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Relationship between urban morphology and microclimate based on parameterized scenarios in a city with a tropical savannah climate

Relação entre morfologia urbana e microclima a partir de cenários parametrizados em cidade de clima tropical de savana

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ABSTRACT

The process of urbanization of cities results in a typically urban climate characterized, in most cases, by loss of quality of life due to climatic phenomena, such as urban heat islands. The urban form suitable to local climatic conditions promotes a sustainable urban environment, with outdoor thermal comfort. This research aimed to analyze the relationship between urban morphology and microclimate in scenarios parameterized by different land use and occupation parameters, taking the city of Arapiraca - AL as an object of study. Thus, four urban scenarios were elaborated from an analytical approach using computer simulation by ENVI-met software, for the typical period of summer, hot and dry. The base scenario was elaborated on a fraction of the city with a tendency to verticalization the buildings. The other scenarios differ according to the thermodynamic properties of the materials, canyon geometry, and the presence of vegetation. The results showed significant thermal effects as a function of urban morphology. The presence of high albedo materials promoted the decrease in air temperature. The streets orientation and the geometry of the urban canyon determined the solar access, the number of hours of exposure to direct solar radiation, and the use of winds. The presence of vegetation favored the thermal conditions of the microclimate. Therefore, it was evidenced the need to insert the study in the urban climate in the urban planning process of the cities, to promote quality of life for its inhabitants.

RESUMO

O processo de urbanização das cidades conforma um clima tipicamente urbano, na maioria das vezes caracterizado pela perda da qualidade de vida em função de fenômenos climáticos, como as ilhas de calor urbano. A adequação da forma urbana às condições climáticas locais tem o potencial de compor um meio ambiente urbano sustentável, com conforto térmico ao ar livre. A presente pesquisa objetivou analisar a relação entre morfologia urbana e microclima em cenários parametrizados por diferentes parâmetros de uso e ocupação do solo, tomando a cidade de Arapiraca - AL como objeto de estudo. Para tanto, foram compostos quatro cenários urbanos a partir de uma abordagem analítica com uso de simulação computacional pelo *software* ENVI-met, para o período típico de verão, quente e seco. O cenário-base parte de uma fração da cidade com tendência à verticalização. Os demais cenários variam em função das propriedades termodinâmicas dos materiais, geometria do cânion e presença de vegetação. Os resultados indicaram efeitos térmicos significativos em função da morfologia urbana. A presença de materiais de alto albedo promoveram a diminuição da temperatura do ar. A orientação das vias e a geometria do cânion urbano determinaram o acesso solar, a quantidade de horas de exposição à radiação solar direta e o aproveitamento dos ventos. A presença de vegetação apresentou o potencial de favorecer às condições térmicas do microclima. Evidencia-se, portanto, a necessidade da inserção do estudo no clima urbano no processo de planejamento urbano das cidades, a fim de promover qualidade de vida a seus habitantes.

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Introduction

The process of urbanization of cities alters the natural physical environment, causing changes in the local energy balance, which forms a typically urban climate (Higueras, 1998). The global trend towards rapid urbanization poses a threat to the urban climate, due to a number of environmental impacts, such as the increase in air temperature, a phenomenon known as urban heat island (UHI), which directly influences outdoor thermal comfort; degraded air quality, increased energy demand, et cetera. (Johansson, 2017; Emmanuel, 2005, 2016; Kravcik et al., 2008; Jauregui & Romales, 1996; Rosenfeld et al., 1995; Oke, 1988).

Urban planning and design guided by the adoption of climate adequacy strategies will have the potential to promote resilient and sustainable cities (Xu et al., 2018; Yang et al., 2016). Making cities resilient and sustainable corresponds to the 11^{th} Sustainable Development Goal (SDG) of the United Nations (UN): Sustainable cities and communities, since sustainable development cannot be achieved without significantly transforming the way we build and manage urban spaces (ONU, 2022).

The morphology of the city has an effect on the urban climate, according to the following factors: thermodynamic properties of surface materials, by determining the amount of solar radiation to be absorbed/reflected/emitted (Alchapar et al., 2018; Krüger & Gonzalez, 2016); orientation of the roads in relation to solar radiation and the predominant direction of winds, by the potential to optimize the use of these local natural resources (Baruti et al., 2019; Rui et al., 2019; Vasilikou & Nikolopoulou, 2019; Tork et al., 2017); geometry of the urban canyon, based on the relationship between the average height of the buildings and the width of the roads (H/W ratio) and the visible sky factor (Muniz-Gäal et al., 2020; Nakata-Osaki et al., 2016); and presence of vegetation, which provides shading and benefits air temperature conditions and relative humidity (Davtalab et al., 2020; Shinzato & Duarte, 2018; Minella & Krüger, 2017). It´s also worth mentioning that urban geometry is directly linked to the formation of urban heat islands, because the impact of the incidence of solar radiation near the urban surface is proportional to the H/W ratio (Romero, 2001).

Several studies used ENVI-met software as a computational simulation tool for predictive analysis of urban thermal behavior on a microclimatic scale (Leal & Barbosa, 2022; Pereira, Brandão & Barbosa, 2021; Muniz-Gäal et al., 2020, among others). ENVI-met corresponds to a computational tool based on a three-dimensional model of urban climate that simulates the relations between urban structure and the environment, offering various possibilities of application and associations, allowing the simulation of the urban thermal environment (Bruse, 2022). The software also features the ability to estimate wind conditions at any point in model space or on building facades, continuously considering the effects of thermal conditions, vegetation or weather patterns on the flow field from the calculation of three-dimensional wind and turbulence in complex conditions. ENVI-met features an interface called *Leonardo*, which offers a wide range of viewing options, from simple 2D maps to 3D flow trajectories.

From this context, the present study aimed to analyze the relationship between urban morphology and microclimate based on parameters of land use and occupation in an urban fraction with a tendency to verticalization, in the city of Arapiraca, Alagoas. To this end, the study compared four hypothetical scenarios for the same urban fraction in order to contribute to factors related to urban legislation being treated more appropriately to the local climate.

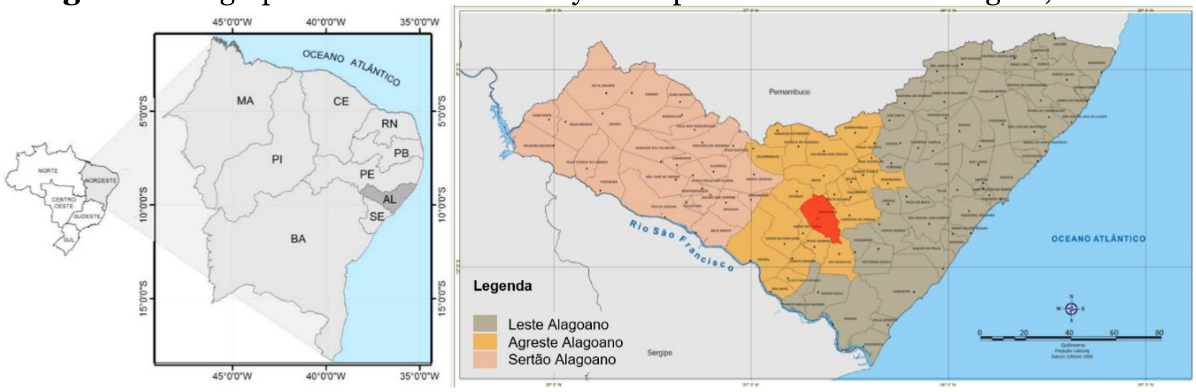
Materials and method

The methodological procedures were divided into the following stages: (1) selection of the study area, (2) description of local climatic conditions, (3) description of computational simulation parameters in the ENVI-met 4.0 program, (4) detailing the proposed scenarios and the resulting urban microclimate assessment procedures and (5) analysis of environmental variables.

Study object

Arapiraca is located in the interior of the state of Alagoas, in the Northeast region of Brazil, at an altitude of approximately 280 m; at south latitude 9°75'25" and west longitude 36°60'11" (see Figure 1). It occupies an area of 356,179 km², with an estimated population of 214,006 inhabitants (IBGE, 2010). The predominant climate of the city is the tropical savannah type As, according to Köppen-Geiger classification (Alvares et al., 2013), with two prominent seasons, hot/dry summer and hot/humid winter, average annual temperature of 24.6°C, average rainfall index of approximately 890.0 mm annually, average annual air humidity of 73.8% and prevailing winds from the east, in summer, and southeast, in winter (Silva, 2019; Silva & Barbosa, 2022).

Figure 1. Geographical location of the city of Arapiraca in the state of Alagoas, Brazil.



Source: Adapted from SEPLAG - AL (2022).

The city has four morphological types of urban fabric, determined by different patterns of occupation of urban soil, with nearby altitudes and determined by the uniformity of the building patterns. Among them, the *Horizontal Disperso* fabric tends to verticalize and densification (with commercial and residential occupation), and can be found in the neighborhoods *Nova Esperança*, *Alto do Cruzeiro*, *Novo Horizonte*, in new allotments in the *Santa Esmeralda* neighborhood and in gated communities such as *Ouro Verde*, in the *Arnon de Melo* neighborhood (Torres, 2017). However, the municipal legislation that deals with the occupation and use of urban land has not been revised since 2001 and there is no constructive parameter that regulates the vertical growth of the city, presenting only the indications of the initial minimum retreats (Municipal Law No. 2,220, 2001).

In order to study the possibilities provided for in the legislation on land use and occupation in force and its impact on the local microclimate and the pedestrian's thermal comfort, an urban fraction of the *Horizontal Disperso* fabric was selected between the neighborhoods *Novo Horizonte* and *Itapuã*, a region of low density and with possibilities of density and verticalization. The fraction has the following characteristics: larger lots, buildings with larger recoils, presence of green areas and some streets are not yet paved (see Figure 2).

Figure 2. (A) Insertion of the selected urban fraction (yellow highlight) in *Horizontal Disperso* fabric; (B) Urban fraction taken as object of study; (C) View from *Ceci Cunha* avenue from the perspective of the pedestrian.

Source: Adapted from Google Earth Pro (2022).

The study area includes a cutout of 340 m x 300 m (x and y), which corresponds to 102,000 m². The collection of field data was made from on-site visits and from the digital cartographic base, granted by the City Hall. The selected urban fraction presents roads with an average width of 8.0 m, sidewalks 1.5 m wide and lots with frontal recoil of 3.0 m. The urban fraction encompasses a linear green area called *Área Verde Dom Constantino Lüers*, with large and medium trees; a central striped road with wooded construction site, while the other roads are of natural soil (permeable). Approximately 90% of the roofs of existing buildings are with ceramic tiles, 10% with fiber cement tile. The sidewalks are concrete and the vertical surfaces have varied paints.

Computer simulation

Computer simulations were performed based on the use of ENVI-met 4.0 software. The ENVI-met program is a tool developed for the study and prediction of the urban microclimate that simulates the interactions between urban surfaces, vegetation and atmosphere (Bruse & Fleer, 1998). The main climate data were adopted from the local meteorological archive.

The analysis was performed during a hot summer day with the ability to analyze a typical climatic situation of the hot and dry period, with high air temperature combined with low relative humidity during the daytime period. The input data for simulation considered the conditions of time type of the day 01/01/2017 that presented maximum air temperature of 32.4°C at 3:00 p.m., and minimum of 21.4°C at 6:00 a.m., average air temperature of 26.9°C, average relative humidity of 72.4%, with minimum of 41.4% at 3:00 p.m and maximum of 94.6% at 6:00 a.m. Wind speed at 10 m was 3 m/s.

Climate data were collected from the National Institute of Meteorology (*Instituto Nacional de Meteorologia* - INMET) for Arapiraca city, on the day selected for computer simulation. Regarding the specific humidity of the air at 2500 m, it was possible to collect the data collected from the region closest to Arapiraca, which is Recife - PE (82900), which corresponded to 8.53 (g/kg)², from the website of the Department of Atmospheric Sciences of the University of Wyoming, United States (*Departamento de Ciências Atmosféricas da Universidade de Wyoming*). The simulation in the ENVI-met program requires two main files: a climate configuration, which contains all startup values and schedules; and the other of urban configuration, in which the study area is modeled (including location of buildings, vegetation, soil and surfaces). The input data for ENVI-met simulation is shown in Chart 1.

Chart 1. Input data for simulation in ENVI-met.

Parameters	Data	Parameters	Data
Simulation Start Date	01/01/2017	Main Model Area	x:170, y:150, z:20
Simulation Start Time	9:00 p.m.	Number of nesting grids	5
Total of Simulated Hours	48 hours	Soil profile for nesting grids	Soil A: 00, soil B: 00
Wind speed at 10 m (m/s)	3 m/s*	Grid size	dx: 2m, dy: 2m, dz: 2m
Roughness	0.1	Generation method of vertical network	Equidistant
North	320°	Standard wall/roof properties	Wall: C2 (clear concrete), roof R1 (ceramic)
Latitude/Longitude	-9,75/ -35,60	Reference Time Zone	CET/UTC-3
Reference to Sea Level	264	Reference Longitude	45

*Data of INMET for Arapiraca/AL (2022).
Source: The authors (2022).

Study scenarios

The materials used in the modeling of the study area and the proposed scenarios were based on the default materials of the ENVI-met 4.0 program. In order to approximate the representation of the real area, we searched the standard database of the model for the types of vegetation that most closely resembled the vegetation found in the urban fraction. The proposals for the study scenarios were based on aspects of the urban legislation that deals with land occupation and use: Code of Works and Buildings of Arapiraca (Municipal Law No. 2,220, 2001), which provides only the initial minimum retreats; and the Code of Urbanism and Buildings of the capital Maceió (Municipal Law No. 5,593, 2007), to extract the formula of progressive retreat to a residential area (see Chart 2).

Chart 2. Urban parameters of the Code of Works and Buildings (*Código de Obras e Edificações*) of Arapiraca (2001) and of the Code of Urbanism and Buildings (*Código de Urbanismo e Edificações*) of Maceió (2007) adopted in the scenarios.

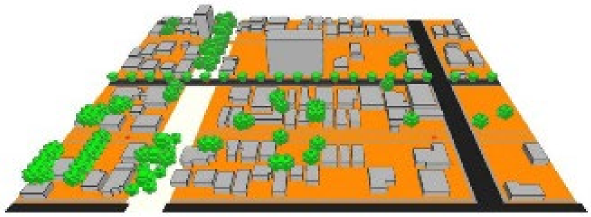
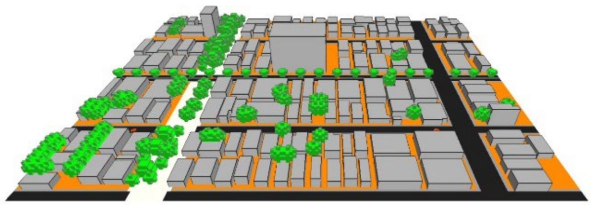
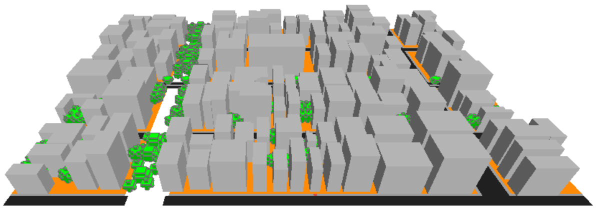
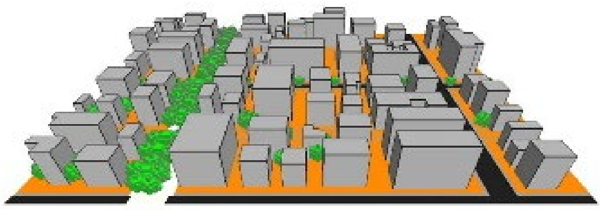
Front Initial Minimum Recoil	3.0 m
Minimum Initial Lateral Recoil with Opening	1.5 m
Initial Minimum Posterior Recoil	1.5 m
Progressive Recoil	Ri + (n-2)/2

Legend:
Ri: initial recoil
n: number of pavements
Source: The authors (2022).

In order to analyze the influence of urban morphology on the microclimate, four computational models were defined, varying the following parameters: Scenario I: modeling of the current urban scenario; Scenario II: modeling with occupation of all lots of single-end buildings using the initial minimum recoil; Scenario III: modeling with occupation of all lots of verticalized buildings using the initial minimum recoil; Scenario IV: modeling with occupation of all lots of verticalized buildings using progressive recoil.

The vertical buildings were implemented considering the redevelopment of up to four lots of 10 m x 30 m. Regarding the thermodynamic properties of the materials that constitute the urban surface, in scenario I it was considered natural soil pathways, because it corresponds to the current scenario, but in the other hypothetical scenarios were considered potted pathways, because it corresponded to a future trend. Regarding urban geometry, the H/W ratio ranged from 0.17 (scenarios I and II); 1.76 (scenario III); and 1.2 (scenario IV). The presence of vegetation was maintained in all scenarios according to the current reality observed *in loco* visit. The scenarios are presented in Chart 3.

Chart 3. Urban fraction selected with four scenarios parameterized for simulation in ENVI-met software.

Scenario I: Modeling of the current urban scenario.	**Scenario II:** Modeling with occupancy of all single-story building lots using the minimum initial recoil.
	
Scenario III: Modeling with occupation of all lots of verticalized buildings using the minimum initial recoil.	**Scenario IV:** Modeling with occupation of all lots of verticalized buildings using progressive recoil.
	

Source: The authors (2022).

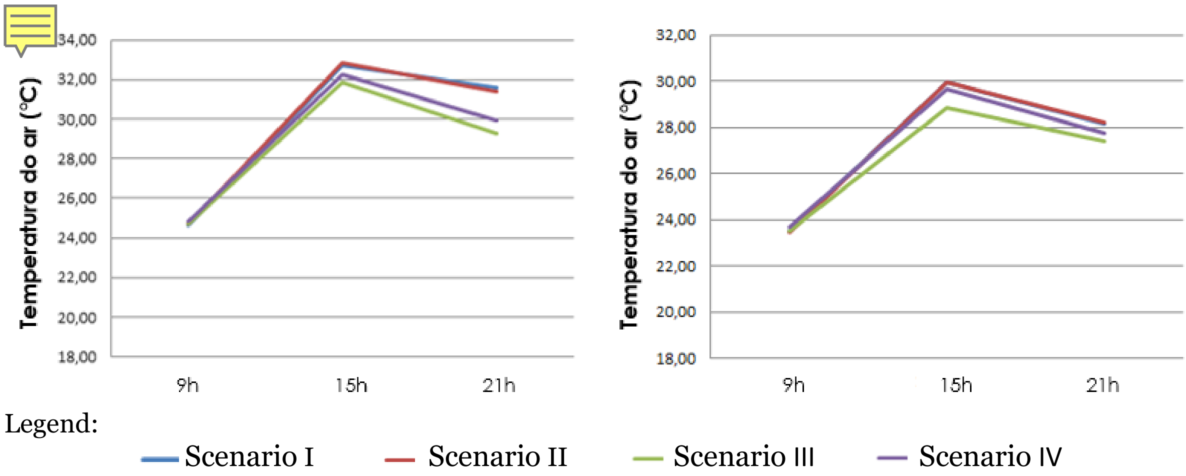
Results Analysis

The analysis of the influence of urban morphology on the different microclimatic parameters was based on the simulated results of the external environment based on the data of air temperature and wind speed and direction.

Air temperature

From the computational simulations it was possible to extract the maximum and minimum air temperature data from the scenarios at 9:00 a.m., 3:00 p.m. and 9:00 p.m., to analyze the air temperature variation (Figure 3).

Figure 3. Thermal curve charts - Maximum and minimum air temperature of the four simulated scenarios.



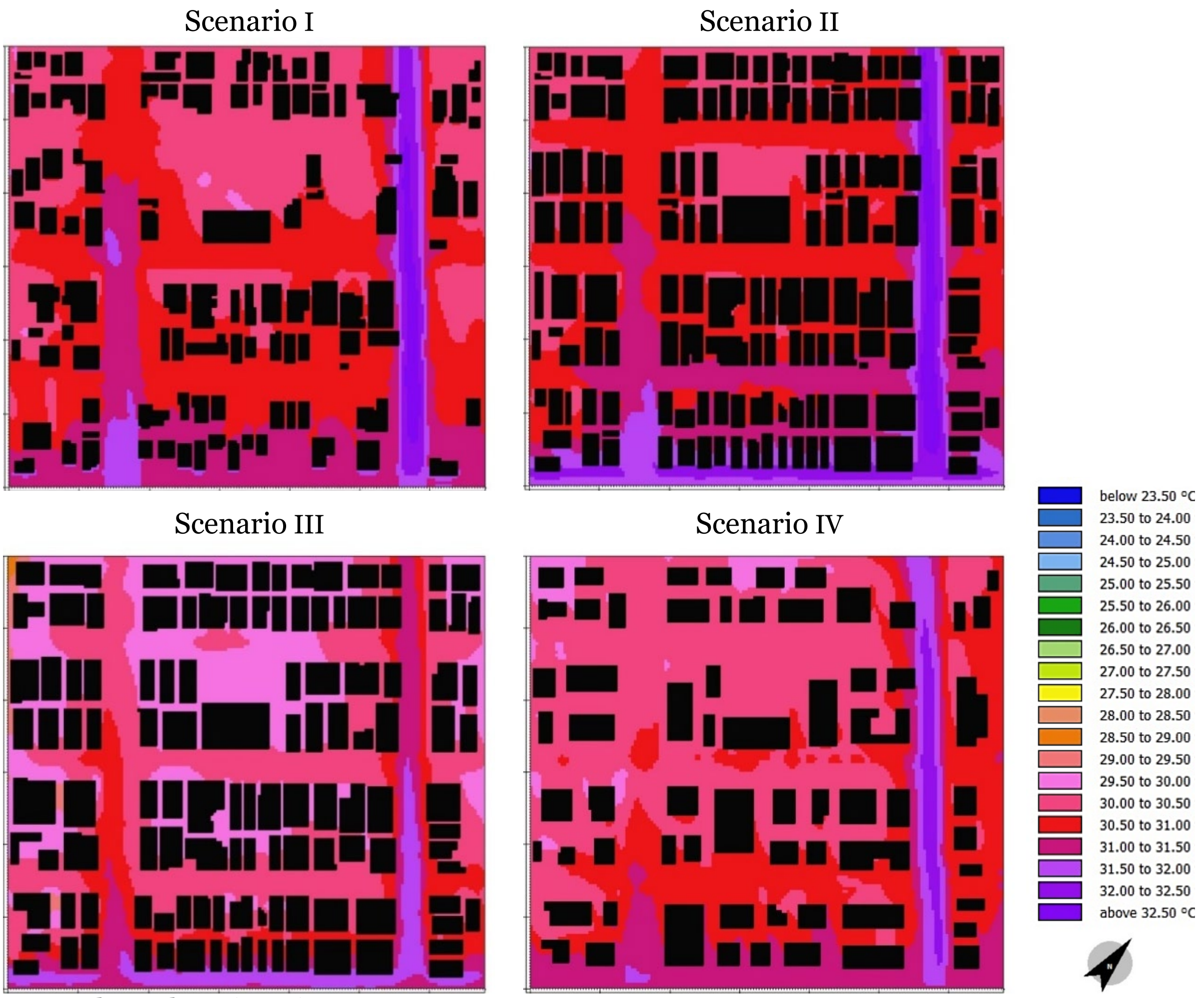
Source: The authors (2022).

It can be verified that Scenarios I and II presented higher air temperature values during the heating time (at 3:00 p.m.). Scenarios III and IV showed a difference of -1 °C compared to the other scenarios especially due to the shading generated by verticalized buildings that decreased the thermal load absorbed by the city, softening its heat gain, contributing to human thermal comfort. Scenario III presented the lowest air temperature values, because the use of the initial minimum recoil allowed the building to occupy a larger area of the lot, which generated larger areas of shade compared to the scenario with the use of progressive recoil.

In addition to the quantitative data, the *Leonardo* interface, linked to the ENVI-met software, made it possible to perform quali-quantitative analysis, with the identification of the most and least heated points in the simulated scenarios in cutting at 1.4 m from the soil at 3:00 p.m., supporting the understanding of the determining factors of local climatic conditions. The 2D maps of the scenarios show the influence of urban morphology in relation to air temperature (Figure 4).

In Scenario I, the air temperature variation at 3:00 p.m. was 29.96°C to 32.73°C. The layout of the single-end buildings allowed greater solar access. Thus, the open surfaces absorbed a greater amount of shortwave radiation and reflected the radiation of longer waves, increasing the air temperature (Darbani et al., 2021). Regarding the thermodynamic properties of the materials, the maximum temperature values were distributed in the grounded roads of northwest-southeast and northeast-southwest direction. The orientation of the pathway influenced the portion of solar radiation that penetrated the external space, causing greater heat accumulation. On the other hand, in the perimeter with the presence of vegetation, there was a decrease in air temperature due to the shading generated by the treetops, in addition to the presence of natural soil (permeable).

Figure 4. 2D maps of air temperature (°C) in the four scenarios parameterized in the urban fraction studied.



Source: The authors (2022).

At 3:00 p.m., in Scenario II, the minimum temperature was 29.94°C and the maximum was 32.84°C. The model of urban morphology open to the sky, with earthly buildings, contributes to more stressful thermal conditions, corroborating the studies by Yahia et al. (2017) and De & Mukherjee (2018). The maximum air temperature values are still distributed in the northwest-southeast and northeast-southwest direction, due to the presence of asphalt. It´s noteworthy that the southeast-northwest direction, on the right, presented high air temperatures, reaching 32.5°C, while the other road, on the left, presented mildair temperatures, possibly due to the presence of asphalt pavement on the first road, while in the second way the cover is still of natural soil and the proximity to wooded spaces (Linear Green Area Dom Constantino Lüers/*Área Verde linear Dom Constantino Lüers*).

Scenario III, at 3:00 p.m., presented a minimum temperature of 28.86°C and maximum of 31.88°C - with more mild results than the previous scenarios, due to the shading caused by verticalized buildings that softened heat gain, lowering the air temperature in the environment and generating better outdoor thermal comfort conditions. These results are in agreement with Jamei et al. (2016) and Yıldırım (2020) who demonstrated that the deepest canyons have lower air temperature compared to shallow urban canyons. Asphalt-coated roads remained as points where air temperatures are higher, especially in the northwest-southeast direction. It was also possible to observe that inside the blocks the temperatures reached 31.5°C, while the blocks near the green area showed milder temperatures, about 29°C, evidencing the importance of the adoption of green spaces in the city.

In Scenario IV, at 3:00 p.m., the maximum air temperature was 29.64°C and the minimum of 32.23°C, with values lower than Scenarios I and II, but higher than Scenario III. This result is possibly due to the use of progressive recoil that generated an H/W ratio of 1.2, increasing solar access and decreasing the shadow area generated by buildings. Regarding the thermodynamic properties of the materials, it was possible to observe that the highest air temperature values are concentrated in the points characterized by soil coating with the presence of asphalt and concrete. The perimeter with natural soil cover and presence of vegetation presents 30.5°C of air temperature, which corresponds to -2°C compared to the same direction track with asphalt cover and without vegetation, presenting conditions more favorable to thermal comfort. Thus, it´s important to opt for coatings with better albedo and preserve the spaces with vegetation, in order to ensure thermal comfort in the urban mesh.

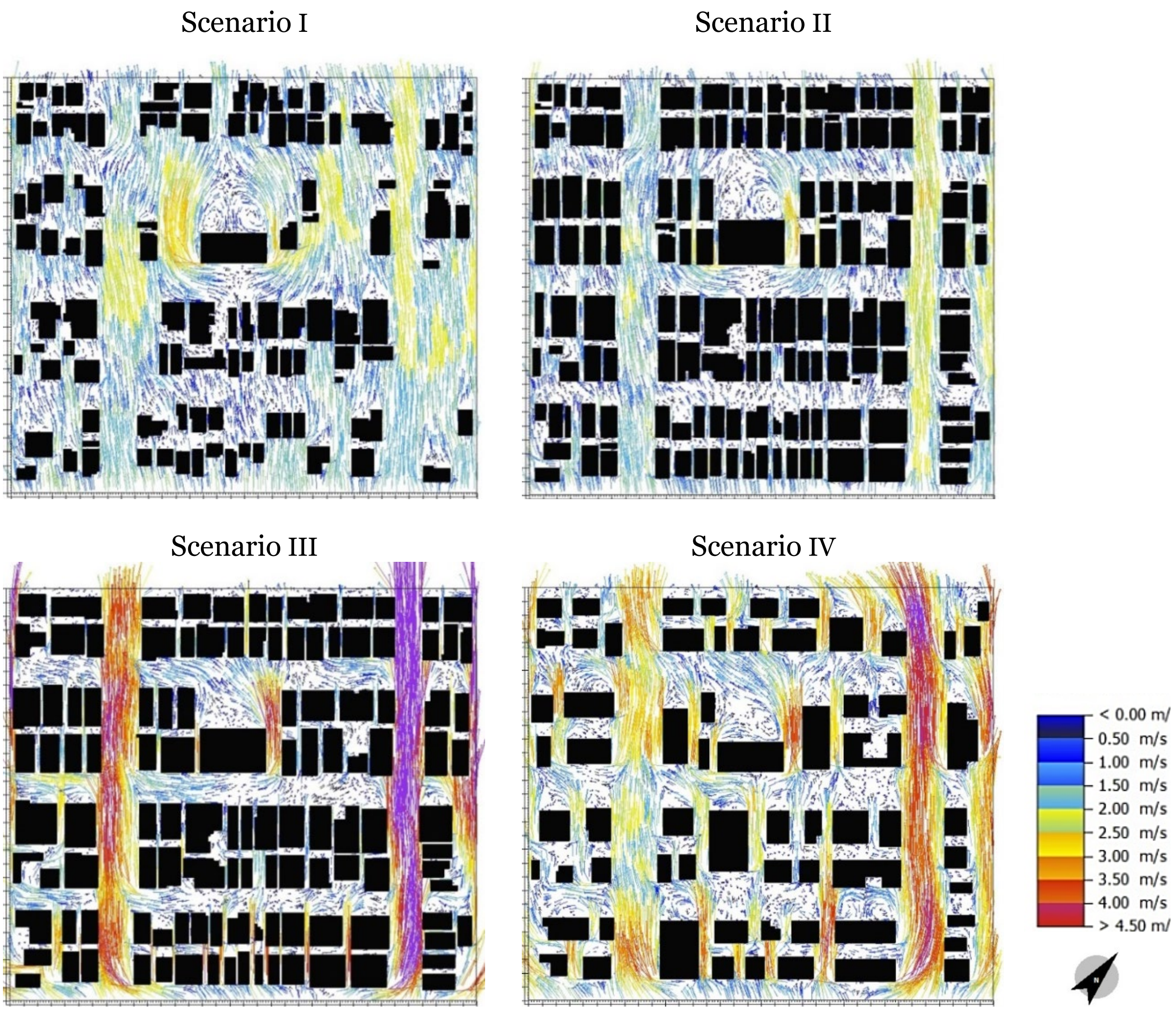
Wind speed

The wind speed results did not show significant differences throughout the day, since the entry of wind data in the model is constantly presented throughout the simulation, representing a limitation of the software version used in the study. Thus, for the analysis of the 2D maps of the simulated models, the time corresponding to 3:00 p.m. was considered because it was the hottest period of the day (Figure 5).

In Scenario I, it was observed that in the northwest-southeast direction, parallel to the predominant direction of natural ventilation, the wind velocity reached 3.0 m/s, since the urban morphology of the simulated fraction presents low roughness due to the earth's buildings and several empty lots, resulting in accordance with Oke (1996). At the windof the buildings it was possible to visualize several areas with wind shadow and the speed was practically nil.

Scenario II presented a similar wind behavior pattern, with some modifications. Due to the occupation of all urban lots by single-end buildings, in the northwest-southeast direction, on the right occurred the channeling of the winds, generating increased speed, however, causing air stagnation inside the blocks and in the roads oriented to the northeast-southeast axis. There was also a significant loss of speed in the areas of the windscreen and the formation of areas of air stagnation due to the use of the initial minimum recoil.

Figure 5. 2D wind speed maps (m/s) in the four scenarios parameterized in the urban fraction studied.



Source: The authors (2022).

Scenario III presented the worst performance regarding the utilization and permeability of winds in the urban structure. The verticalization of the buildings with the use of the initial minimum recoil formed in the northwest-southeast direction routes true urban ventilation channels, with a speed greater than 4.5 m/s, causing air stagnation inside the blocks and reducing the speed of winds in the northeast-southwest orientation. In this scenario, the effect of vegetation on the northwest-southeast direction on the left was evident.

The adoption of progressive recoil in verticalized buildings directly interfered with the geometry of the urban canyon that conforms from the verticalization of the buildings to the margins of the roads (Nicholson, 1975). The greater spacing between the buildings generated favorable conditions for the performance of natural ventilation in the urban fraction, with a result similar to that obtained in the study by Ramyar et al. (2019). The effect of wind channeling on northeast-southwest bound routes decreased significantly. As for the permeability of the winds inside the blocks, smaller areas of wind shadow were observed. De & Mukherjee (2018) stated that the higher wind speed improves the conditions of outdoor thermal comfort and passive ventilation of buildings, contributing to the dispersion of pollutants by mixing the air.

Final considerations

In order to obtain resilient and sustainable cities, it´s essential to apply the principles of bioclimatic urbanism in the urban planning process. In regions with tropical savanna climate, with predominance of hot periods, the importance of analyzing the impact of urban morphology on the microclimate becomes even more indispensable, due to high temperatures.

The analysis of the simulated scenarios from an urban fraction with a tendency to verticalization in the city of Arapiraca, allowed the understanding of how urban morphology can interfere in the microclimate and, consequently, in outdoor thermal comfort. The thermodynamic properties of the materials directly influenced the air temperature, regulating heat gains. With the heating of the air, there are also changes in the phenomena of thermal exchange (Krüger & Gonzalez, 2016).

The orientation of the roads interfered in the air temperature due to solar access and the amount of hours of exposure to direct solar radiation and wind speed, in relation to the predominant direction of the winds that determined the degree of permeability of the urban form and the speed of the winds in the local roadways. For future studies, it would be important to add how the orientation of ventilation perpendicular to the road pathway can influence the performance of the microclimate.

The H/W ratio also influenced the air temperature, due to the shading generated by the verticalized buildings, as well as the degree of permeability of the winds. In a tropical savanna climate reality, it was clear that, in the hierarchy of local bioclimatic strategies, shading has a greater impact on the microclimate and outdoor thermal comfort, which corroborates the study by Yahia et al. (2017). However, it´s important to deepen the present study in order to balance the application of the two strategies: shading and natural ventilation.

Finally, it can also be highlighted that the vegetation emerged as an attenuating element of high temperatures because it presents more favorable conditions regarding thermodynamic properties, as well as the favoring of shading at pedestrian level, without significantly interfering in the permeability of winds. Thus, the importance of the study of the urban microclimate in relation to the morphology of cities is highlighted, in order to provide environmental quality for the inhabitants of the city.

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