; PAIVA, 2013).

Among the strategies for tropical areas, Emmanuel (2005) lists the need to act in small spaces, seeking improvements in comfort conditions in each city block, *i.e.*, a more punctual action. Oliveira, Andrade and Vaz (2011) state that even small green areas can contribute to the mitigation of the effects of heat islands and global warming in cities. However, the authors alert to the detail that the thermal performance of green infrastructures and their influence on the surrounding environment depending on the city's climatic and urban characteristics. They, therefore, indicate the need for timely and specific evaluations. In the computer simulations developed by Monteiro (2020), the author studies vegetation appropriate for Macapá city, in Amapá state, Brazil. The canopies are dense to meet the need for shading, but it is recommended to evaluate the distance between tree species not to promote wind blockage.

In addition to vegetation, other factors that influence the ventilation and area of urban spaces are the road's orientation and the form, dimensions and spacing between the buildings. Its teaching is fundamental for forming more pleasant urban spaces, especially in tropical climate environments, since they can mitigate the effects of heat energy.

Streets' orientation and building characteristics are likely to change the regime of the winds in an area. To make the best ventilation conditions feasible, Givoni (1994) states that the streets should be parallel to the main direction of the winds at night since higher temperatures occur during this period. However, this configuration causes their channelling (ROMERO, 2013) and makes it difficult to ventilate buildings if they are a little spaced (GIVONI, 1994). On the other hand, on the roads perpendicular to the wind, it is verified that the indicators act as a barrier, blocking its passage (ROMERO, 2013; GIVONI, 1994). The existence of poorly ventilated areas can induce the formation of heat islands (DRACH; CORBELLA, 2010). Therefore, the design must be done in such a way as to avoid the creation of zones of stagnation.

Therefore, streets positioned in angulation between 30° and 60° with the prevailing winds in the ideal configuration favour ventilation in hot and humid climate regions (GIVONI, 1994). Orienting them in the North-South direction also improves the microclimate since it provides greater sun protection, which presents a high incidence angle (EMMANUEL; ROSELUND; JOHANSSON, 2007). In addition, switching tall buildings with low ones and-or leaving them apart makes the environment more permeable to the winds (ROMERO, 2013).

Streets and buildings’ size and shape and the effects on ventilation can also contribute to the shadowing of urban spaces. Some researchers point to urban densification as a possible strategy for urban sustainability and improved life quality (GIRARDET, 1999; ROGERS; GUMUCHDJIAN, 2000). However, further studies are needed to verify its applicability in tropical climate zones despite its benefits.

The compact city model has emerged as a solution to the problems arising from urbanization. It makes it possible to shorten displacements, reduce the car use and the pollutants emission, have a greater facility in the implantation of mass transportation means, and have smaller infrastructure costs. However, excessive densification can lead to exaggerated virtualization of the cities, which impairs ventilation and natural light, besides favouring the accumulation of atmospheric pollutants (BARBOSA; DRACH; CORBELLA, 2010) contributing to the formation of heat islands, especially in tropical regions.

One of the ways of evaluating the occupation density of a given region is using of the relation between the height of the buildings and the width of the roads (H / W). In the research done by Emmanuel, Rosenlund and Johansson (2007) and Chatzidimitriou and Yannas (2016), it was verified that this factor has a strong link with the average radiant and air temperatures, consequently influencing comfort conditions. In both cases, the authors observed that the increase in the H / W ratio led to the reduction of the PET index (HÖPPE, 1999), mainly due to the shadowing provided by the buildings.

Factors such as the acclimatization process and air conditioning and heating equipment can influence the responses related to the PET values for each region. Krüger, Rossi and Drach (2017) presented a comparative study for three cities: Glasgow - UK, Curitiba, and Rio de Janeiro in Brazil. The survey in the two Brazilian cities, Curitiba and Rio de Janeiro resulted, as expected, in different bands of PET. The highest heat tolerance was observed in the sample of Curitiba, although this city is the coldest capital of the country. An explanation for this may be due to the more common use of air conditioning equipment in Rio de Janeiro, which influences the perception of temperature in the urban environment (KRÜGER, DRACH; BRÖDE, 2015).

Another indicator used to evaluate urban density is the sky-view factor (SVF). This dimensionless index varies from 0 to 1 and represents the amount of visible sky existing at a given point. SVF is reduced as new buildings emerge in the environment. In addition, the vegetation also reduces the possibility of observation of the celestial vault. SVF analysis helps to understand the thermal changes in the urban environment. One of the first experiments which associated the sky vision factor and the urban heat islands was presented by Oke (1981). This was followed by Unger's studies in 2004 and 2009, indicating contradictory or sometimes fragile relationships related to SVF and urban heat island - UHI (Unger, 2004; 2009). In a study developed in Gothenburg, Sweden, Svensson (2004) obtained consistent results (R2 = 0.78) for some specific regions of the city during their measurement campaigns.

Drach and Emmanuel (2014) showed the relationship between urban design (represented by SVF) and intra-urban temperature variations. The study developed in Glasgow, UK, pointed to a 'parabolic' relation with the air temperature measured during the day. The lower temperatures are observed in open spaces like green areas and those densely constructed with shaded places.

For Hien and Jusuf (2010), open spaces with higher SVF tend to have higher temperatures during the day since they receive more solar radiation, whereas, at night, denser areas with lower SVF take more time to cool because of the loss of heat is slower.

Therefore, the investigation of the effects caused by the densification should be made before choosing it as a guideline for urban development, especially in tropical regions.

In this sense, Wei et al. (2016) verified that the SVF decreases with the increase of the occupation rate for the same land use index. The reduction of the spacing among the buildings is more significant for the SVF than the reduction of the templates. Moreover, the authors realized that the same effect happens when the occupancy rate is set and the templates are increased. Because of microclimates, this study showed that the increase in the occupancy rate, up to certain limits, could reduce the daily average radiant temperature and air and improve the thermal comfort of pedestrians.

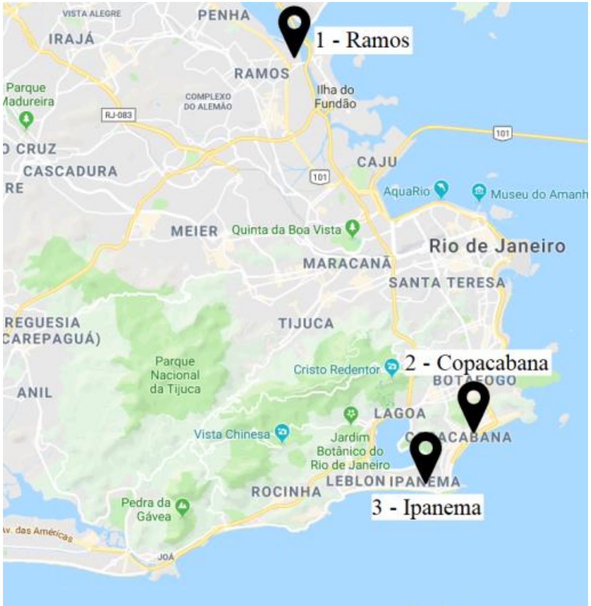
On the other hand, in places already very densely packed, the simple introduction of a building may be sufficient to restrict ventilation and increase the temperature of its surroundings, favouring the formation of heat islands (DRACH; CORBELLA, 2010). For example, in the case of compaction of a whole neighbourhood, the effects are even greater.

Microclimate studies

Location and characterization of study areas

The study area selection searched for places with different characteristics, such as occupancy density, urban compaction level, and geographic localization. However, due to the coastal location of Rio de Janeiro, it was decided to choose regions near the sea, where there is a great influence of the sea breeze. Besides that, the locations chosen possess a flat relief with 600m x 600m dimensions because of the limitation of Envi-met software. Figure 1 shows the study area localizations.

Figure 1 – Location of Study Areas



Source: adapted from Google Maps (2018).

The first area (area 1), located in the Ramos neighbourhood (Figures 2a and 2b), is situated between Brazil Avenue and the Guanabara Bay, next to a leisure area known as "Piscinão de Ramos" and an open area of the Brazilian Navy. The region presents irregular urban forms and highly densified territory, mostly low buildings (below three floors), practically without frontal and lateral spacing and narrow roads. The seafront has no strip of sand except for a small portion of the "Piscinão", and there is almost no vegetation present.

Figure 2 – Areas of Study: Ramos (a)Satellite image and (d) Street view; Copacabana (b) Satellite image and (e) Street view; Ipanema (c) satellite image and (f) Street view

Source: adapted by Google Maps (2018).

The second study area (area 2) is located in the Copacabana neighbourhood (Figures 2b and 2e), next to Serzedelo Corrêa square. This region presents an orthogonal urban form and highly densified territory. However, different from area 1, it is composed of high buildings (12 floors), practically without lateral spacing but with small frontal spacing. The streets are approximately 12m wide, except for the Atlântica Avenue (seafront) and Nossa Senhora de Copacabana Avenue, which are wider. There is a large sand strip between the seafront and the sea, approximately 80m long, and the vegetation is sparsely distributed.

The third studied area is in the Ipanema neighbourhood, next to Copacabana (Figure 2a and 2e), near Nossa Senhora da Paz square (Figure 2c and 2f). Some similarities with Copacabana could be seen, such as the average width of the streets (12m) and the urban orthogonal shape.

However, Ipanema has lower buildings than Copacabana and presents lateral spacing, which increases the free area. In addition, the sand strip is slightly smaller, at about 50m, and there is a significant presence of vegetation along some roads of the neighbourhood.

Methodology

The methodology for this study was divided in two stages. The first stage consist of microclimatic simulations with ENVI-met (BRUSE, 2010) and the second stage consists of the calculation of the comfort index Equivalent Physiological Temperature - PET (HÖPPE, 1999) by RayMan software (MATZARAKIS *et al*., 2010).

Microclimatic simulations using ENVI-met software

Initially, the microclimate simulations were performed for three areas (1, 2 and 3) using ENVI-met software version 3.1 (BRUSE, 2009). It was used as input data for the urban configurations of each location and the average climatic data from the Copacabana Fort meteorological station for summer 2017 (INMET, 2018). This study is looking to understand the influence of urban design on the microclimate and identify the places with greater possibilities of thermal discomfort.

ENVI-met (BRUSE, 2009) is the tridimensional model for urban microclimate simulation based on fluid mechanics principles, thermodynamics law, vegetal physiology, soil science and their relationships (2018). The energy balance is calculated by climatic variations and information of urban configuration organized as an entry data: solar radiation, air flux, humidity, temperature, local turbulence and their dissipation, water and heat exchange inside the soil, building shade and vegetation.

The cell dimension choice for simulation should be performed by considering the greater mesh refinement, thus providing more data regarding the soil, vegetation, and buildings in the study region. So, 3,0m x 3,0m x 3,0m dimension cells were chosen for all models. Finally, the grid chosen for each study area was 200 x 200 x 3. Areas were rotated so that the blocks became parallel to the model's border to facilitate the cell filling. The North rotation values for each study area were 40° for Ramos, 320° for Copacabana and 0° for Ipanema.

The software allows the cell filling to incorporate information on the soil surface, such as vegetation type and building height. Moreover, it supplies the database (open access) that allows the introduction specific features. The tree species used in the models were "sk" (15 m high trees, high density, and defined crown) and "g" (50 cm high grass, medium-density) because they are more similar to the vegetation present in the studied neighbourhoods. It is possible to add punctual data readers, i.e., receptors, positioned at specific points and provide more detailed information about the atmosphere, surfaces, and soil. The receptors' results were used later as entry data for PET index calculation (Physiological Equivalent Temperature).

For the simulation of the set, besides the model, it is necessary to define the initial conditions of the simulation. The climatic data used were air temperature, relative humidity, velocity, and wind direction in summer 2017/2018, provided by the Copacabana Fort station, Rio de Janeiro (INMET, 2018). They were: initial air temperature of 300.45K, relative humidity of 73.1%, speed wind of 2,6 m/s and wind directions of 135° (south-west). In addition, the specific humidity consideration of 9.8 g of water per air kg and roughness of 0.1. The simulations were performed in the summer of 2017/2018, and data were recorded every hour.

PET index calculation using RayMan software

For the PET index calculation (Physiological Equivalent Temperature), climatic data obtained for specific points in the computational model (receptors), geographic information of Rio de Janeiro and the average human aspects (clothing, height, weight, etc.) were used as input data for the RayMan Pro software (3.1 beta version), to estimate thermal comfort in different city locations.

In the RayMan Pro software, a micro-scale model calculates the radiation flux in a simple or complex environment, in a specific date, time and locals (MATZARAKIS; RUTZ;

MAYER, 2010). Besides the PET index, the software also gives the results for other comfort indexes and, still, for solar orbit, global radiation, and shading, among others. In addition, it can determine the mean radiant temperature based on global radiation and cloudiness. The simulations can be performed with only three microclimatic parameters: temperature, air humidity and wind speed. However, it allows other input data, including the surface temperature, global radiation, air pressure, and its mean radiant temperature.

Herein, the input data used in RayMan were obtained from ENVI-met simulation receptors. Each receptor supplies the following information: air temperature, relative humidity, speed wind, surface temperature, and mean radiant temperature. Some individual data such as height, weight, sex, age, clothing, activity, and the individual position were considered. Personal data adopted were those software defaults (MATZARAKIS; RUTZ; MAYER, 2010), such as height (1,75m), weight (75 kg), sex (masculine), and age (35 years). Moreover, it is possible to insert information about terrain topography, obstacles (buildings and vegetation) and sky vision factors. In addition, the simulation considered the same date and time for the PET index calculation. Table 1 presents the fixed parameters for all calculations.

Table 1 – RayMan Input Parameters

Parameter	Value
Date	01/01/2018
Hour	12:00
Geographical Latitude (°E)	-43°16’
Geographical Longitude (°N)	-22°54’
Altitude (m)	0
Time Zone (UTC + h)	-3.0
Height of the individual (m)	1,75
Weight of the individual (kg)	75,0
Age of the individual	35
Sex of the individual	Masculine
Clothing (clo)	0,6
Activity (W)	200
Position	Standing

Source: the authors.

It can be seen from Table 1 that the position set for the user was standing, and he was assigned movement.

Results analysis and discussion

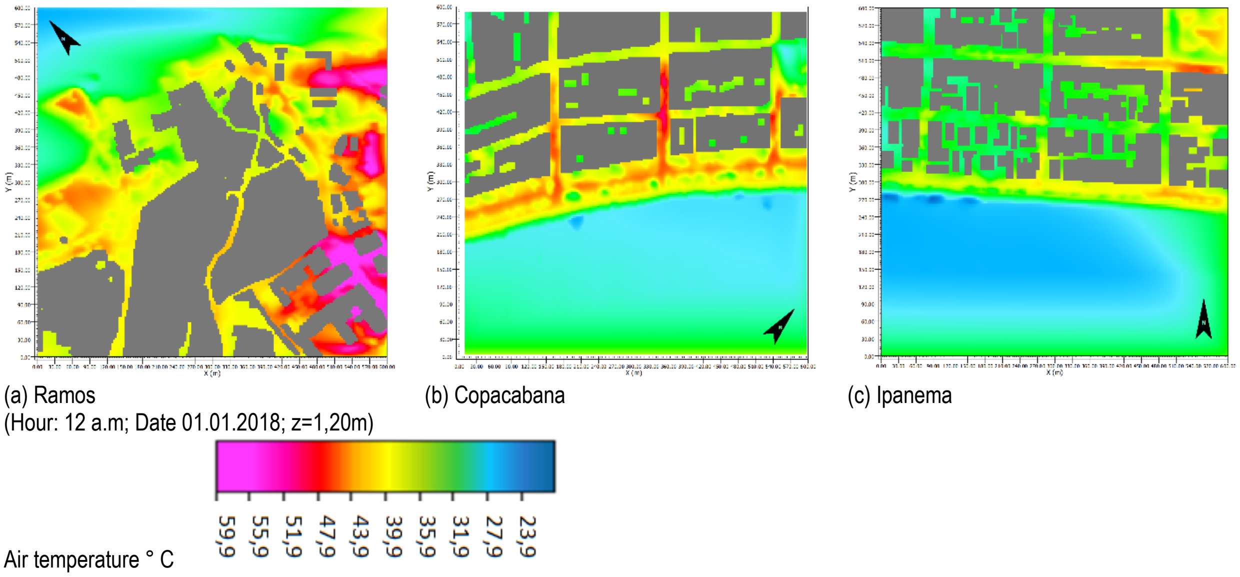
As in previous items, the results were divided into two subtopics; the first one referring to the ENVI-met simulations, followed by the PET index calculation obtained using RayMan.

Microclimate simulations: ENVI-met

ENVI-met models simulations provided several parameter maps, such as air temperature, wind speed, relative humidity, Sky View Factor Calculation, direct radiation, diffuse radiation, mean radiant temperature and surface temperature. According to the 3.2.1 item, the results refer to 01/01/2018 at 12 a.m. (1 p.m., DST). In addition, all of them were obtained at the height of the pedestrian level (z = 1.20 m).

Figure 3 shows the air temperature variation in the studied neighbourhoods. Herein, the worst conditions were found in the Ramos neighbourhood and the best ones, in the Ipanema neighbourhood, with differences of approximately 3°C. The Copacabana neighbourhood was slightly less hot than the first and hotter than the second.

Figure 3 - Air temperature: (a) Ramos; (b) Copacabana; (c) Ipanema



(a) Ramos
(Hour: 12 a.m; Date 01.01.2018; z=1,20m)

(b) Copacabana

(c) Ipanema

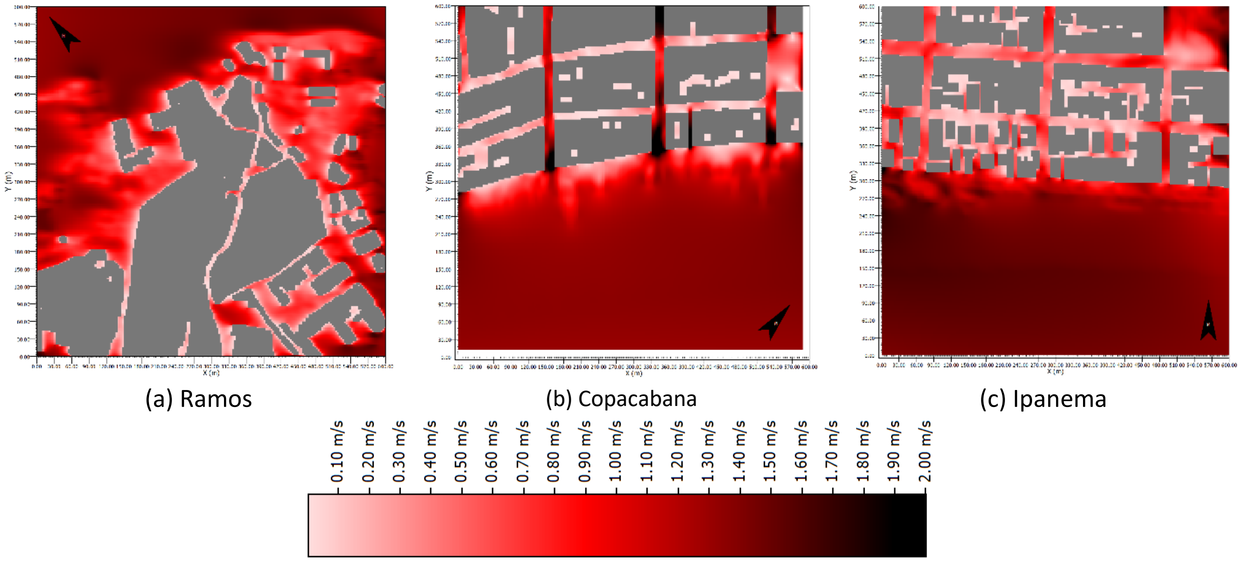
Source: the authors.

By looking at the graphs with air temperature values in Figure 3, it is possible to notice that the colour scale has enough range to represent the values observed in each image. Figures 3b and 3c show Copacabana and Ipanema, respectively, the extreme values of the colour scale are not observed. The interior of the Ipanema neighbourhood has a predominance of the colours green and light blue, even in the neighbourhood's interior (Figure 3c). Copacabana (Figure 3b) brings yellow scale values with green points in the areas of greater shading and the presence of red points in the asphalt regions. The values observed in the Ramos region indicate the dominance of yellow with orange, reaching even the extreme values of the table with red and pink, even in its interior. There is a strong presence of concrete and asphalt in the region and almost no vegetation.

In the Ramos neighbourhood, it is observed that the narrow streets of the neighbourhood, associated with intense densification and the presence of buildings of the same height, make the whole not very porous, hindering the penetration of wind and, therefore, the thermal exchanges. This fact contributes to the permanence of high air temperature values around the region. These aspects hinder the wind penetration in the internal streets of the neighbourhood, as seen in Figure 4. The opposite situation was found in Ipanema, where larger roads and urban configurations with lower and spaced buildings promote air ventilation and justify the lower air temperature.

In addition to these factors, the wind's permeability may also have been influenced by the orientation and positioning of the streets. This effect is most observed in Copacabana, where perpendicular streets of the seafront are practically parallel to the wind direction, causing its channeling. Concerning air temperature, the consequences of this appear to be negative. Due to the seafront's higher temperatures, the winds that enter the neighbourhood possess the same features. On the other hand, the transversal streets presented a much-reduced ventilation level.

Figure 4 – Wind speed: (a) Ramos; (b) Copacabana; (c) Ipanema



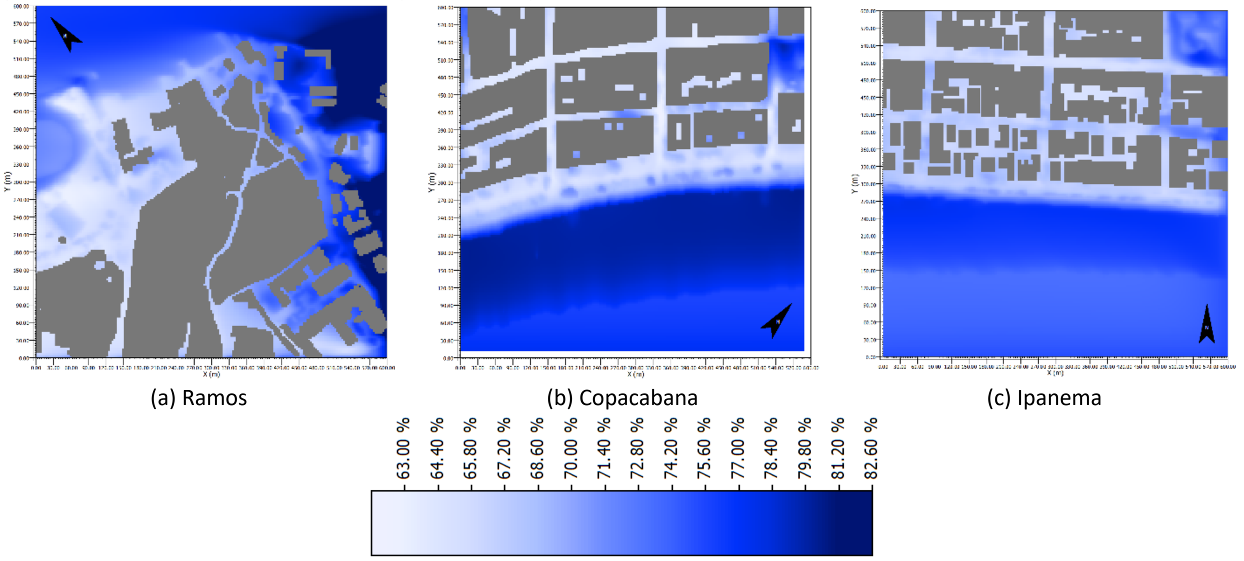
(a) Ramos (b) Copacabana (c) Ipanema

(Hour: 12 a.m; Date 01.01.2018; z=1,20m)

Source: the authors.

Also, it has been verified that high wind permeability helps reduce the relative air humidity (Figure 5). The humidity indexes in Copacabana and Ipanema showed similar results, being slightly smaller for the first. The faster winds could explain this difference in some streets and less vegetation. In addition, higher humidity was noticed in the squares in these two neighbourhoods, possibly generated by the greatest number of trees. Ramos, however, presented the highest percentages, possibly due to lower wind penetration.

Figure 5 – Relative Humidity: (a) Ramos; (b) Copacabana; (c) Ipanema



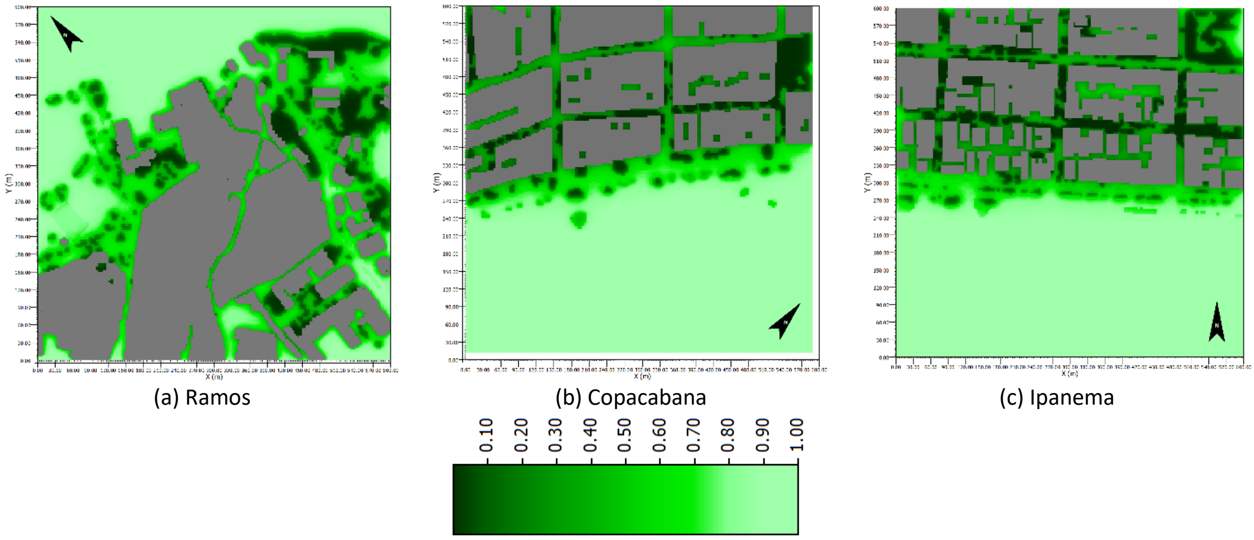
(a) Ramos (b) Copacabana (c) Ipanema

(Hour: 12 a.m; Date 01.01.2018; z=1,20m)

Source: the authors.

Sky View Factor Calculation (SVF) represents the amount of visible sky at a given point. Figure 6 presents this parameter considering the buildings and vegetation of the neighbourhood. Due to taller buildings and tree-lined streets, Ipanema possesses the lowest SVF values. In Copacabana, despite the higher buildings, the SVF is slightly greater because it has a less vegetated area. Lastly, the highest SVF occurs in Ramos, where the low buildings and the streets count on little tree cover.

Figure 6 - Sky View Factor: (a) Ramos; (b) Copacabana; (c) Ipanema



(a) Ramos (b) Copacabana (c) Ipanema

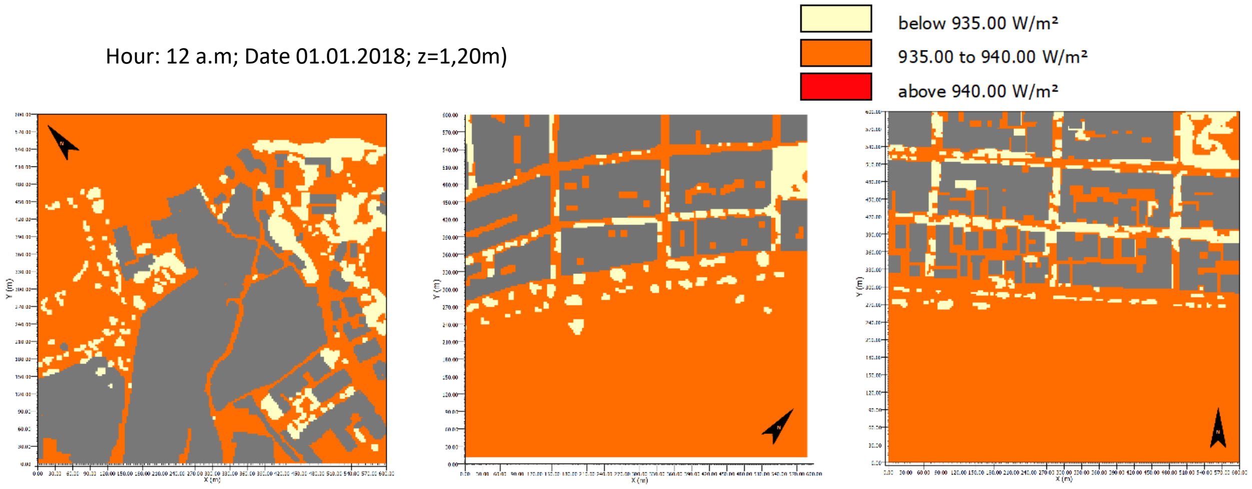
(Hour: 12 a.m; Date 01.01.2018; z=1,20m)

Source: the authors.

The SVF results could be related to direct and diffuse radiation (Figure 7 and 8, respectively). It is possible to see that the direct radiation incidence is between 935 W/m² to 940 W/m² in all parts of the neighbourhoods, except for those protected by vegetation, where there is no direct incidence. Moreover, it is noticed that for this time of year and at this time, there is no shading provided by the buildings since the angle of solar incidence is close to 90°.

However, in Figure 8, the diffuse radiation is lower in areas with lower SVF. As the rays scattered through the atmosphere reach the earth's surface at varying angles, the tallest buildings act as a shield, protecting the interior streets of the neighbourhood. The incidence of diffuse radiation in the Ramos neighbourhood was higher than in the other two neighbourhoods, which may be related to the practically total absence of green cover, with the important presence of concrete slabs with fibre cement roofs. The non-natural materials of urban covering and the intense densification, which does not allow the presence of distance between buildings, can be pointed out as contributing factors to the higher air temperature values observed in Ramos if compared to the neighbourhoods of Ipanema and Copacabana.

Figure 7 - Direct Solar Radiation: (a) Ramos; (b) Copacabana; (c) Ipanema

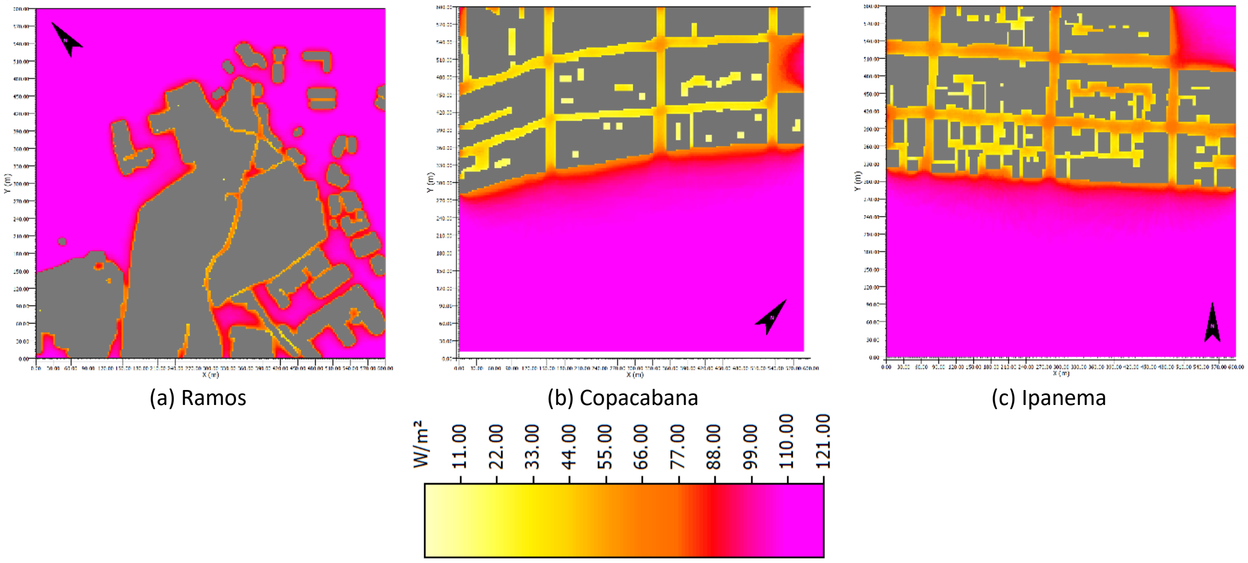


Hour: 12 a.m; Date 01.01.2018; z=1,20m)

(a) Ramos (b) Copacabana (c) Ipanema

Source: the authors.

Figure 8 - Diffuse Solar Radiation: (a) Ramos; (b) Copacabana; (c) Ipanema



(a) Ramos

(b) Copacabana

(c) Ipanema

(Hour: 12 a.m; Date 01.01.2018; z=1,20m)

Source:the authors.

Two other relevant results for the microclimate in these neighbourhoods were also analyzed: the mean radiant temperature and the surface temperature. According to the first parameter, the Copacabana and Ipanema neighbourhoods provide more variation, with temperature spikes in the areas between buildings. This is possibly due to the higher level of reflected radiation provided by the buildings. However, the points under vegetation presented lower radiation values because of shading.

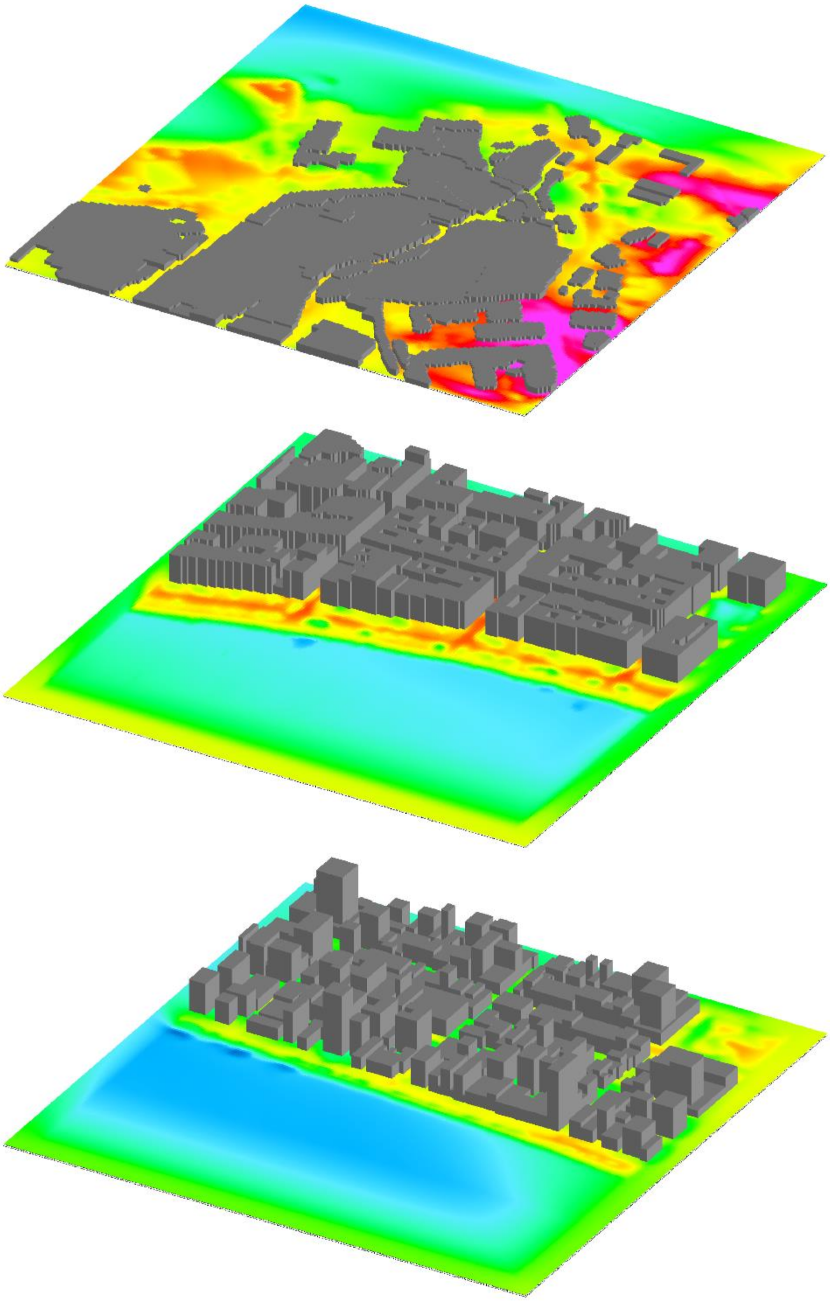
Figure 9 shows the three urban configurations analyzed and their volumetrics. It is possible to observe the different characteristics of each neighbourhood. As the low light of the houses and the narrow streets of the neighbourhood of Ramos. The barrier of buildings in Copacabana or the spacing between the buildings in Ipanema.

The comparative assessment indicates that for the same climatic condition, with various building volumes, streets and city block orientations and dimensions, the amount of vegetation could cause significant variations in the local microclimate. The configurations of urban spaces might be aimed at ventilation expansion and the protection against radiation, consequently improving the micro climatic condition in tropical climate regions.

Density and the absence of space between buildings in the Copacabana and Ramos neighbourhoods were the main factors of the temperature increase. In Ramos, the lack of vegetation cover was responsible for increasing this effect. In contrast to these areas, the Ipanema neighbourhood results suggest that a certain degree of urban densification may benefit shading in cities in light of greater space porosity, height interchange, spacing between buildings and greater urban vegetation cover distribution.

Lastly, ENVI-met allows performing relevant analyses of the different microclimate parameters necessary for the good health and satisfaction of the city's inhabitants. The uses of these computational features might be helpful in important decisions regarding changes in urban areas.

Figure 9 - 3D Modeling: (a) Ramos; (b) Copacabana; (c) Ipanema



(a) Ramos

(b) Copacabana

(c) Ipanema

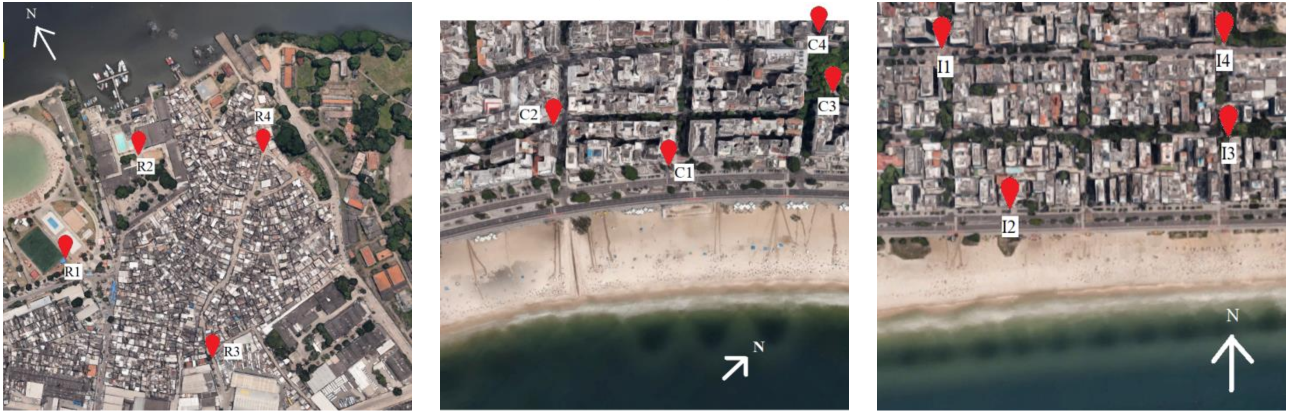
Source: the authors.

PET index calculation using Rayman software

In this work, the data input for the RayMan software was obtained from the receptors in ENVI-met software simulations. Figure 10 shows their approximate positions. Each receptor gave the following information: air temperature, relative humidity, wind speed, surface temperature and average radiant temperature.

Table 2 shows the calculated results by RayMan software for the PET index. The Ipanema neighbourhood presented the lowest index average (39.5°C), while Copacabana presented the highest (43.1°C) index. The average in Ramos was 42.

Figure 10 - Localização aproximada dos receptores: (a) Ramos; (b) Copacabana; (c) Ipanema



(a) Ramos (b) Copacabana (c) Ipanema

Source: adapted from GOOGLE MAPS in 2018.

Table 2 - PET index for the three neighbourhoods studied

NEIGHBORHOOD	RECEPTOR	PET (°C)
Copacabana	C1	43,0
Copacabana	C2	45,4
Copacabana	C3	47,1
Copacabana	C4	37,0
average in Copacabana		43,1
Ipanema	I1	45,5
Ipanema	I2	42,0
Ipanema	I3	29,0
Ipanema	I4	41,3
average in Ipanema		39,5
Ramos	R1	41,9
Ramos	R2	40,1
Ramos	R3	41,1
Ramos	R4	45,9
average in Ramos		42,3

Source: the authors.

It should be mentioned that the air temperature variation between all the receivers was less than 1°C, having little significance for the PET variation. On the other hand, it was noticed that the changes in the wind speed and the average radiant temperature were most important.

Copacabana's highest PET index value is in Serzedelo Corrêa Square (C3). Although this location is heavily wooded, this receptor was at a point exposed directly to the Sun. Although the air temperature was slightly lower than elsewhere in the neighbourhood, it is believed that the high humidity, the average radiant temperature, and the low wind velocity explain this value. Still, the vegetation may have blocked the passage of wind in this region, strengthening the assumption that it may negatively affect the thermal comfort of a space.

On the other hand, the best conditions in the neighbourhood were found in the highest wind regions (C4). In addition, the air temperature, approximately 0.5°C lower than that of the C1 and C2 receptors, may be a consequence of the proximity to the tree-covered squares. One of the factors by which this point presented the lowest PET.

The point that presented the lowest PET was in Ipanema, on the corner of Maria Quitéria and Prudente de Morais streets (I3). It is assumed that the good distribution of the vegetation provided effective shading and considerably reduced the average radiant temperature. In addition, the fact of having ventilation collaborated with the reduction of PET.

The most critical point of Ipanema was on the corner of Visconde de Pirajá and Aníbal de Mendonça streets (I1). It is believed that, because it is one of the less wooded areas of the neighbourhood, this point had the highest average radiant temperature and, consequently, the highest PET.

In Ramos, it was noticed that the variation of the average radiant temperature and PET was lower than in other neighbourhoods. The highest PET was found for the R4 receptor, located at the neighbourhood's two-way street intersection, where there is poor ventilation. The lowest index was verified for receiver R2, near Guanabara Bay, where the wind speed is higher.

In general, the sensation is hot or extremely hot. This is because, in summer, due to the high angle of solar incidence, the shading provided by the buildings is reduced, causing an increase in air temperatures and average radiant temperature. In addition, the denser urban configurations tend to demonstrate lower wind speeds, contributing to the discomfort.

Matzarakis, Mayer and Iziomon (1999) indicate that the range of thermal neutrality on the PET scale is between 18 °C and 23 °C PET. The authors point out that this range corresponds to the thermal sensation scale of the Predicted Mean Vote - PMV from -0.5 to +0.5 of Fanger's (1970) seventh scale. From the relationship presented by Matzarakis, Mayer and Iziomon (1999), it is possible to identify the thermal perception of the users of the spaces and understand the degree of thermal stress (Table 3) observed at a given PET value.

Table 3 - PET index - Thermal Perception and Grade of Physiological Stress

PET	Thermal Perception	Grade of Physiological Stress
>4	Very Cold	Extreme Cold Stress
8	Cold	Strong Cold Stress
13	Cool	Moderate Cold Stress
18	Slightly cool	Slight Cold Stress
23	Comfortable	No Thermal Stress
29	Slightly warm	Slight Heat Stress
35	Warm	Moderate Heat Stress
41	Hot	Strong Heat Stress
<41	Very hot	Extreme Heat Stress

Source: adapted from (MATZARAKIS; MAYER; IZIOMON, 1999).

Observing the results in Table 2, we notice that in most points at 12:00 pm, the thermal sensation is "Extreme Heat Stress". Only one point in Ipanema shows "Moderate Heat Stress" and another in Copacabana "Strong Heat Stress". Despite the temperature variation in °C PET, it can be seen that the result for the three neighbourhoods is in the "Extreme Heat Stress" range.

Conclusions

The modifications in the cities demanded by urban population growth and the climatic changes present major challenges for society today. The efficient solution propositions require that each city's particular knowledge, the relationship between the constructed and natural spaces, and how these factors affect the individual's well-being are considered. This paper examines these interactions and their effects on the microclimate of the neighbourhoods with different urban configurations which have proximity to the sea in common: Ramos, Copacabana and Ipanema in Rio de Janeiro.

The ENVI-met software simulations allowed a broader microclimatic analysis since they provided results for several parameters. However, the simulations were for a specific time of year. They are based on summer averages, representing, in general, the conditions of this specific season of the year. These results agree with the bibliographic references and reinforce the importance of ventilation and shading in urban spaces, especially in tropical climate regions.

Regarding ventilation, the best situation occurs in the space between buildings and their distinct heights, giving porosity to the urban fabric, such as was found in the Ipanema neighbourhood. This fact, therefore, reinforces the need to preserve the permeability of the urban structure. On the other hand, the lack of space between buildings of equal's height can negatively influence air circulation. Besides that, it was noted that the orientation of streets and their width could also change the wind dynamics.

Urban occupation is characterized by replacing natural soil and vegetation with impermeable pavements and large buildings, which increases heat retention. In addition, the solar incidence on these surfaces further increases the temperature in urban areas, being one of the main factors for the deterioration of the microclimate. The environment must be protected against radiation to mitigate this effect. In this way, shading in the urban environment can be done through the buildings and vegetation.

Given its latitude, during the summer in Rio de Janeiro, the solar angles are very high, limiting the shading provided by the buildings. In addition, the excessive equality of the building templates can make it difficult for the wind to penetrate. The association of high solar radiation with the low wind speed can result in the formation of heat islands, which has, among its consequences, the greatest energy expenditure with cooling systems, air pollution and thermal discomfort (BARBOSA; ROSSI; DRACH, 2014).

Regarding vegetation, it was noticed that its presence in the urban environment could benefit the microclimate. In addition, the points under the trees or near more vegetated areas presented lower values of temperature, possibly due to the reduction of direct solar radiation and the average radiant temperature. However, their distribution should be made after further studies since the effects on ventilation may be negative.

The simulation results were also used as input data for PET calculation. At this stage, it was found that the thermal sensation of high temperatures predominates in all the neighbourhoods during the summer. In this way, the strategies mentioned above are even more important.

The article confirmed that urban morphology directly interferes with urban microclimate. Such a study can contribute to urban design choices for new neighbourhood projects considering the local climate. The microclimate that is more suitable for pedestrians contributes to better walking and use of urban space and contributes to lower energy expenditure with air conditioning in buildings.

The relationship between urban form and the microclimate of urban spaces is highly complex. The analysis presented here contributes in part to the understanding of this complex relationship.

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