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Study of the microclimate effect in the urban vertical structure in Ourinhos, São Paulo State

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ABSTRACT. This study aimed at analyzing the effect of buildings height on the thermal comfort in Ourinhos city – São Paulo State. The following variables were analyzed: air temperature, specific humidity, solar radiation and heat flows. Ourinhos is located in the Southwest of the São Paulo State, on the border with the North of Paraná State. The climate is tropical, with hot humid summer, and cold dry winter. The city has an urban area of 40 km2, with few buildings with more than one floor. In this study the three-dimensional micro-climate ENVI-met model was employed, providing the comfort indices. Two simulations were accomplished, one with the actual height of existing buildings, average height of 5 m, and the other with the hypothetical height of 30 m, in order to examine the changes generated in the thermal comfort caused by the change in the city structure. The date chosen (February 15st, 2010) for the simulation was a summer day at this latitude. The increase in the buildings' height led to changes in the studied variables modifying the dynamics of local microclimate.

Keywords: modeling, ENVI-met, flows, potential temperature.

Estudo do efeito da estrutura vertical urbana no micro-clima de Ourinhos, Estado de São Paulo

RESUMO. O objetivo deste trabalho é analisar o efeito da altura das construções, no conforto térmico na cidade de Ourinhos, Estado de São Paulo, por meio das seguintes variáveis: temperatura do ar, umidade específica, radiação e fluxos de calor. A cidade de Ourinhos está localizada no Sudoeste do Estado de São Paulo, na divisa com o Norte do Estado do Paraná. Possui clima de regiões tropicais, com verão quente e úmido e inverno frio e seco. A cidade possui área urbana de 40 km^2, com poucas construções de mais de um pavimento. Neste estudo foi utilizado o modelo micro-climático ENVI-met e por meio deste modelo foram obtidos os índices de conforto para situações simuladas nesse município. Efetuaram-se duas simulações, uma com a altura real das construções existentes, que possui uma altura média de 5 m e outra com a altura hipotética de 30 m, com a finalidade de analisar as modificações geradas no conforto térmico causadas pela modificação da estrutura da cidade. A data escolhida para a simulação foi 15/02/2010, portanto um dia de verão nesta latitude. Verificou-se que o aumento das alturas das construções provocou alteração nas variáveis estudadas modificando a dinâmica do micro-clima local.

Palavras-chave: modelagem, Envi-met, fluxos, temperatura potencial.

Introduction

The planetary boundary layer (PBL) is the part of the atmosphere that is directly influenced by the surface. The characteristics of the PBL depend on the underlying surface and vary over the day. The effect of the cities with their physical structure and inhabitants on the atmosphere guides the researchers for the study of urban climate. These changes in the local climate create the need to know more about the physics and biology of urban environments; also generating interest on environmental sustainability in relation to energy, concerns with population health related to air quality, thermal stress, and spread of toxic substances in these spaces occupied by humans.

The layer close to Earth's surface may vary between 100 and 3,000 m (STULL, 1988) and is the part of the atmosphere where most meteorological phenomena takes place, such as air masses, squall lines, fog, vortices and others. At the boundary layer of this region are the driving forces that occur in time of 1h or less. Among these forces, there are: the drag friction, evaporation/transpiration, heat transfer, and induction of the flow modified by the surface. Although, indirectly, the entire atmosphere undergoes change in response to surface characteristics, this change is very small outside the PBL, where the air is influence by macro-scale processes and reacts more slowly to changes. The height of the convective boundary layer (CBL) is the base of the inversion layer, where the temperature increases and the specific humidity decreases with height, (FISCH et al., 2004).

The urban landscape is composed of a mosaic of buildings, land uses, and streets with complex shape and arrangement, creating an own microclimate. Studies show that one of the causes of this climate is the design or geometry of the city (ARNFIELD; GRIMMOND, 1998).

Emmanuel et al. (2007) consider the urban geometry and its shading more important for the thermal comfort than the characteristic of surface materials, i.e., the interaction between the urban area shape and the incident solar radiation.

The urban climate of the city of Trier, Germany, was studied by Junk et al. (2003) using the ENVI-met model. In that study, the authors analyzed the parameters: heat islands, concentration of air pollutants, ozone concentration, and thermal comfort. The temperature difference registered by a station in the city center and another in the vicinity showed the existence of heat islands. The greatest difference in average air temperature was 1.8ºC found in July, summer in the region. If, on the one hand, the heat islands demand less expenditure of energy to heat homes in winter, in summer, they are responsible for thermal stress and pollutant concentration. To describe the variation of thermal comfort, the authors used the parameter 'haze', whose occurrence is associated with the vapor pressure above 18.8 hPa and air temperature above 25.0ºC. Daily averages recorded between 1996 and 2001 showed values above 24 hPa, with frequency of 0.06%, showing the vapor pressure above the level set. The combination of high temperature and vapor pressure results in an uncomfortable situation. High pressure and temperature lasting 1 to 2h had frequency of 32.6%. In two special cases, this occurrence lasted 11h. Thus, the authors concluded that the 'haze' event only rarely affect the health of the people living in the city. The topography, buildings structure, land use, and anthropogenic emissions influence the air quality in the city. The authors propose the reduction of vehicle traffic and the reduction the pollutant emission by these same vehicles and the incentive to public transportation.

According to Ali-Toudert and Mayer (2006), the structure (design) of a street is the key factor for studies on urban bioclimatology, which influences the internal and external micro-climates, and changes the thermal sensation of people and the energy consumption of buildings. In a study performed in Ghardaia, Algeria, under a typical summer condition for a region part of the Sahara desert, where the climate is characterized by intense solar radiation and high temperatures, the authors used the ENVI-met model in order to understand the thermal sensation in urban canyons and suggest models of urban structure that may contribute to improve the comfort of people in the cities. Simulations were undertaken for different canyons, in other words, for different height/width ratios and with directions North-South and East-West. It was analyzed graphs of solar radiation direct, diffuse, and global, graphs that show the spatial and temporal variation in air temperature and mean radiant temperature, besides graphs as thermal comfort index, named PET (Physiologically Equivalent Temperature). Simulations showed that values of PET and thermal stress are strongly influenced by the ratio between the building height and street width and their orientations. The results were important to observe that the air temperature decreases with reducing the ratio height/width, i.e., increasing the streets width. The East/West orientation caused the higher thermal stress in the study area. Thus an orientation of the streets North/South combined with a height/width ratio would allow a better thermal environment, with low values of PET and shorter periods of thermal stress.

Ourinhos city was chosen for this analysis because it is a region with a medium-sized city, located on the Tropic of Capricorn, therefore with great convergence of energy and mass (water vapor) and with a series of automatic weather stations installed, which allowed the monitoring of meteorological data in real time. Ourinhos is located in the Southwest of São Paulo State, on the border with the North of Paraná State. Its climate is tropical, with hot and humid summer; and cold and dry winter.

The goal of this study is to analyze the effect of the buildings height on the thermal comfort in the city of Ourinhos, São Paulo State, by means of the following variables: air temperature; specific humidity; radiation; and heat flows.

Material and methods

Ourinhos (Figure 1) has an urban area of 40 km^2; rural area of 296 km^2; population of 104,542 inhabitants (IBGE, 2009); with a demographic density of 353.2 inhabitants km^{-2}. Also according to IBGE, has degree of urbanization of 96.3%; forest areas with 398 hectares; and an area of natural pastures with 1,703 hectares (IBGE, 2009).

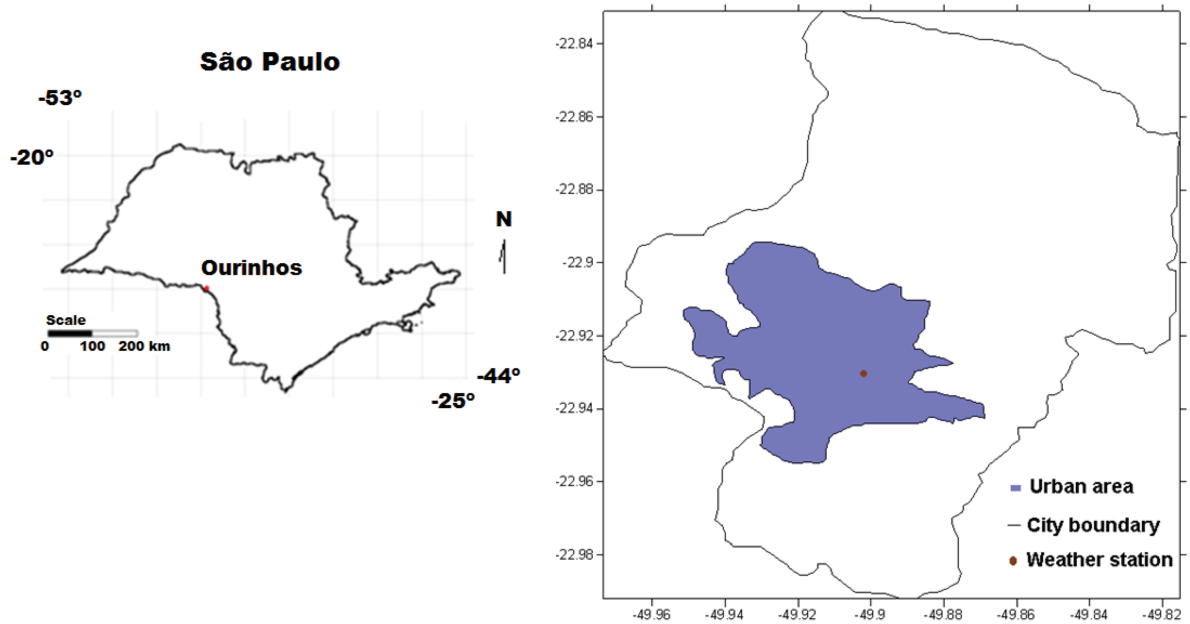

Figure 1. Map of São Paulo State with the location of Ourinhos city. Ourinhos municipality and urban area.

In the present study, the ENVI-met model version 3.1 was employed. The micro-climate model is three-dimensional designed to simulate the interaction surface – plant – atmosphere in urban environment, with a resolution between 0.5 and 10 m. This model was developed by Bruse and Fleer (1998).

Two distinct simulations were carried out, one for the actual structure (Figure 2) considering the average height of the buildings at 5.0 m. We also collected data of temperature, humidity, wind speed and direction, obtained from the automatic weather stations installed. The second simulation, virtual situation, is based on change of the buildings height to 30.0 m. It was used the same meteorological input data of the real situation.

The energy balance is a determinant of the micro-climate of a region and depends on the nature of the surface and the heat transport capacity of the soil and atmosphere. When the soil nature is changed, its capacity to absorb and release heat is also changed, increasing or decreasing the energy flow, within the open system (for energy exchange) land/atmosphere. The heat transfer in the free surface is usually classified according to classical concepts: radiation, convection, conduction, and evaporation.

The exchanges of radiant energy between urban elements are usually calculated by the emissivity (ε) of the elements of this landscape. This emissivity is related with the radiation difference between the real forms and a black form, the shape of the forms (buildings), the radiation absorption in a gas (such as the air) and the difference in the relative temperature (HOLMAN, 1990).

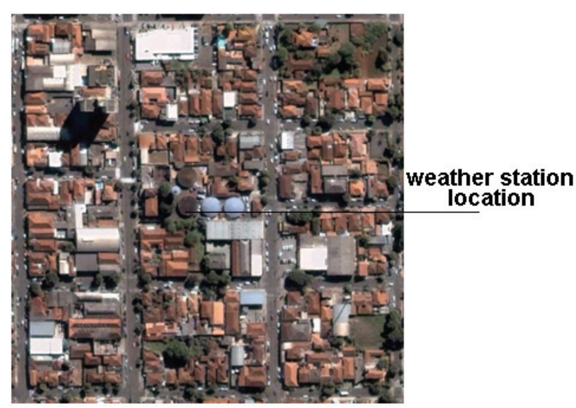

Figure 2. Study area with 3 x 3 blocks downtown the Ourinhos city, and location of the meteorological station.

Results and discussion

The model was calibrated for the day February 15th, 2010 by the comparison of temperature data registered by the automatic station installed at SAE (Superintendence of Water and Sewage), downtown of Ourinhos, and the data was furnished by the model during 24h. The Table 1 lists the input data for the model to perform the simulation.

The Figure 3 shows the hourly evolution of the temperature between 6 a.m. of the day 02-15-2010 and 6 a.m. of the day 02-16-2010, in the location where is installed the automatic weather station.

In the city downtown, the maximum temperature registered by the station was 32.4°C, at 2 p.m., and the by the model, 31.2°C at 1 p.m. In this temporal evolution, both the data measured and obtained by the model were remarkably similar.

Table 1. Input data for the model (SAE, downtown).

Input data for the model - SAE Downtown	
Start of simulation day^{-1}	02-15-10
Start of simulation timing^{-1}	6h
Time of simulation	24h
Wind speed in 10 m	0.6 m s^{-1}
Wind direction	39.0 °
Roughness length	0.7
Initial temperature in 2.500m	296 k
Specific humidity in 2.500m	4.0 g kg^{-1}
Relative humidity at 2m	79.0%

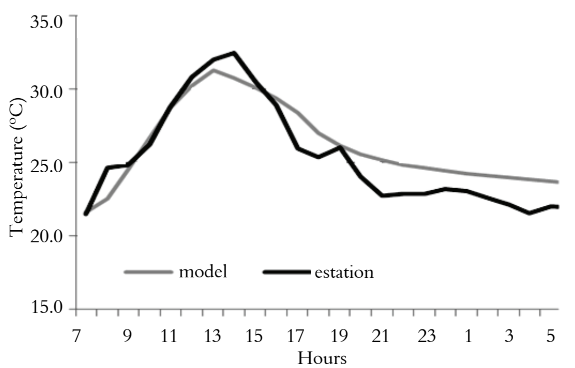

Figure 3. Evolution of the air temperature in Ourinhos downtown, where is located the SAE, for the day 15 and 16-02-2010, during 24h.

Based on these results, a regression analysis was performed, obtaining a coefficient of determination (R^2) and probability test (p value). The correlation (r = 0.93945) is a measure of the closeness between the values estimated and observed of the dependent variable within the sample used to estimate the regression.

By means of the p value ($p < 0.05$), it can be stated that the coefficient of determination is significant, in other words, the temperature calculated by the model represents well the studied area, because when correlating with real data (obtained in the station), the coefficient of determination was 88% (Figure 4). In this way, we can infer that the model explains the temperature variability, in the analyzed area.

In the analysis of daily variation in the temperature (Figure 5) for both situations (real and 30.0 m) in the day 02-15-2010, we observed that the real situation had a thermal amplitude of 9.6°C (Tmin = 21.7°C and Tmax = 31.3°C). In the situation of 30 m, we obtained 8.7°C (Tmin = 21.8°C and Tmax = 30.5°C). Thus, the shading caused by the buildings with 30 m, in the virtual situation, had reduced in 0.8°C the maximum temperature at 1 p.m. The average temperatures were 25.7 and 26.1°C, for the virtual and real situations, respectively.

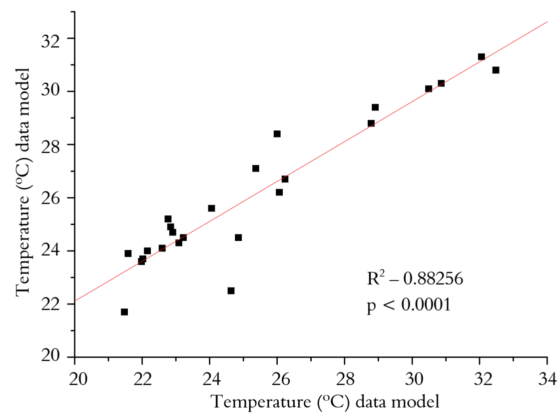

Figure 4. regression analysis. Comparison between the data of temperature of the station (downtown) and the model data for the day 15 and 16-02-2010.

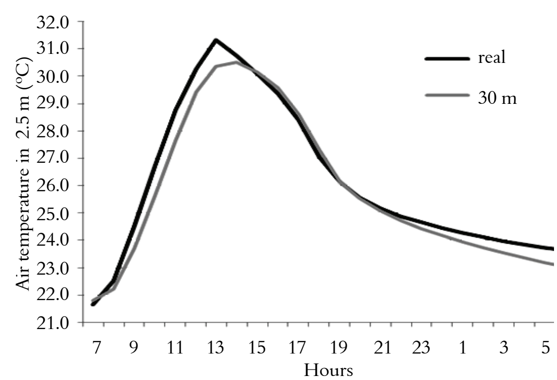

Figure 5. Hourly evolution of air temperature for the day 15 and 16-02-2010 at 2.5 m in height.

The Figure 6 shows the vertical variation of potential temperature up to 122.5 m for the both situations. The real situation has varied 1.9°C, and the virtual situation, 4.8°C. A sharp variation in potential temperature was observed for the real case examined.

Comparing the two situations, real and virtual, the increase in building height decreases the value and the emission time of maximum long-wave radiation at the point on the asphalt (Figure 7). For the virtual situation, the value found was de 559 W m^{-2}, between 1 p.m. and 2 p.m. This can be explained by the Sky View Factor (SVF), which is 0.7 for the real situation, and 0.3 for the virtual situation, at the point of study. Thus, there is a decrease in the time of receipt of direct radiation. This is due to the greater shading for the tallest building, thus presenting lower SVF.

The radiation flows are changed by obstructions of buildings and of vegetation. For a given grid point in the model, if a building block prevents the passage of direct solar radiation, then the Sky View Factor is zero. Another consequence of the SVF is that the more obstructed is the sky view, the greater will be the difficult to disperse thermal energy stored to the atmosphere, since the increase in the buildings means an increased re-irradiation, consequently increasing the absorption. The increased contact area means that more energy is retained in the region, increasing temperatures. Oke (1987) places the Sky View (canyon geometry) as one of the causes for the formation of heat islands, since it increases absorption and decreases the loss of long-wave radiation. This can be noticed in Figure 8, where the maximum emission of radiation that reaches the upper atmosphere is 244 W m^{-2} for the real situation and with smaller contact area, and a maximum emission of 126 W m^{-2} after the elevation of buildings and increased contact area.

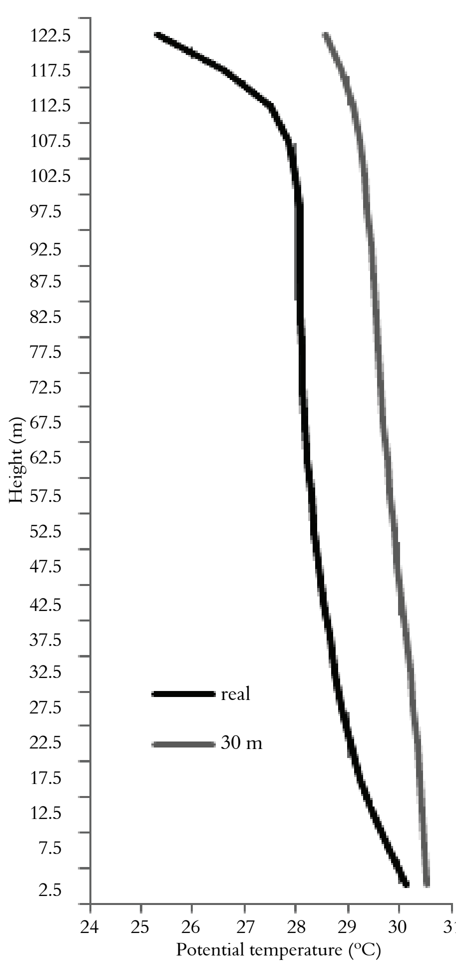

Figure 6. Vertical gradient of potential temperature.

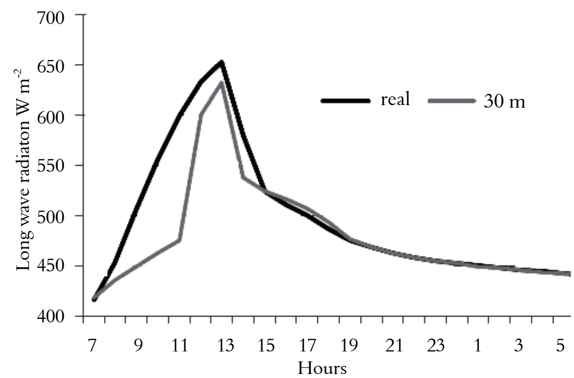

Figure 7. Emission of long-wave radiation by the surface.

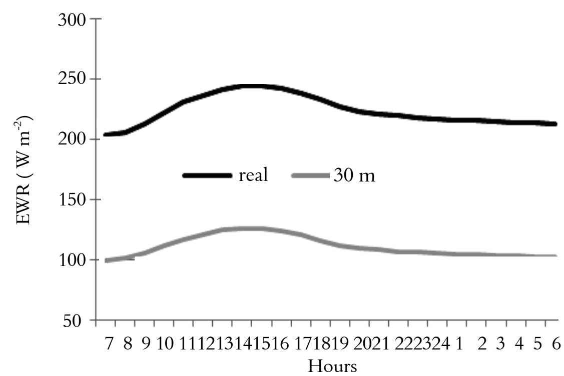

Figure 8. Emission of long-wave radiation by the surface, which reaches the upper atmosphere (EWR).

One of the main differences between rural and urban areas, according to Oke (1982) is that in rural zones, more heat is lost by evaporation (latent heat), and in the cities, the higher transference of heat occurs by sensible heat as a function of soil sealing. Vegetated surfaces with height greater than 1 m may cause mutual shading, hindering the penetration of solar radiation and the resulting processes, such as evapotranspiration. Convective processes are present in these simulations, where there is vegetation, because with heat and humidity there will be use of energy to status change or vapor transport for the upper atmospheric layers, causing the cooling of the environment.

The balance between latent and sensible heat depends on the water availability. In urban environments, the humidity may significantly vary between the center areas of the city, consisting almost entirely of masonry, asphalt, concrete, and glass, and the suburban areas with lower sealing of the soil and more vegetation, such as lawns and trees.

The flow of latent heat presented in Figure 9, at the point of paved surface, shows a very dry system, remaining at zero during the 24h of simulation.

The heat flow is considered positive (OKE, 1987) when toward the ground, and for this to occur there must be a temperature gradient between the surface and soil. Thus, it was observed (Figure 9) that from 9 a.m. the heat flow to the ground is positive, because the ground temperature is lower than the surface. This situation remains until 2 p.m. when the flow becomes negative and the ground has higher temperature than the surface.

The maximum flow of sensible heat in the real situation was 454 W m^{-2} at 1 p.m. Between 12 p.m and 1 p.m. remained above 400 W m^{-2}, and after 2 p.m. there was a sharp drop to 275 W m^{-2}. This is explained by the shading of the buildings in the study site, which does not receive direct solar radiation after 2 p.m.

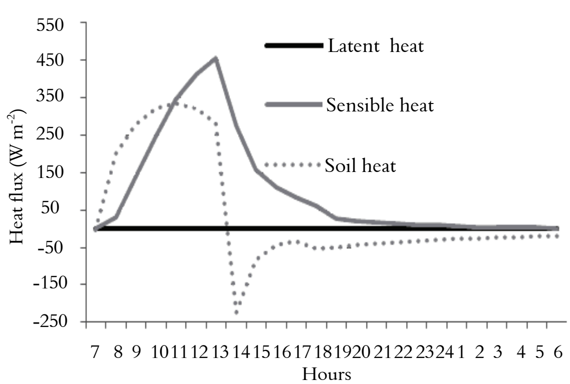

Figure 9. Hourly evolution of heat flow for the real situation.

For the virtual situation, Figure 10, the maximum flow of sensible heat to the atmosphere, 459W m^{-2} occurred at 1 p.m. After this time, the location is shaded and does not receive direct solar radiation, and the flow of sensible heat drops to 123 W m^{-2}.

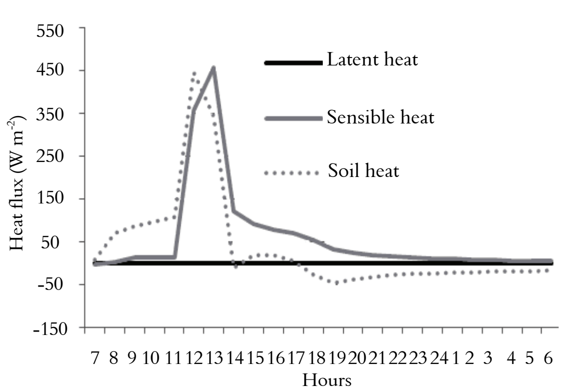

Figure 10. Hourly evolution of heat flow for the situation with increasing in the buildings height.

Vertical profiles of temperature and specific humidity can be used to determine the height of the atmospheric boundary layers (CLA). The potential temperature and specific humidity remain almost constant in the mixed layer.

In the Figure 11 is shown the vertical variation of air temperature, starting at 2.5 m from the surface at the point on the asphalt. For both situations, the temperature decreases with the altitude, and the real situation had a gradient of 4.9ºC, and the virtual situation, 9.5ºC. At 2.5 m from the surface, the temperature difference between the situations in this point on the asphalt was 5.7ºC, and at 1,000.0 m, the difference decreased to 1.2ºC.

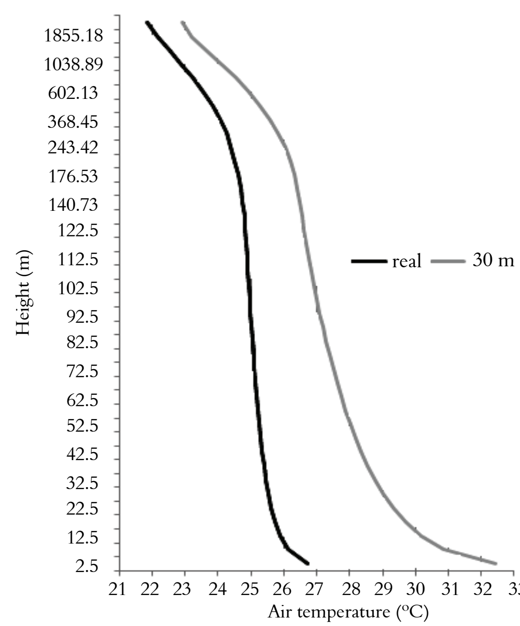

Figure 11. Vertical variation of air temperature.

For the real situation, we found a variation in the specific humidity of 11.53 g kg^{-1} along the 1,800.0 m of height. For the virtual situation (30 m), the specific humidity varied 20.45 g kg^{-1} along the 1,800.0 m (Figure 12).

In the analysis of the turbulent kinetic energy (TKE; Figure 13), it was verified that it increases with the height up to, approximately, 400 m, and then starts to decrease, both for 12 p.m. and 3 p.m. The maximum turbulence at 9 a.m. is 0.48 m^2 s^{-2}, and at 3 p.m. is 1.54 m^2 s^{-2}. The mechanical turbulence occurs up to 42.5 m, and after this height, the turbulence is only generated by the fluctuation (thermal turbulence).

The Figure 14 shows that the TKE increases with height up to 380 m and after this height, it starts to reduce between 12 p.m. and 3 p.m. At 9 a.m. the TKE increases to 1,391.0 m, and then starts to reduce. The mechanical production occurs up to

32.5 m and after this height, there is only heat production at 3h p.m. as observed in the Figure 13. The production of turbulent kinetic energy by the fluctuation was greater in the real situation, between 0.3 and 0.4 $m^2 s^{-2}$, compared to the situation with increase in buildings height, which was around 0.003 $m^2 s^{-2}$.

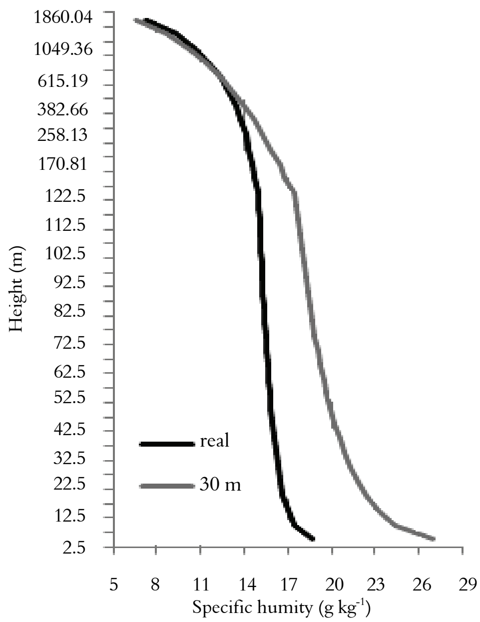

Figure 12. Vertical variation of specific humidity.

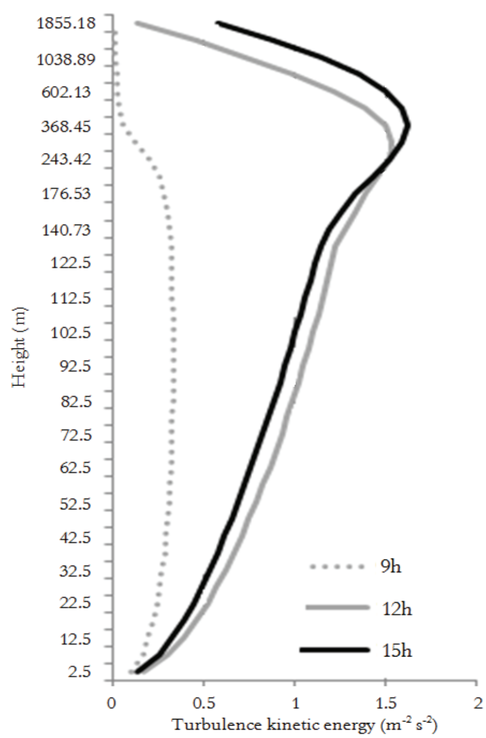

Figure 13. Vertical profile of turbulent kinetic energy for the real situation.

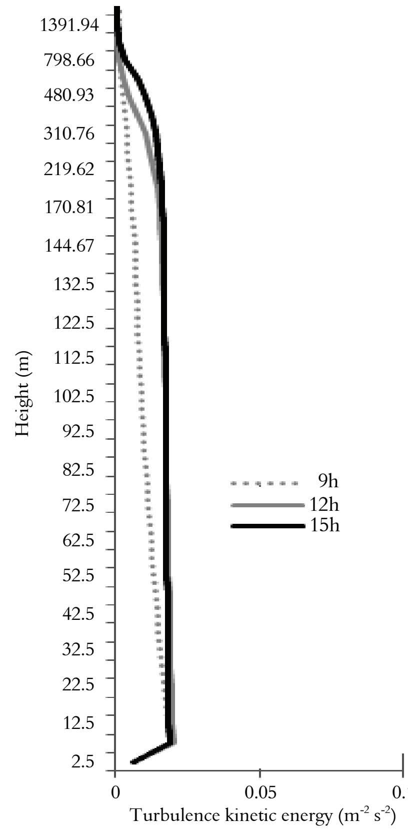

Figure 14. Vertical profile of turbulent kinetic energy for the situation with increase in buildings height.

Conclusion

The model used was effective in representing the air temperature of the study area. In this way, we can infer that the other calculations performed were able to represent satisfactorily the analyses proposed in the present study.

The buildings have positive effect on the urban climate of the city, since Ourinhos is located in latitude near the Tropic of Capricorn, considered a hot and humid city in the summer, therefore, uncomfortable in this period due to the excessive heat. In the winter, the city is sometimes cold and dry, also generating discomfort to most population. The shading is important to minimize the summer temperatures, but can also cause problems during the winter. The model represents well the energy balances in the boundary layer, allowing planning the buildings to reduce the energy use by the population, in order to obtain thermal efficiency in their workplaces or homes.

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