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Characterization of the urban heat Island phenomenon in Niamey, Niger, in the context of climate change

Garba BOUBACAR [1, *], Abdoul Aziz SAIDOU CHAIBOU [2], YAHOUZA Zaneidou [1] and Amadou Ibrahim ABDOURAHAMANE [3]

[1] *Department of Didactics, Faculty of Educational Sciences, Djibo Hamani University of Tahoua, P.O. Box 225, Tahoua, Niger.*
[2] *Department of Physics, Faculty of Science and Technology, Abdou Moumouni University, P.O. Box 10662, Niamey, Niger.*
[3] *Directorate of Architecture, Ministry of Urban Planning, P.O. Box 502, Niamey, Niger.*

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Abstract

In African cities, urban areas often experience a microclimate characterized by significantly higher temperatures than surrounding rural regions, a phenomenon known as the Urban Heat Island (UHI) effect. This effect is frequently attributed to poorly planned urban development and can have harmful health consequences due to increased thermal stress. This study evaluates the intensity of the UHI in Niamey based on urban morphological parameters, specifically building height and street width. Data were obtained from the National Geographic Institute of Niger (IGNN) and the National Directorate of Urban Planning of Niger (DNUN). Two main indicators were employed: the aspect ratio (AR) and a thermal index related to urbanization (ΔT_{URMAX}), which reflects the potential amplification of heat perception in urban settings. The results reveal that UHI intensity decreases linearly with increasing building height when street width ranges from 10 m to 100 m. The recorded thermal amplitude varies between −5.74 °C and +3 °C. At the same height of building, UHI intensity also decreases as street width increases.

Keywords: Urban Heat Island (UHI); Niamey; Climate Change; Aspect Ratio (AR); Urban Morphology; Thermal Stress; Africa

1. Introduction

The rapid growth of African cities is often accompanied by poorly planned urbanization, which leads to significant changes in the urban microclimate. One notable change is the urban heat island (UHI) phenomenon, which is characterized by significantly higher temperatures in urban centers compared to surrounding rural areas [2-5]. Urban overheating results from the artificialization of surfaces, building density, and reduced green spaces. Urban overheating contributes to increased heat stress, which can have serious consequences for public health, infrastructure, and urban ecosystems [6-8]. Temperature variations at different time scales are amplified by the effects of global climate change, which manifests as a general rise in average temperatures. According to the Intergovernmental Panel on Climate Change, the expected warming on the African continent in the 21st century could exceed the global average. This would expose urban populations to more frequent, longer, and more intense heat waves. In this context, the vulnerability of African cities to climate extremes is exacerbated by the Urban Climate Island (UCI) effect, which is defined as a positive air temperature anomaly between urban centers and rural or peripheral areas. This phenomenon is of particular concern in Sahelian cities, where the climate is already arid and resources are limited [12, 13]. This study focuses on Niamey, the capital of Niger and a city located in the Sahel region on the banks of the Niger River. Niamey has a semi-arid tropical climate with two distinct seasons: a dry season from October to May and a wet season from June to September. Average annual temperatures range from 28.7°C to 30.97°C, and annual rainfall varies between 300 and

* Corresponding author: Garba BOUBACAR

600 millimeters [14]. This climate, combined with urban expansion, makes the city particularly susceptible to the heat island effect. A simple methodology was adopted to characterize this phenomenon. It is based primarily on urban morphological parameters, such as building height and street width, that are known to influence local-level energy exchanges and heat trapping [15]. However, this approach has significant limitations in capturing all intra-urban microclimatic variations in Niamey. Therefore, it is necessary to clearly specify the assumptions and simulated conditions used in this study. This study aims to characterize the effect of ICU intensity on building height and street width in Niamey.

2. Data and Methodology

2.1. Study area

With an area of 1,267,000 km^2, Niger has a tropical Sudanese climate with two distinct seasons: a long dry season from October to May, and a short rainy season from May to September. The highest average temperatures are recorded between March and April, exceeding 40°C, while the lowest temperatures are recorded between December and February, dropping below 10°C.

For this study, we selected Niamey, a city located between 13°28' and 13°35' north latitude and 2°03' and 2°10' east longitude (Figure 1). With a surface area of 240 km^2, Niamey is built on a plateau on the left bank of the Niger River and on an alluvial plain on its right bank, between 180 and 250 meters above sea level. On a global scale, the location of urban areas also strongly impacts the intensity of ICU [13].

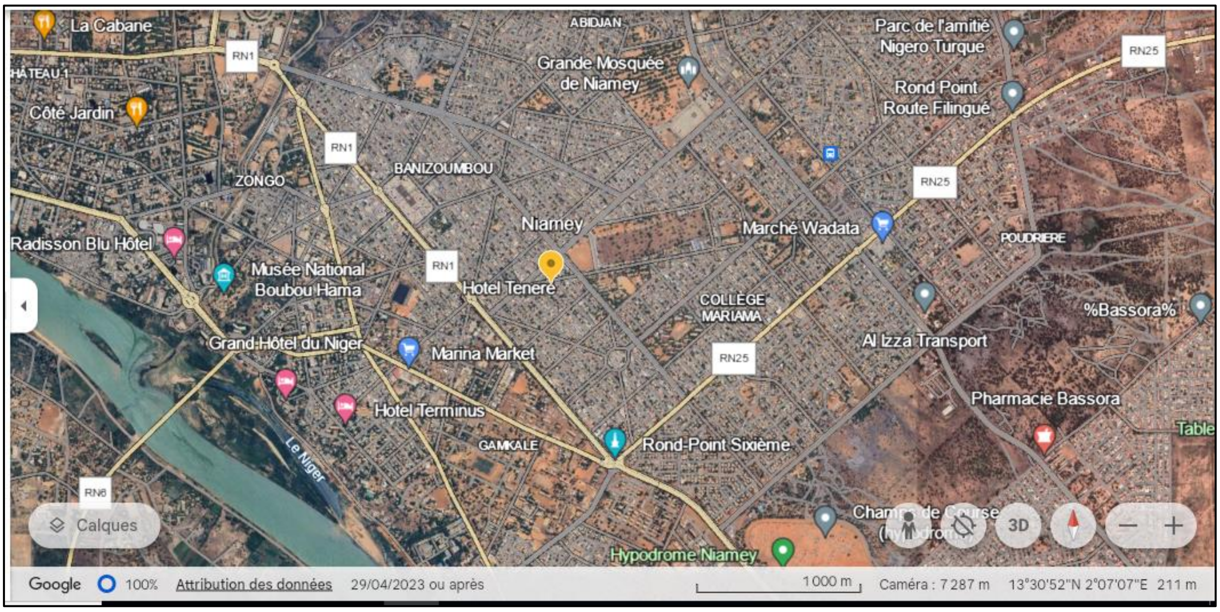

Figure 1 Map of buildings and street widths in a section of Niamey, Niger. Source: Google Earth and ArcGIS, February 26, 2024

Niamey was chosen because it is the administrative capital of Niger. Like most African capitals, Niamey has experienced constant urbanization and demographic growth for several decades. This includes the construction of paved roads, housing, and other infrastructure, as well as an increase in rural exodus. This growth increases the city's vulnerability to extreme weather events, such as heat waves and floods. We expanded our study to cover the entire city of Niamey, where there are no building standards in place and French regulations (AFNOR, DTU, BAEL, etc.) are enforced without adaptation to the local context.

2.2. Data

In this study, we used data on street widths and building heights in Niamey, obtained from the National Geographic Institute of Niger (IGNN) and the National Urban Planning Directorate of Niger (DNUN). The IGNN provided data on street widths of 3, 5, 8, 10, 12, 15, 20, 25, 30, 40, 50, and 100 meters, while the DNUN provided data on street widths of 3.6, 4, 8, 12, 16, 20, 24, 28, and 32 meters. However, streets measuring 3 m, 5 m, 8 m, and 12 m in certain neighborhoods that do not meet regulatory standards according to the land registry service were excluded from this study.

2.3. Methodology

We aim to characterize the urban heat island phenomenon in Niamey using two indicators. The first indicator is the aspect ratio (AR). The AR provides morphological information about the urban canyon section based on building height (H) and street width (W), as given by equation (1) [3]:

$$AR = \frac{H}{W} \quad (1)$$

H is the height of buildings, W is the width of the street, and AR is the aspect ratio of building height to street width.

The second factor is likely to exacerbate the sensation of heat associated with uncontrolled urbanization, such as the destruction of green spaces for housing, paving of streets, and the effects of large buildings and narrow streets. An empirical relationship can be established to estimate these effects using equation (2), which expresses the variation in ΔT_{URMAX} as a function of the aspect ratio, H/W (the ratio of building height to street width) [3].

$$\Delta T_{URMAX} = 7,45 + 3,97 Ln\left(\frac{H}{W}\right) \quad (2)$$

We applied equation (2) to Niamey using different values for building height (H) and street width (W).

3. Results

Tables 1 and 2 show the aspect ratios and temperature differences relative to the environment, respectively, as a function of building height and street width. Figure 2 shows the corresponding variations.

Table 1 Summarizes the aspect ratio (AR) values.

Street (w in m)	AR(h=3.6 m)	AR(h=4 m)	AR(h=8 m)	AR(h=12 m)	AR(h=16 m)	AR(h=20 m)	AR(h=24 m)	AR(h=28 m)	AR(h=32 m)
10	0.36	0.4	0.8	1.2	1.6	2	2.4	2.8	3.2
15	0.24	0.26	0.53	0.8	1.06	1.33	1.6	1.86	2.13
20	0.18	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6
25	0.14	0.16	0.32	0.48	0.64	0.8	0.96	1.12	1.28
30	0.12	0.13	0.26	0.4	0.53	0.66	0.8	0.93	1.06
40	0.09	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
50	0.072	0.08	0.16	0.24	0.32	0.4	0.48	0.56	0.64
100	0.036	0.04	0.08	0.12	0.16	0.2	0.24	0.28	0.32

The model (see equation 1) suggests that the moment of maximum urban heat island intensity occurs when the aspect ratio (H/W) is greater than three (3). This allows us to determine the values of urban heat island intensity corresponding to different aspect ratios, summarized in Table 2.

Table 2 The urban heat island effect as a function of building height and street width.

Street width w in m	ΔT_{URMAX} (°C) H=3.60m	ΔT_{URMAX} (°C) H=4m	ΔT_{URMAX} (°C) H=8m	ΔT_{URMAX} (°C) H=12m	ΔT_{URMAX} (°C) H=16m	ΔT_{URMAX} (°C) H=20m	ΔT_{URMAX} (°C) H=24m	ΔT_{URMAX} (°C) H=28m	ΔT_{URMAX} (°C) H=32m
10	3.39	3.81	6.56	8.17	9.31	10	10.92	11.53	12.06
15	1.78	2.1	4.92	6.56	7.68	8.58	9.31	9.91	10.45
20	0.76	1	3.81	5.42	6.56	7.45	8.17	8.78	9.31
25	-0.35	0.17	2.92	4.53	5.67	6.6	7.28	7.84	8.43
30	-0.96	-0.64	2.1	3.81	4.92	5.8	6.51	7.16	7.68
40	-2.1	-1.7	1.06	2.67	3.81	4.69	5.42	6.03	6.56
50	-2.99	-2.57	0.17	1.78	2.92	3.81	4.53	5.14	5.67
100	-5.74	-5.32	-2.6	-0.96	0.17	1.1	1.78	2.39	3

As shown in Table 2, the heat island effect decreases as street width increases for buildings of the same height. However, for streets of the same width, the effect increases with building height.

3.1. The intensity of the urban heat island varies depending on building height and street width.

Most models of anthropogenic heat emission take into account emissions from three sources: vehicles, buildings and human metabolism.

However, heat from buildings contributes the most to the total [19]. Heat produced inside a building can cause it to overheat in summer, particularly when combined with direct solar radiation or poor thermal insulation. Household appliances, lamps and computers, for example, convert the energy they consume into heat. These internal heat inputs are not simultaneous, instead representing a diffuse source of heat within buildings.

Figure 2 below shows that the greater the height of buildings and the narrower the streets, the greater the intensity of the ICU.

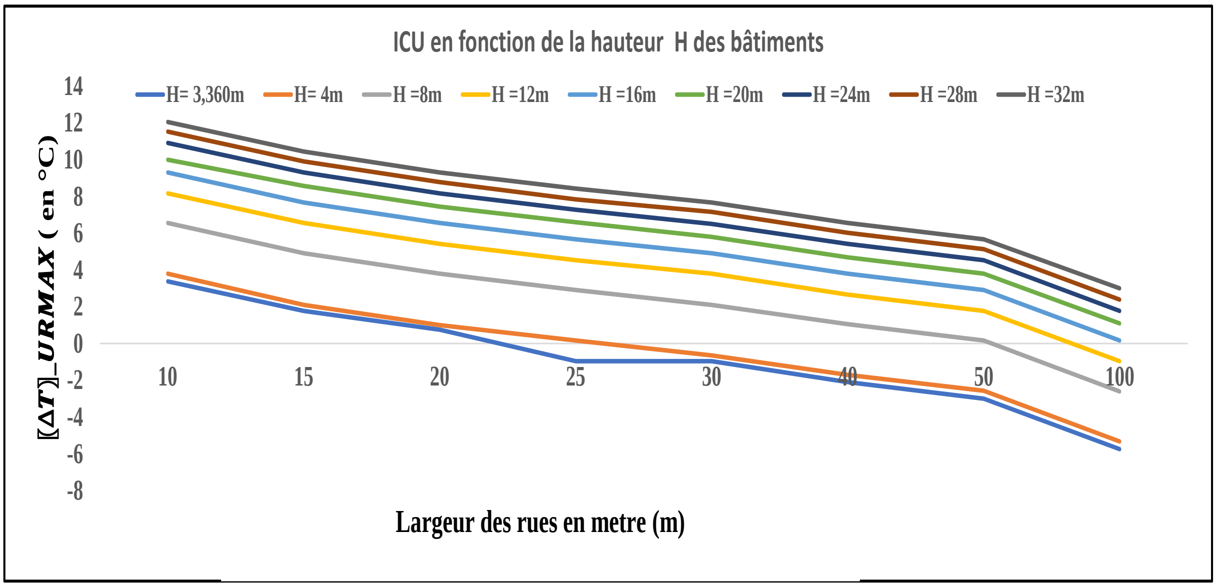

Figure 2 The variation in ICU according to building height and street width.

Figure 2 shows the variation in temperature difference with the surrounding environment and indicates that, in Niamey:

For a street width of 10 m, the temperature variation amplitude increases from 3.39 °C to 12.06 °C for buildings ranging in height from 3.60 m to 32 m. This temperature difference decreases linearly with building height as street width increases from 10 m to 100 m, with the range varying from -5.74°C to 3°C.

For buildings of the same height, the temperature decreases as the street width increases. In other words, major thoroughfares without overly tall buildings improve the circulation of fresh air from the surrounding area.

Therefore, narrow streets are not conducive to comfort when buildings are too tall. Wide streets promote comfort for buildings of the same height. We also know that very compact neighbourhoods with tall, closely spaced buildings prevent air from circulating properly.

4. Discussion

This study focuses on the urban heat island (UHI) phenomenon. It first establishes the presence of UHI by measuring an increase in air temperature. Similarly, analyzing data on building height and street width reveals morphological information about the urban canyon. Urban centers absorb more solar radiation than surrounding rural areas. Materials commonly used in construction, such as concrete, asphalt and glass, absorb heat during the day and release it slowly at night. These surfaces have a characteristic called low albedo, meaning they reflect only a small amount of the solar radiation they receive. Consequently, urban air remains warmer, sometimes by several degrees, long after sunset <https://www.action-climatique.com/changement-climatique/adaptation-et-resilience/les-ilots-de-fraicheur-urbains-enjeux-et-solutions-pour-attenuer-l-effet-des-ilots-de-chaleur>

Our results confirm the idea that large buildings and narrow streets can hinder proper ventilation in urban centers by creating canyons where heat from solar radiation and human activities accumulates and becomes trapped. Several studies have shown that the geometry of cities exacerbates the intensity of urban heat islands [20, 23]. According to these studies, the shape of the city — i.e. the layout of its streets and buildings, and their respective sizes, shapes and orientations — affects energy and air flows, thereby influencing phenomena such as the UHI. Contrary to the work of Hinse et al. and Landsberg [24, 25], our results corroborate the intensity values reported in the international scientific literature on heat islands, which range from 0.6°C to 12°C [26]. Indeed, large cities exhibit an urban-rural air temperature difference ranging from 2 to 10°C.

4.1. Factors that influence the intensity of the urban heat island effect

Heat islands are urbanized areas characterized by air or ground temperatures that are 5 to 10°C higher than the surrounding area at the measurement point [24-26]. Furthermore, the intensity values observed in the international scientific literature have shown that heat island intensity can range from 0.6°C to 12°C [26].

The formation, intensification and spatio-temporal variability of heat islands are associated with six main factors of different natures [27]:

- climate: clear skies, no wind and air pollution;
- energy: heat emissions from energy consumption;
- geography: the location of the city;
- morphological factors: building density, vegetation concentration and growth rate;
- practical land use planning policy ;
- structure: size of the city, ratio of mineralised to vegetated surface area, land use.

4.2. Measures to combat the urban heat island effect:

Four measures can be considered to combat urban heat islands: vegetation measures; measures related to urban infrastructure, such as architecture and land use planning, stormwater management and soil permeability; and measures to reduce anthropogenic heat [20, 28].

Vegetation measures create coolness through various processes, such as seasonal shading of infrastructure, evapotranspiration and minimizing ground temperature differences [20].

Vegetation improves air quality by producing oxygen, capturing CO_2, filtering suspended particles and reducing the demand for air conditioning energy.

It also improves water quality by retaining rainwater in the soil and controlling soil erosion, and has health benefits for the population, including protection against ultraviolet (UV) radiation, reduction of heat stress, and providing places for physical activity [28–32].

4.2.1. Measures related to urban infrastructure

Large paved areas in urban centers, such as school playgrounds, roads and car parks, are often covered in dark materials like asphalt that absorb most of the sun's rays. On hot days, these surfaces can reach temperatures of 80°C, which contributes significantly to the urban heat island effect [33].

To reduce the amount of heat accumulated by paving stones, it is possible to increase their albedo using the following techniques:

Reversed pavers: This method involves laying the paver with the side that has a higher albedo facing upwards. This is achieved by spreading the paver over a thin layer of bitumen, on which the high albedo aggregate (e.g. 0.60) is laid. This increases the pavement's reflectivity to solar radiation, reducing the paving stone's temperature. However, these types of paving stone are not recommended for use on high-speed roads, as pieces of aggregate can become dislodged and damage windshields [20].

4.2.2. Coloring asphalt and concrete: This method increases reflectivity.

Concrete surface layer: for an asphalt road in good condition, a layer of concrete between 2.5 and 10 cm thick must be laid. When the albedo value of the concrete is high, between 0.30 and 0.40 (i.e. when it is new), it helps to keep the surface temperature cooler [34].

Measures related to urban infrastructure: For vehicle use, paints with a high solar reflectivity rating should be recommended by manufacturers. These paints are composed of special elements that increase albedo by an average of 17.5% [35].

4.3. Energy balance

Solar radiation is the main source of energy for the Earth–atmosphere system. This can be broken down into two parts: one corresponding to the solar band (short-wavelength radiation, including visible and near-infrared light, between 0.15 and 3.0 μm), and the other to infrared exchanges (long-wavelength radiation, between 5 and 100 μm) [36].

The concept of energy balance is explained here based on the article by David J. Sailor (2011) [37], to which we will refer:

$$Q_F = Q_H + Q_E + \Delta Q_S - Q^* \qquad (3)$$

At any given moment, any imbalance in surface radiation can be attributed to a combination of convective exchanges with the atmosphere in the form of net radiation (Q^*), sensible heat flux (Q_H), latent heat flux induced by the phase change of water (Q_E) and work (W), which reflects changes in pressure or volume. All of these processes represent the element's internal energy (E) (4).

$$dE = (dQF + dW) = (dQH + dQE + d\Delta QS - dQ^*) + dW \qquad (4)$$

We know from thermodynamics that, for an ideal gas, a change in internal energy is proportional to a change in temperature (4).

$$dE = C_V \,.\, dT \qquad (5)$$

(C_V : Thermal capacity)

Thus, the change in temperature at ground level can be expressed for a given volume as follows:

$$dE \,/\, C_V = dT = (dQH + dQE + d\Delta QS - dQ^* + dW)/C_V \qquad (6)$$

This equation reflects the energy balance between radiation and sensible and latent heat fluxes.

Furthermore, in the case of an energy balance at the Earth's surface involving a solid body with zero volume or pressure variations, the work term (W) is also zero.

The energy balance of the urban environment is significantly affected by its particular characteristics. Building materials generally have higher thermal properties than natural soils in terms of thermal capacity (Cg) and thermal diffusivity (κg).

If we consider urban areas to be surfaces that are virtually impervious to rainwater, then dry latent heat flows are significantly reduced during the day ($Q_E \approx 0$). Therefore, temperature variation would result from the combined effect of radiative flux (Q*) and sensible heat flux (Q_H). The geometry of the urban canopy amplifies this temperature variation by increasing the greenhouse effect. This is achieved by trapping solar radiation through multiple reflections in the canyon, and by preventing the release of infrared radiation into the atmosphere (2). The result is an increase in air temperature. Mariethoz [38] considers the high energy consumption required for activities in the heart of urban areas, which represents a considerable additional source of sensible heat released into the environment (e.g. road traffic, heating and air conditioning). Similarly, in an urban center, the mechanical resistance that buildings oppose to the movement of air masses must be taken into account, as this limits the vertical transfer of accumulated heat and therefore losses by convection.

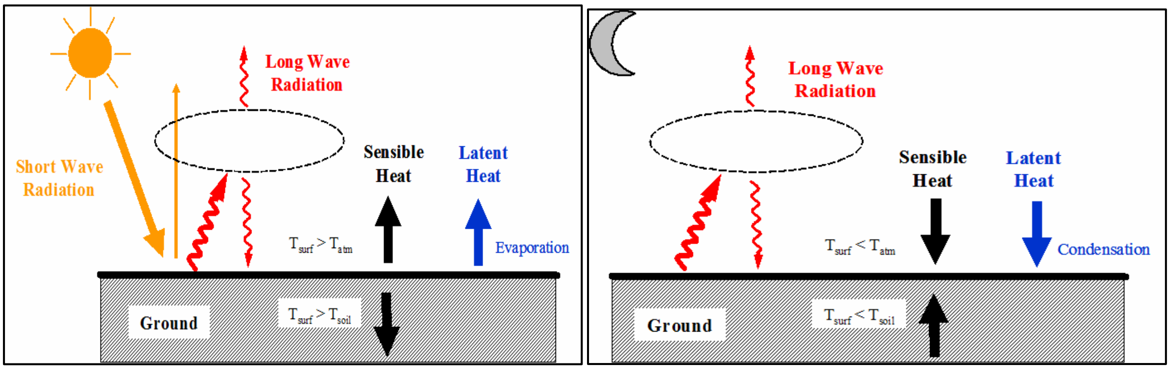

Figure 3 Energy flow at ground level during the day and night (source: ENAC-SSIE Air Pollution Laboratory)

A heat island is an anomaly in the energy balance, reflecting excess heat in urban areas relative to surrounding rural areas [38].

The intensity of heat islands varies on a daily and seasonal basis, depending on various meteorological and human-related factors. Generally, urban canopy heat islands are more intense at night than during the day [36, 39].

The radiation balance relates to the flow of sensible and latent heat. In the presence of water bodies and vegetation, some of the radiation is used to evaporate water, contributing to plant transpiration. This reduces the flow of sensible heat in favour of latent heat, thereby lowering the air temperature.

Thus, the thermal comfort of city dwellers depends greatly on urban temperatures, which are affected by the shape and size of cities, the orientation and spacing of buildings within cities, the increase in urban traffic and anthropogenic energy production. Another factor that negatively impacts thermal comfort in urban areas is the reduction in vegetation, which decreases coolness. Vegetation plays a key role in providing protection against heat through evapotranspiration and by providing shade for the ground and buildings. During the natural process of evapotranspiration, ambient air cools by releasing some of its heat to allow evaporation [41-44].

5. Conclusion

This study focused on urban heat islands and the worsening of heat stress linked to poorly controlled urbanization. Studying the variation in urban heat island intensity according to building height and street width showed that narrow streets do not promote comfort when buildings are tall, whereas wide streets do.

This phenomenon is exacerbated by a lack of ventilation, resulting in increased temperatures. For a street width of 10 m, the temperature variation amplitude increases from 3.39°C to 12.06°C as the height of buildings increases from 3.60 m to 32 m. This temperature difference decreases linearly with building height as street width increases from 10 m to

100 m. The temperature difference ranges from -5.74°C to 3°C for buildings of the same height, decreasing as street width increases.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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