URBAN MICROCLIMATE AT HEIGHT: DIFFERENCES IN AIR TEMPERATURE VERTICAL PROFILE

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ABSTRACT
Cities' morphologies determine the urban microclimate. The thermal conditions may differ according to the distance from the ground. For instance, air velocity and solar incidence tend to be higher as the height increases due to the decrease of obstacles to wind and radiation. This work discusses the gradient of vertical air temperatures in a high-rise building area. In winter and spring, measurements in the field at two heights on the same building occurred in the coastal Brazilian city of Balneário Camboriú. The air temperature was generally higher during the daytime at the highest point than the near ground one, especially in clear sky conditions, and lower during nighttime. As the sky view factor increases with height, the shading obstacles decrease, leading to generally higher solar access and a higher heat released through longwave radiation to the sky. Also, the studied area was modelled in ENVI-met and compared to field measurements. Simulation's results in the vertical profile showed the opposite behaviour than the field observations. Especially in high-density cities, understanding the vertical microclimate profile may guide the development of urban climate improvement strategies.

Key words: urban microclimate, air temperature profile, urban physics, computational simulation.

1. INTRODUCTION

Urban microclimate refers to the specific atmospheric conditions within an urban environment due to various factors such as the built environment, vegetation, and human activities (OKE et al., 2017a). The urban heat island is the most studied phenomenon, characterized by the air temperatures in the cities being higher than their non-urban neighbors (SANTAMOURIS, 2006).

Over half of the world's population lives in urban areas (UNITED NATIONS, 2018). This urbanization process has led to the rise of high-density and verticalized urban spaces that create deep urban canyons affecting air and heat movement. The impacts of urban microclimates relate to human health (PATZ et al., 2005; SARRAT et al., 2006), extreme weather events (LI; BOU-ZEID, 2013), and energy consumption in cities (KOLOKOTRONI et al., 2012; SANTAMOURIS et al., 2015). In this context, comprehending how the city's morphologies and human activities impact the microclimate is fundamental to urban planning and design.

As urban verticalization increases, it is reasonable to assume significant differences between the microclimate generated at the street level and at a height close to that of rooftops. These levels are exposed to distinct intensities of solar exposure, wind speed, and anthropogenic heat generation. Furthermore, given the challenge of measuring climatic variables and assessing the impact of urban heat mitigation applications at different heights, computational simulations are suggested. Utilizing computational models enables the assessment of diverse approaches for enhancing urban climate efficacy while maintaining variable control and reducing expenses (CRANK et al., 2018; SHARMIN; STEEMERS, 2017).

This study aims to evaluate the differences in air temperature in the urban canopy layer between the street level and immediately below the buildings' roofs. Field measurements and CFD simulations with the ENVI-met model made the evaluation. This study aims to contribute to the knowledge of urban physics and provide insights for urban planners and designers to improve the quality of life in high-density urban spaces.

2. OBJECTIVE

The study aims to evaluate the air temperature at two different heights by field measurements and computational simulation in a high-density area of Balneário Camboriú, Brazil.

3. METHOD

This section presents the methodology, from the characterization of the studied area and the field measurements to the setup of the computational simulations in ENVI-met.

3.1. Field measurements

The study occurred in a high-density area of Balneário Camboriú, Brazil. This city has a humid subtropical climate (Cfa) by Koppen-Geiger classification (KOTTEK et al., 2006). The studied area represents the denser zone of the city, being the principal commercial and services center, with high-rise buildings and narrow streets. As a matter of quantifying the morphological parameters, the studied area shows an average building height of 31 meters and a site coverage ratio of 0.5.

On the second and last floor balconies of an 8-floor building (approximately 24 meters from the ground), thermohygrometers with data loggers were installed. The HOBO data loggers, model MX1101, were installed with low-cost shelters to protect them from solar radiation and adverse weather conditions. The accuracy and resolution of the temperature sensor are 0.21 °C and 0.024 °C, respectively. The measurements were taken at 4.5 and 22.5 meters high. Figure 1 shows the studied area, the building, and the point of measurement sites schematically.

The building was monitored during two weeks of winter and another two weeks in spring. In winter, measurements started on 24 June and ended on 9 July 2021. In the spring season, the equipment was installed from the 9th to the 23rd of November of the same year. The interest in studying the microclimate in different seasons is justified mainly by solar access throughout the year. For instance, the studied building's façade does not receive direct solar radiation in winter. While in spring, this exposure occurs in the early morning.

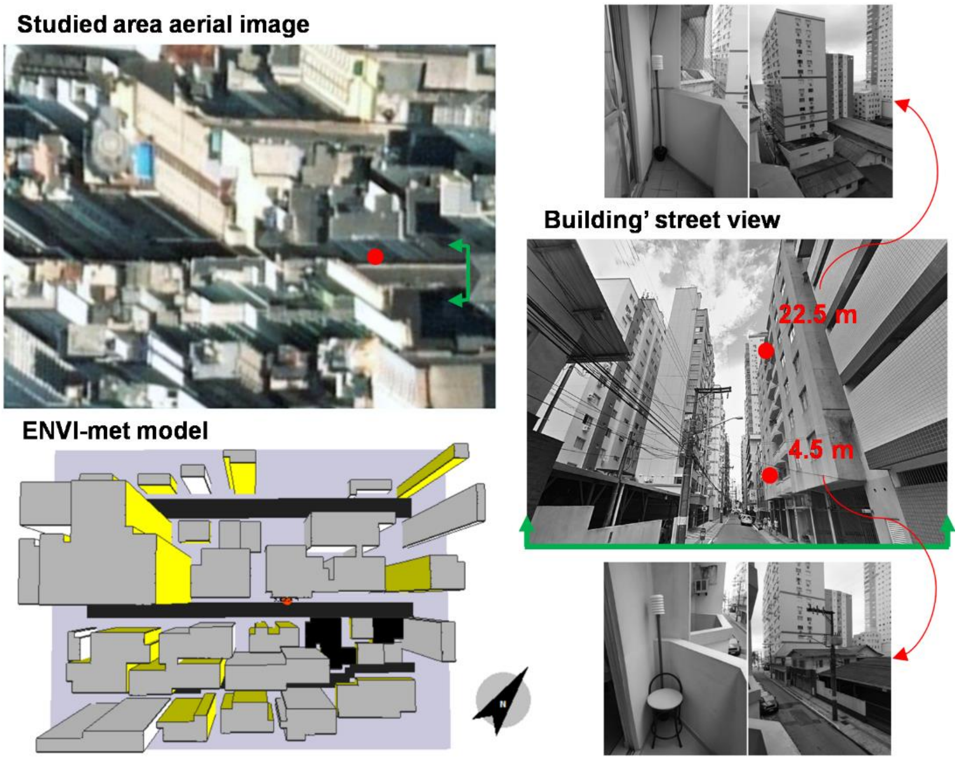

Figure 1 - Studied area in aerial image and the model on ENVI-met on left, street view with building's equipment installed on right

3.2. Computational simulation

A day from each season's measurement period was selected to simulate in the ENVI-met version 4.4.6 model. The days simulated were defined based on two main criteria: clearest sky and uniform wind speed and direction throughout the day since these conditions are more likely to return a higher UHI effect since it relates to atmospheric stability. According to the criteria, the selected representative days were 06/30/2021 and 11/22/2021 in winter and spring (in the southern hemisphere), respectively.

The simulated area was modelled in 120 meters x 160 meters in a 2 x 2 meters grid. In height, the model is 170 meters in a grid of 3 meters until it reaches 30 meters from the ground, then a 5% of telescope factor was considered. The materials attributed to the buildings were fibercement roofs (2.06 W.m-2.K-1) and ceramic bricks walls (2.39 W.m-2.K-1). The solar reflectance of façades and roofs was divided into three and two categories, respectively, according to observations in loco and aerial images. The possibilities for façades were low, medium, and high solar reflectance (0.2, 0.5, and 0.8). For roofs, only medium and low solar reflectance was considered to represent the actual degradation state of the buildings: 0.4 and 0.15, based on Maestri (2017). For the pavements, ENVI-met default profiles of asphalt were assigned to the streets and concrete pavement to the sidewalks.

The simulations were run for 44 hours, starting at 04:00. The start time was set before sunrise, and the first day was excluded from the analysis as a spin-up period (SINSEL et al., 2021). Tests were conducted to determine the simulation settings, and the "simple-forcing" mode was ultimately selected due to its optimal performance and computational cost. Table 1 provides an overview of the initialization parameters used for the winter and spring base case scenarios in the ENVI-met version 4.4.6 model.

The hourly air-temperature profile was obtained from the weather data of the nearest station, the University of Vale do Itajaí. The air relative humidity profile was estimated using the maximum and minimum average field measurements. The wind speed and direction were maintained constant, and the wind speed average was adjusted to represent an urban location. The global solar radiation calculated by ENVI-met was adjusted to match the peak value of the nearest weather station.

The tridimensional model in ENVI-met brings information about some morphological parameters. The sky view factor, for instance, can be defined as a geometric characteristic that represents the proportion of the visible sky that is accessible for the dissipation of thermal energy. This factor varies from zero to one, representing a more open sky as approximate to one. The SVF estimated by ENVI-met for the modelled geometry is indicated for both heights in Figure 2. The near street point (at 4.5 m) shows an SVF of 0.39, increasing as it distances from the ground, reaching 0.67 at 22.5 m height.

Table 1 - summary of simulations' input data

	Winter	Spring
Start date (YYYY.MM.DD) – start time (HH:MM)	2021.06.29 - 04:00	2021.11.21 - 04:00
Total simulation time	44 h	44 h
Wind speed (m/s)	2.2	2.2
Wind direction (deg)	260	0
Simple forcing	Yes	Yes
Air temperature	Itajaí weather station at 2021.06.30	Itajaí weather station at 2021.06.30
Relative humidity (max (%)/time – min (%)/time)	60%/07:00 - 45%/15:00	78%/05:00 - 55%/09:00
Cover of clouds (octas)	0	2 (*low clouds*) 0 (*medium clouds*) 0 (*high clouds*)
Adjustment factor for solar radiation	0.9	1.2
Advanced radiation transfer scheme (IVS)	Yes	Yes

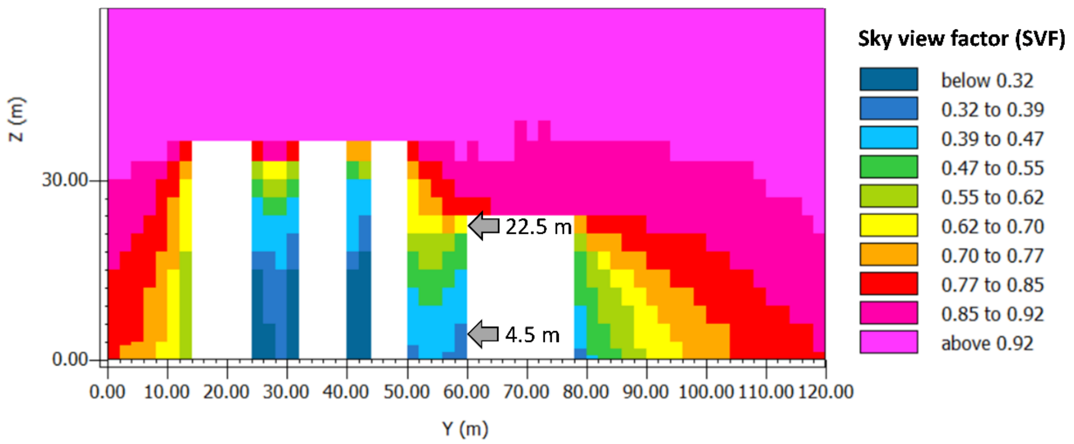

Figure 2 - SVF in the Y-Z section at the measuring points (at 4.5 m and 22.5 m height) estimated by ENVI-met

4. RESULTS AND DISCUSSION

4.1. Difference in measured air temperatures

The results are presented and discussed in this section. First, the field measurements made in winter and spring are shown. Figure 3 shows the air temperature for two weeks in winter. It is observed that both points - at 4.5 m and 22.5 m height – follow the same pattern, as expected. In this period of measurements, the temperatures reached a minimum of 8.7 °C (29th June) and a maximum of 23.4 °C on 25th June.

The air temperature difference between 22.5 and 4.5 m (ΔT) is also plotted in the graph in red (Figure 3). It is observed that air temperature is usually higher at 22.5 meters height during daytime and lower at nighttime. The only exception occurred on 28th June, when the air temperatures at 22.5 m maintained lower than at 4.5 m the whole day, probably due to the high cloud cover, which was confirmed by the airport weather station data at Navegantes city (NOAA, 2021).

At 4.5 m, the air temperatures generally showed a smaller range than at 22.5 m. As the height increases, the sky view factor also does, due to the decreasing surrounding building areas. Although none of the points received direct solar radiation during winter measurements, the solar access is lower at 4.5 m. It is important to highlight that this relationship (high solar access in high SVF locations) is not an absolute truth. For instance, depending on the orientation, irregular canyons might be the opposite since the building façade reflects the solar incidence to the canyon.

Figure 4 presents the measurements of air temperature in the spring season. The measurement period registered a minimum air temperature of 17.2 °C and a maximum of 26.2 °C; both occurred at 22.5 m height. The thermal range of air temperature in spring was lower than in winter, and most days were cloudy. These conditions may have contributed to minimizing the difference between both points. The highest negative difference of ΔT for the spring occurred at 7:00 on 12th November, reaching 1.5 °C. It is observed that the last three days monitored presented positive peaks on the difference that happened in the early morning, meaning the 22.5 m location was up to 2 °C hotter than at 4.5 m. This difference rapidly decreases, meaning that the higher temperature was probably caused by solar exposure, which occurs first on the highest point.

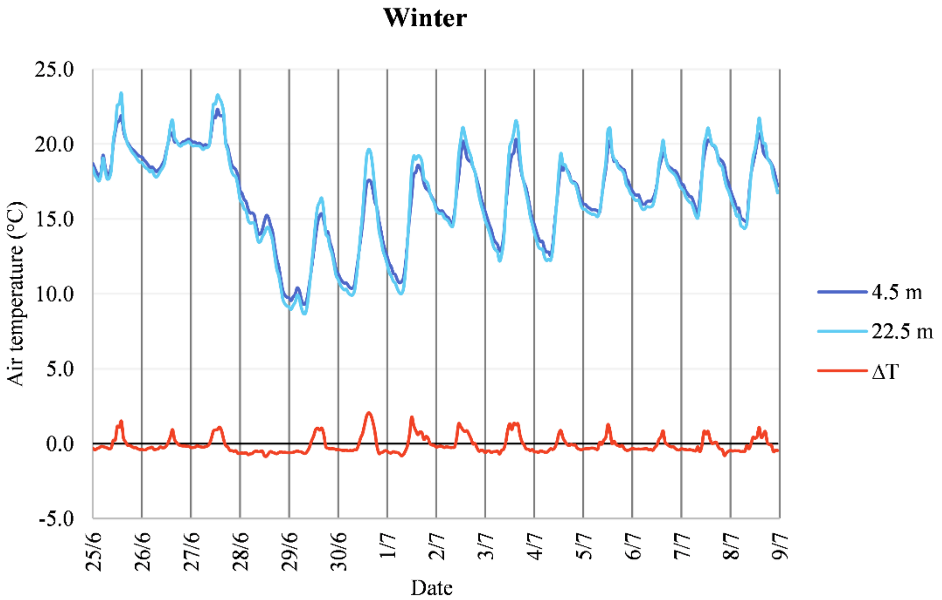

Figure 3 - Air temperature during winter field measurements and air temperature differences (ΔT = T22.5 - T4.5)

As in winter measurements, the daily temperatures at 22.5 m were usually higher than at 4.5 m height in spring (Figure 4). While during the nighttime, the air temperatures near street level (4.5 m) were greater than at 22.5 m. This behaviour also occurred in the winter measurements and can be explained based on the SVF of both locations. The lower SVF of 4.5 m height point indicates a more limited amount of heat released through longwave radiation to the sky than the point at 22.5 m and higher SVF.

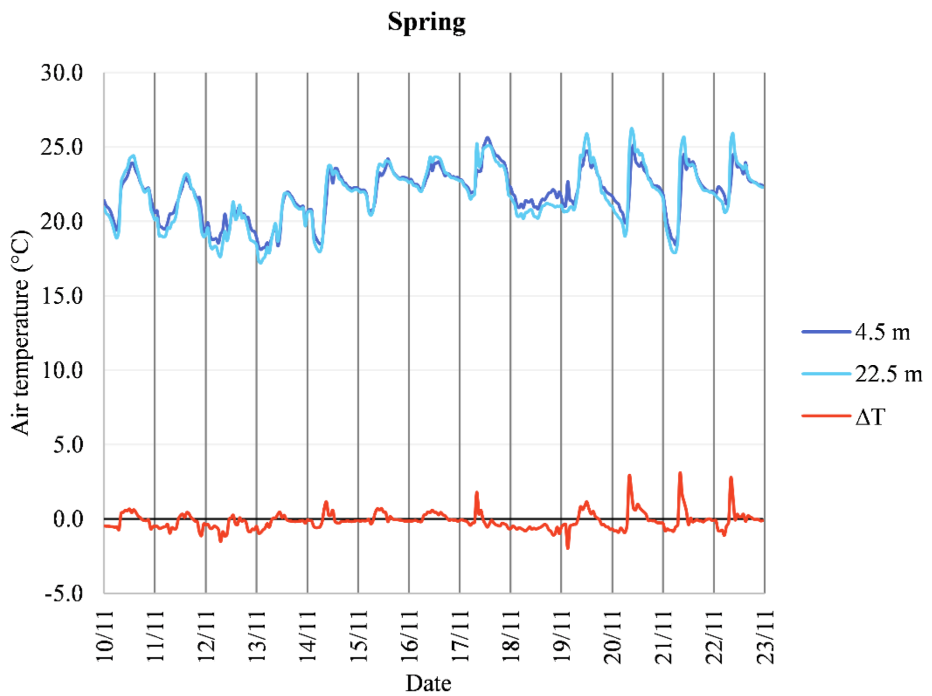

Figure 4 - Air temperature during spring field measurements and air temperature differences (ΔT = T22.5 - T4.5)

4.2. Field measurements *versus* ENVI-met model

One day of each measurement period was selected to perform a simulation with the ENVI-met model. The tridimensional modelled area is simplified to fit in a predetermined grid, which means the actual dimensions of the urban geometry are not fully attended. In the case of the studied location, the balconies of the building were not modelled, since they were lower than 1 meter. This singularity may have an impact on the results, which were taken from the first grid in front of the building.

Despite this geometrical limitation, the comparison of both methods (field measurements and computational simulation) are further discussed. Figure 5 shows the air temperatures registered by the data loggers and from ENVI-met results on 30 June and 22 November 2021. The air temperature differences were plotted in green when the higher point showed a higher temperature than the lower point (ΔT positive) and red when the air temperature was higher at 4.5 meters. It is observed that field measurements and ENVI-met simulations showed the opposite behaviour.

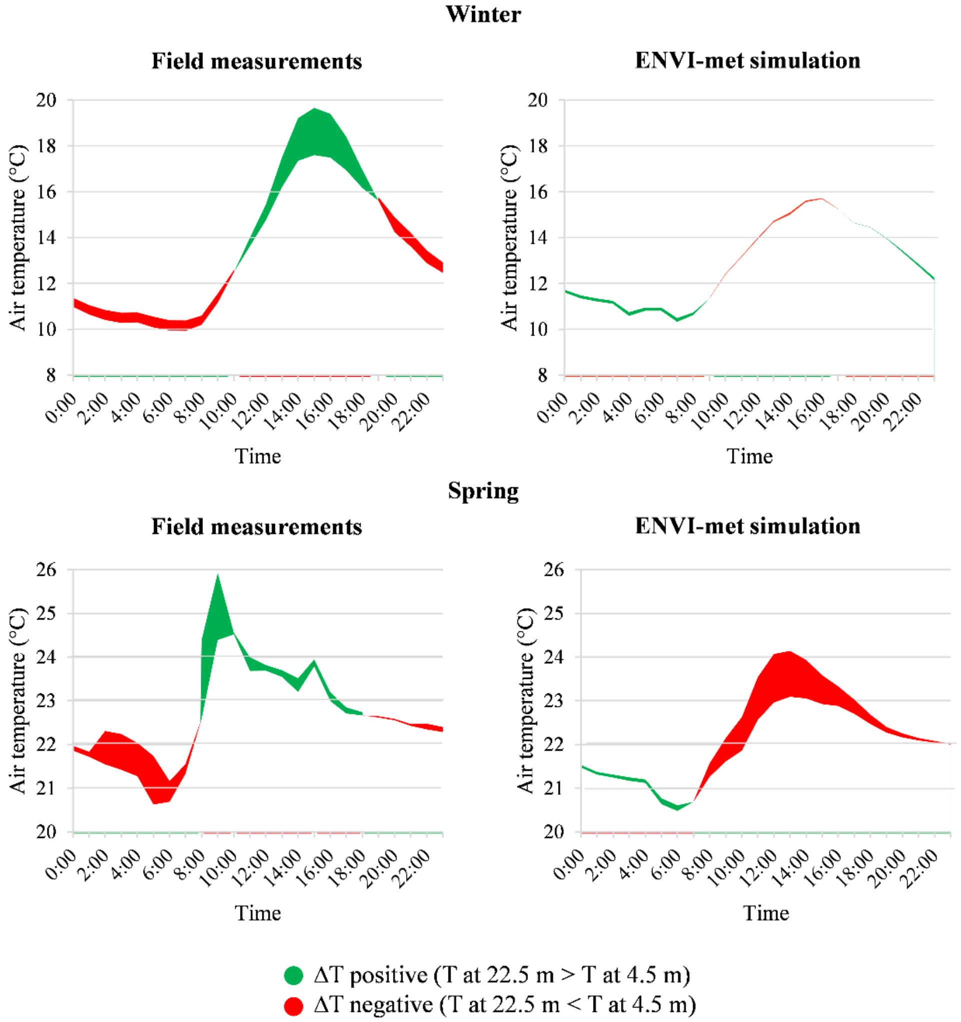

Figure 5 - Air temperature difference (ΔT = T22.5 - T4.5) by observation and by simulated model in winter and spring

In winter, the field observations exhibited a maximum positive difference of 2.1 °C at 15:00 and a maximum negative ΔT of 0.65 °C at 20:00. ENVI-met winter results showed a low difference between the temperatures at 22.5 m and 4.5 m height, with an absolute maximum of only 0.17 °C and occurring at 4:00 and 7:00. Besides the low absolute difference, the simulation also estimated higher air temperatures on the street level at daytime, which is contrary to the field observations consistently showing higher temperatures at the 22.5 m height.

In spring, the greater negative ΔT was 1.1 °C at 5:00, and the greater positive (2.7 °C) occurred at 8:00. Although this difference might be under the influence of the equipment's morning solar exposure, its variation maintains throughout the day in lower values (between 0.1 and 0.3 °C). The ENVI-met simulation performed on the spring day revealed air temperature positive ΔT from midnight to 6:00, with a 0.1 °C maximum. Negative differences were found from 07:00 until the end of the day, with a maximum of 1.1 °C at noon

(12:00). It can be stated that ENVI-met simulation keeps presenting positive differences at nighttime and negative at daytime.

The vertical air temperature profile is related to its thermal stability. Thermal stability describes the relationship between air temperature and height. According to Heisler and Brazel (2015), during nighttime, the longwave radiation exchange between the ground and the sky cools the ground and the air nearby. Since the cool air tends to stay near, the atmosphere is stable. During the day, the urban surfaces are heated, warming the nearby air. Since warm air is less dense, it rises with turbulence, creating thermal instability. As the air temperature profile of ENVI-met simulations followed this pattern, thermal stability is assumed to occur at night and instability during the day. However, these assumptions might be more speculative than known facts (OKE et al., 2017b) and are not supported by field observations.

It is also relevant to recognize some limitations in the model that may have contributed to or caused this incoherence between simulation results and field observations. First, the simplifications on the geometry are mentioned in the first paragraph of this section. Second, no anthropogenic heat sources were considered in the model. Concerning the computational part of the model, the tridimensional model is discretized in the first x-y grid, right above the ground, and the detail level decreases with the height (z). Crank et al. (2018) warned that the ENVI-met performance might be limited to near-surface temperatures and could not correctly represent the vertical heat transfer. Salvati et al. (2021) validated the ENVI-met model using IVS with reflected radiation measurements at two heights of an urban canyon in London. They found the model was more accurate near the ground. Finally, it is worth noting that similar studies validating the air temperature vertical profile in the ENVI-met model were not found.

5. CONCLUSION

This study aimed to evaluate an urban canyon's vertical air temperature profile. The case study was conducted in the Brazilian city of Balneário Camboriú and involved both field measurements and ENVI-met simulations. The field observations showed that the air temperature at 22.5 m was generally higher than at 4.5 m from the ground during daylight hours. At nighttime, the air temperature was lower as the height increased.

This pattern was verified in both seasons evaluated: winter and spring. In winter, the differences between heights were greater than in spring, which can be caused by the higher thermal amplitude and the lower cloud cover of the winter compared to the spring monitored period. The reason for these findings is sustained by the SVF of each monitored location – approximately 0.39 at 4.5 m and 0.67 at 22.5 m height. Lower values of SVF are related to low air temperatures during the daytime because the shading effect increases. On the other hand, the air temperature during nighttime tends to be higher due to the low heat released through longwave radiation to the sky.

The simulations performed in ENVI-met revealed that the model could not predict vertical differences in air temperatures. Simulated results showed lower temperatures at 22.5 m during the day and higher at night - the opposite behaviour of the field observations. Although the limitations of the microclimate simulation, including the simplifications in the geometry, the model is developed with an emphasis on attending street level.

Finally, the analysis reveals that thermal conditions within an urban canyon vary with height. However, it is crucial to acknowledge that this study solely relies on a single case, thus emphasizing the need for further research in urban canyons with similar orientations and geometry to establish more generalizable results. For future studies, evaluating other climatic variables that may be impacted according to the location is suggested, such as wind and solar radiation, and the impacts these differences may have on energy consumption.

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