Mapping humidity plume over local climate zones in a high-altitude tropical climate city, Brazil

Mapeamento da pluma de umidade sobre zonas climáticas locais em clima tropical de altitude, Brazil

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Abstract

The aim of this research is to detect the cooling effects of water body evaporation in different Local Climate Zones (LCZs) in a tropical area. We attempted to register the humidity action over the urban environment caused by the evaporation of an urban lake according to the typical regional winds. The method was developed on the basis of three steps: the physical characterization of the LCZ conditions, the definition of data collection procedures with the mesoclimate analysis; and the interpretation of data by mapping the local measured variables. The study also included a microclimate data collection campaign aimed to evaluate more specifically the typical behaviour of the air temperature and absolute humidity in areas near the water body and in environments of the urban centre of São Jose do Rio Preto in Brazil. The air temperature range in areas near the water surface presented values lower than the denser areas, reaching differences close to 4 °C, and as the environment becomes drier and impermeable, the air temperature tended to be higher. This fact highlights the need to being outlined urban occupation strategies for improving the thermal quality of the built environment, mainly in cities located in regions with a predominantly high altitude tropical climate.

Keywords: Local climate zones. Urban humidity. Water bodies. Urban warming. Urban evaporation.

Resumo

O objetivo desta pesquisa é detectar os efeitos do resfriamento da evaporação do corpo de água em diferentes Zonas Climáticas Locais (LCZs) em uma área tropical. Foi registrada a ação da umidade sobre o ambiente urbano causada pela evaporação de um lago urbano de acordo com os ventos regionais típicos. O método foi desenvolvido com base em três etapas: a caracterização física das condições da LCZ, a definição dos procedimentos de coleta de dados com a análise do mesoclima; e a interpretação dos dados, mapeando as variáveis medidas localmente. O estudo incluiu também uma campanha de coleta de dados do microclima destinada a avaliar mais especificamente o comportamento típico da temperatura do ar e da umidade absoluta em áreas próximas ao corpo d'água e em ambientes do centro urbano de São José do Rio Preto, Brasil. A faixa de temperatura do ar em áreas próximas à superfície da água apresentou valores inferiores às áreas mais densamente construídas, atingindo diferenças próximas a 4 °C, e à medida que o ambiente se torna mais seco e impermeável, a temperatura do ar tendeu a ser maior. Este fato evidencia a necessidade de serem delineadas estratégias de ocupação urbana para melhoria da qualidade térmica do ambiente construído, principalmente em cidades localizadas em regiões com clima tropical de altitude.

Palavras-chave: *Zonas climáticas locais. Umidade urbana. Corpos d'água. Aquecimento urbano. Evaporação urbana.*

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Introduction

Urban environmental quality considered from the point of view of environmental quality, energy consumption and the health conditions among the in habitants of a city is closed linked to settlement patterns and the geographical nature of a certain region. Various forms of land use may influence atmospheric behavior patterns, mainly considering changes in temperature levels, humidity and pollutant dispersion. Dams located in urban areas often help to improve residents' quality of life and provide not only leisure facilities and comfort for them, but also create green permeable areas for rainwater on its banks (HOYER *et al*., 2011). In general, urban water bodies play an important role in the city life due to the aesthetic, ecological or human interactions factors, however, their effect on human comfort has rarely been evaluated, as observed by Xu *et al.* (2010).

Many cities all over the world are under the direct influence of physical interventions from water bodies resulting from the impoundment of rivers or streams, which aim to control floods, create urban parks or construct reservoirs to provide water and energy.Although many of these cities are under the influence of thermodynamic effects caused by water surfaces and regional winds, the effects of heat mitigation on the surroundings is usually neglected for planning purposes. Nevertheless, Barlag and Kuttler (1991) have already shown the importance of an efficient thermal surface wind system for urban ventilation. In a study for Bochum city, in Germany, those authors confirmed that the wind regime should be regarded as an essential element in urban planning.

Spatial planning of various cities has included artificial lakes in urban areas, as well as parks and recreational areas.Among these cities are Brasilia, Belo Horizonte, Curitiba (Brazil) and Canberra (Australia). However, local weather conditions are not always taken into account when designing spaces, either because there is insufficient meteorological information available or because of the lack of technical planners´ expertise concerning climate issues (MILLS *et al*., 2010).

The latest Intergovernmental Panel Report on Climate Change - IPCC (INTERGOVERNMENTAL…, 2014), for instance, points to a lack of information in urban areas, which makes it even more necessary to gain knowledge about the effects of such interventions on people´s quality of life in cities.

Often, impoundment or even channeling small streams in urban areas considers few parameters of environmental impacts. Thus, the macro and mesoclimatic parameters of a region should be considered to propose more forceful interventions and estimate the positive and negative impacts on a microclimatic scale in a city, as shown by Theeuwes, Solcerová and Steeneveld (2013).

Increasing air humidity in the urban environment is not always beneficial for the thermal air quality.Concerning predominantly warm and humid climates in a particular city, large water bodies can heighten the inhabitants´ feelings of hygrothermal discomfort. Local climate changes in many urban areas are related to energy flow transformations, influenced by site morphology, the thermal properties of built surface materials and anthropogenic heat (ASSIS, 2006).

The principle of the urban water evaporation, as presented by Collischonn and Tassi (2008), is a liquid water transference process directly driven from surfaces like rivers, lakes, reservoirs and dew drops to the air. As water removes latent heat from the air, evaporation occurs, tending to cool the surroundings surfaces. On the other hand, the air becomes lighter when heated by contact with the ground and rises into the atmosphere, where it is dissipated. When the air above a water body is already saturated with vapor, the evaporation fluxes finishes, even if the solar radiation is still providing energy by the latent heat. The maximum concentration of water vapor in the air is approximately 20g/m³ at 20 °C.

Consequently, the evaporative cooling effect provided by an elevated concentration of humidity over water bodies located in urban areas and combined with the horizontal air masses distribution may significantly influence the vicinity microclimates. Thus, when there is an increase in local evaporation, wind and water mass interacting with the built characteristics determine the air temperature conditions. Chandler (1965) estimated that the evaporation amount of a vegetated urban area abundantly watered would roughly correspond to three-fourths the evaporation amount of water surface. At the time, this research pointed out that water bodies in London had higher humidity rates in the immediate vicinity on days with stable weather conditions. This occurred along the banks of the River Thames near small water bodies and even in areas with soil where there was a high capacity of water retention.

These principles underlie the hypothesis that water surfaces in cities with warm and dry climates may be beneficial to the inhabitants´ thermal quality. Humidity air levels influence the daily air temperature amplitude, and therefore, the drier the weather, themo remarked its extreme temperatures are. The more humid the air is, the greater the water amount will be in suspension. Thus, besides the particles being heated by radiation, they also serve as a barrier to global horizontal irradiance reaching the ground, and at night to heat dissipated by the soil (GARTLAND, 2010). Convection is a physical phenomenon which arises from heat transfer through the difference in density of a fluid subjected to a temperature gradient. For urban environments, this phenomenon occurs in the earth's surface into the air above it. The phenomenon is influenced by wind intensity, surface roughness and air temperature difference between solid (ground), liquid (water body) or gaseous (urban atmospheric air) media. The heat provided by solar energy or other sources transforms the water found on the surfaces into vapour, and therefore, the evaporation of water humidifies the atmosphere and spreads around.

In a study conducted in Sheffield, England, Hathway and Sharples (2012) reported that the seasonal variation of the Don River water temperature influences the temperature variation of its banks, according to the horizontal global irradiance incidence, with the wind speed, the distribution of humidity and the form of urban occupation of the banks of this river. Cooling levels of the surroundings can reach 1.5°C during the spring, compared to a distant area of humidity influence from the river. During the summer, this difference is smaller due to increased water temperatures.

Water body damming in urban environments normally creates more generous ventilated areas and helps to spread the air humidity and atmospheric pollutants. Due to the fact that they occupy large open areas, they are located on lower levels and have few obstacles and smooth surface, these areas contribute to increasing the local atmospheric pressure and renewing urban air more frequently. Thus, increased levels of moisture caused by water evaporation and a consequent reduction in the air temperature can result in minor temperature variations in warm climates and may also reduce respiratory diseases among the population (MASIERO; SOUZA, 2013).

In order to better integrate the knowledge about climatology with urban spatial planning, Stewart and Oke (2012) suggested a climatic classification of the landscape, for which the landscape properties are determined by a set of physical and cultural characteristics, representing urban units, which can influence the temperature in the intra-urban layer. In this classification, it is considered that the physical space structure affects local climates by changing the air flow, the atmospheric transport of heat, as well as shortand long wavelength radiation balance. In turn, surface coverage has the ability to alter the albedo, the potential availability of moisture, as well as soil heating and cooling. Thus, the landscape can be divided into structures with approximately homogeneous properties, generating seventeen classes of similar prototypes, like compact high-rise (LCZ 1) and sparsely built (LCZ 9), for example. Ten of them refer to the characteristics of buildings and seven refer to the soil cover.This landscape classification criterion is called Local Climate Zones (LCZ). LCZs are defined as areas with structure, materials, human activities, uniform surface coverage. Each LCZ is characterized according to a particular air temperature regime on dry surfaces with a calm atmosphere, clear nights and gentle relief.

Recently, the LCZ concept was used to standardize urban climatological mapping procedures, giving rise to the World Urban Database and the WUDAPT - World Urban Database and Access Portal Tools (WORLD…, 2015) and Mills *et al.* (2015). This is an initiative from the international scientific community that aims to collect data ontheformandfunctionofcitiesaroundtheworldandtheimpactof urban interventions on the quality of the environment.

Based on LCZ classification, the main aim of this study is to detect and map the humidity's air and the cooling effect due to a water body evaporation on the urban environment, according to typical winds from the São José do Rio Preto region, Brazil.

Method

The study was conducted in three main steps, considering the physical characterization of the urban environment, defining data collection procedures with the regional climate analysis, and, interpreting data by mapping the measured variables. The main intention is to detect the factors that influence the microclimate formation resulting from the inclusion of water bodies in urban areas located in high-altitude tropical climate areas. Microclimate data collection campaign evaluate more specifically the typical variation of air temperature and absolute humidity in areas near the water body, as well as more dense environments of the urban centre, which were characterized by the LCZ method (STEWART; OKE, 2012). Each LCZ was related to a point of measurement, at which the variation of air temperature and humidity were registered and then compared to each other.

The sites

The first step of this research was to develop a physical characterization of the areas. This step refers to the morphological analysis of the major urban sites that are able to demonstrate the potential influence of the water body on the microclimate and determine the spatial scale of the study in the city.

São José do Rio Preto is located in the north of São Paulo state at coordinates 20°49'11" South Latitude and 49°22'46" West Longitude.The urban area corresponds to 117.43 km² and is crossed by a small river, the Rio Preto, which together with the Córrego dos Macacos (Macacos stream), form the two artificial dams in the urban area (PREFEITURA…, 2010a, 2010b). The city is located at an altitude of approximately 500 meters above sea level and the biomes are characterized by the Cerrado and Atlantic Forest remnants, according to the IBGE (INSTITUTO…, 2012).

Therefore, cut-off values of areas representative of urban morphology needed to be established according to the methodology proposed by Stewart and Oke (2012), so that the physical scale of spatial coverage of the study could be determined.

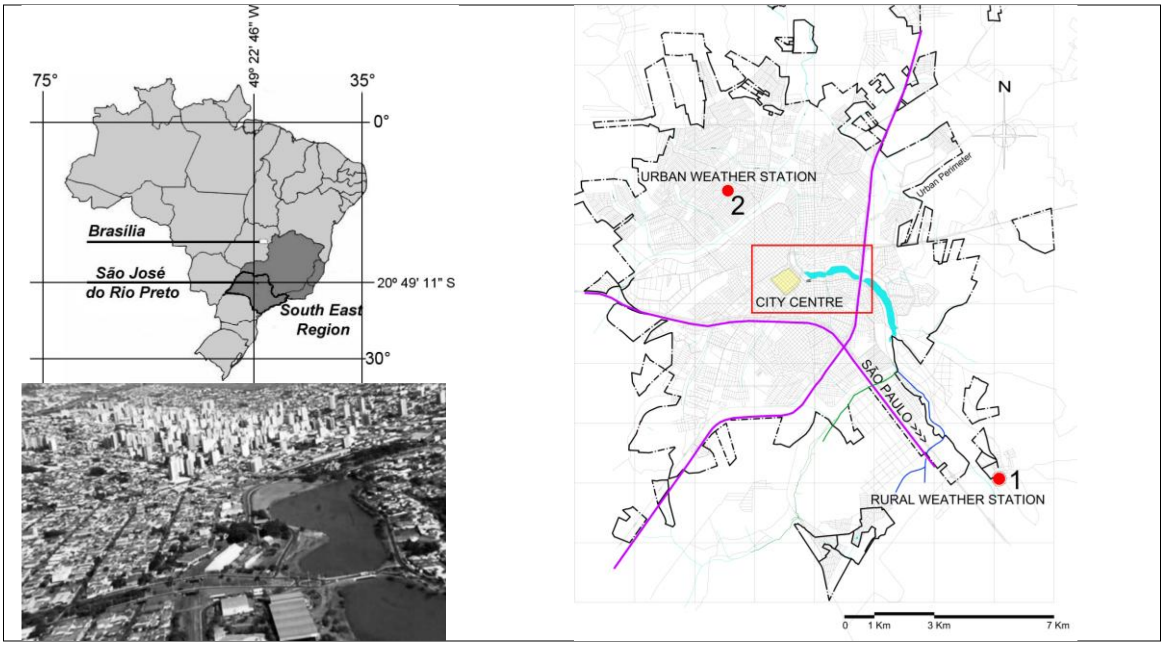
Figure 1 shows the geographical location of São José do Rio Preto, Brazil, the location of the urban fraction value (8.00 km²) with data collection points in the urban network and the position of the water body, which extends for approximately 4km, reaching a maximum width of 350m.

There are two fixed weather stations, one located southeast of the city centre in a rural environment and the other one northwest of the city centre in the suburbs. Both are characterized by the environmental conditions where they are located, their climate data are used as reference for the region. They were named as Point 1 (Southeast) and Point 2 (Northwest), and are classified as Low Plants (LCZ D) and Sparsely Built (LCZ 10), respectively.

Figure 2 shows seven points for measuring microclimatic variables in the central area, which are defined as LCZs used as parameters for analysis. All measuring points were chosen to represent the urban morphology diversity of the city and suffer both the influence of the winds acting on the water surface, and of urban form's characteristics.

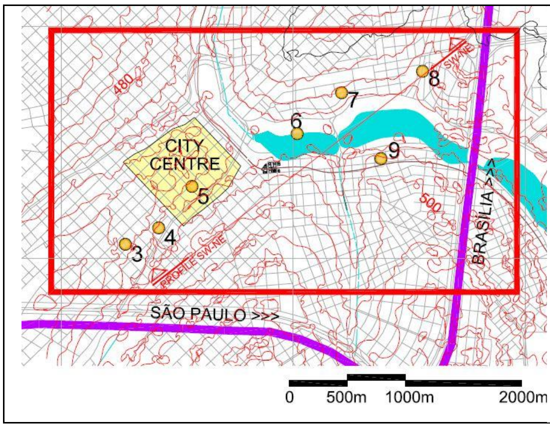
Figure 3 shows a partial topographic profile in the southwest - northeast direction together with the location of sensors used for data collection in each LCZ. It is important to highlight that the most dense area of the city is concentrated in the central part aligned in the northeast – southwest direction and the prevailing wind occurs during the winter months from southeastern direction. The wind from the northeast direction is also quite frequent and mainly predominant on summer and spring, according to Companhia Ambiental do Estado de São Paulo (2012).

Figure 1 – **São José do Rio Preto Location**



Source: adapted from Masiero and Souza (2012) and Prefeitura Municipal de São José do Rio Preto (2010c).

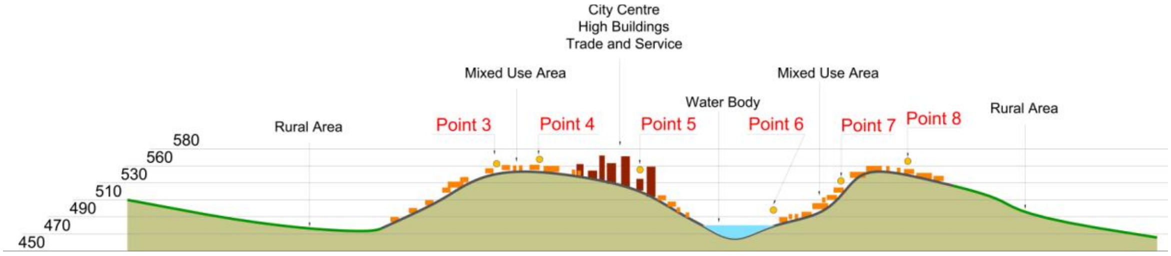
Figure 2 – **Position of each measuring point**



Point at urban site	LCZ name Stewart & Oke, (2012)
1	LCZ D
2	LCZ 10
3	LCZ 6
4	LCZ 2
5	LCZ 2
6	LCZ 8
7	LCZ 6
8	LCZ 6
9	LCZ D

Source: adapted from Prefeitura Municipal de São José do Rio Preto (2010c).

Figure 3 – **SW-NE direction topographic profile of São José do Rio Preto urban area**



To determine the features of the seven LCZs, urban fractions were delimited between 50,000 and 100,000 square meters, considering the predominant building characterization, Sky View Factor, H/W relation (height/width), built surface, impermeable surface, permeable surface, the average height ofroughness, soil roughness and distance from the water body. The Sky View Factor was estimated by collecting digital photographs using a fish-eye lens inserted on a camera positioned in the middle of each street at 1,5m height from the ground, vertically facing the sky. Afterwards, the images were treated by applying the RayMan 1.2 Software (MATZARAKIS, 2009), regarding the Matzarakis, Rutz and Mayer (2010) recommendations. The information about the building environment geometry were provided from the municipal administration map (PREFEITURA…, 2010c), and also checked in loco and subsequently calculated to register the permeable and impermeable areas.

Figure 4 exemplifies with the point 5 data, the kind of information collected for each of the measurement point considered in the study. This same figure also presents the mapping of the urban elements, positioning of the thermo-hygrometric sensor in the urban network, a generic image of the area and the constructed density of the urban local surroundings. The urban fraction corresponding to Point 5 shows typical characteristics of the compact high-rise urban class, according to the methodology proposed by Stewart and Oke (2012). LCZ 2 is located in the central area, presenting buildings that may reach more than 15 floors and are used as commercial warehouses and/or isolated dwellings. There is very little arboreal and underbrush vegetation in the streets. There are few open spaces, because several buildings occupy 100% of the lot and many others without front and/or side setbacks. This area has a typical spatial configuration that concentrates commercial activities and services, being significantly influenced by the anthropogenic heat mainly caused by the excessive number of vehicles circulating nearby the pedestrian area.

Table 1 shows summarized information of the nine assessed points of measurements. Thus, this information allow to verify relationships between the thermal performances of each LCZ, for the identification of the main factors influencing the penetration of humidity into the urban fabric.

Data collection procedures

Phase 2 consisted of determining the data collection procedures. The micrometeorological data in the urban environment were monitored and collected simultaneously by acquiring meteorological data provided by the two fixed weather stations: one in a rural area – Point 1 (CENTRO INTEGRADO…, 2014) and the other in a suburban area – Point 2 (COMPANHIA…, 2013), which establish the LCZs D and 10, respectively. The weather station on Point 1 is located at a rural area southwards of the city centre and the air temperature and humidity sensor is a HMP45C, Campbell Scientific which ranges from -3.2 ºC to 60 ºC, with ± 0.5 ºC of precision (CAMPBELL…, 2013). The installed equipment on Point 2 is a thermohygrometer, positioned at a height of 3 m from the ground. The working range for air temperature is between -30 ºC and 70 ºC, with measurement accuracy of ± 0.1 ºC (COMPANHIA…, 2012).

The air temperature and humidity data of the urban canopy layer were collected hourly using HOBO Pro V2 U23-001 sensors, positioned at approximately 3m height in ventilated PVC shields as recommendations from the manufacturer's specifications, Figures 5 and 6 (ONSE…, 2013).

Two portable weather stations were used to collect data from the bank of the dam, which are at Point 6 on the north bank, and at Point 9, on the south bank, respectively. At Point 6, a Vantage PRO 2 Davis Weather station was located, provided with:

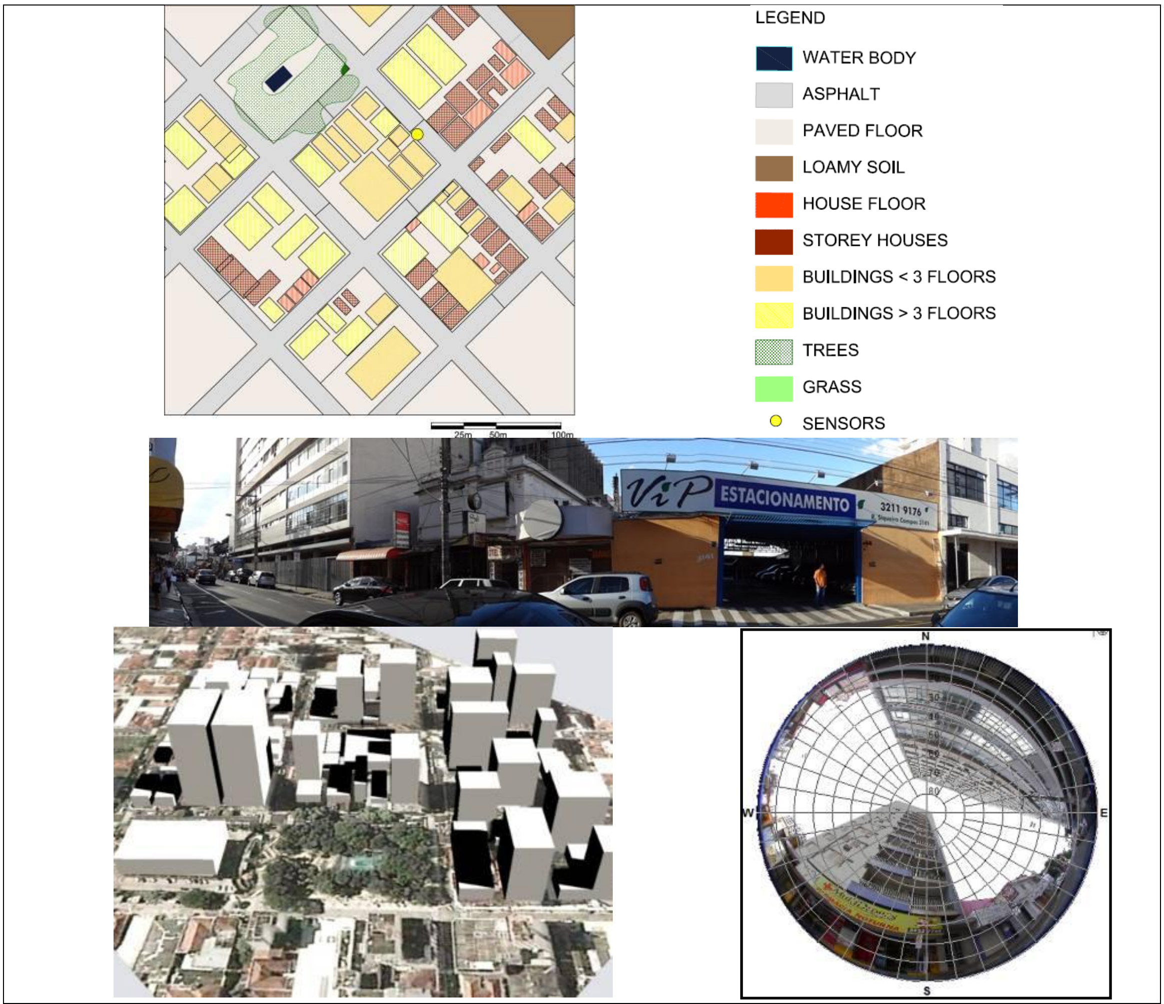
(a) an air temperature and humidity sensor with accuracy of ± 0.5 °C and 3% respectively;

(b) an anemometer;

(c) a solar panel; and

(d) a controller module with data logger (Figures 7 and 8).

Figure 4 – **Kind of data collected for each measuring point: the example of Point 5 – LCZ 2**



Source: adapted from Google Earth (2014) and Matzarakis (2009).

Table 1 – **Comparative information of nine LCZs (Continue…)**

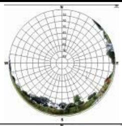
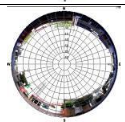
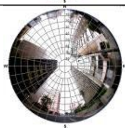
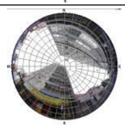
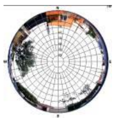
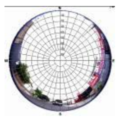
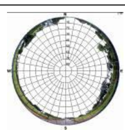
Point at urban site	**Name of LCZ**	**Sample Fraction – Area m^2**	**SVF**		**H/W**	**Built surface**	**Impermeable surface**
1	LCZ D	100.000		0.86	0.25	5%	5%
2	LCZ 10	100.000		0.73	0.4	13.5%	71%
3	LCZ6	70.000		0.70	0.55	25%	91.3%
4	LCZ2	70.000		0.35	4	35.8%	100%
5	LCZ2	100.000		0.29	3.3	29.5%	98.5%
6	LCZ8	50.000		0.75	0.3	15%	70.7%
7	LCZ6	70.000		0.69	0.4	28%	95.2%
8	LCZ6	50.000		0.72	0.4	24%	94%
9	LCZ D	70.000		0.80	0.25	7%	8%

Table 1 – **Comparative information of nine LCZs (continuation)**

Point at urban site	Permeable surface	Average height of roughness (m)	Soil roughness (m)	Classification	Distance from water body margin	View
1	95%	3	0.5	Low Plants	6.000m	
2	29%	5	0.2	Sparsely Built	3.500m	
3	8.7%	12	0.2	Open midrise	1.500m	
4	0%	30	0.1	Compact high-rise	1.100m	
5	1.5%	25	0.2	Compact high-rise	700m	
6	29.3%	5	0.3	Lightweight low-rise	25m	
7	4.8	5	0.3	Open midrise	100m	
8	6%	5	0.1	Open midrise	350m	
9	92%	2	0.5	Low Plants	25m	

Figure 5 **- HOBO Pro V2 U23-001 Sensor**

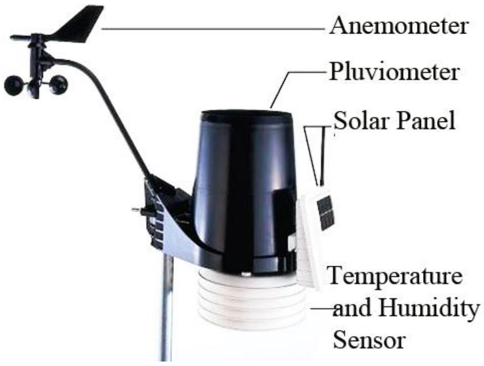
Source: Onset Brasil (2013).

Figure 6 – **Radiation Shield**

Source: Onset Brasil (2013).

Note: Operation range: -40 ºC to 70 ºC; Precision: 0.2 ºC above0 ºC until 50 ºC; and Resolution: 0,02 ºC to 25 ºC.

Figure 7 – **Weather Station DAVIS Vantage PRO 2**



Source: adapted from Davis Instrument (2014).

Figure 8– **Controller Module with datalogger**

Source: adapted from Davis Instrument (2014).

At Point 9, an HOBO Weather Station U30 model (ONSET…, 2014), was placed with a global horizontal irradiance sensor, a temperature and humidity sensor S-THB-M002, an anemometer and a datalogger (Figures 9, 10 and 11).

All equipment was calibrated before the beginning of the studies, using data provided by the weather station of INMET – National Institute of Meteorology as a reference. This calibration was performed for 3 days, intending to understand how discrepancies of values collected by the sensors could affect the precision of the studies. The air temperature differences among all sensors varied between ±0.2 and ±0.5 °C, remainingthe accuracy suggested by the manufacturer´s information (ONSET…, 2014). The values of humidity registered discrepancies lower than 3.5%, and the wind speed and direction stayed at the suggested interval informed by the manufacturer, which corresponds to less than 5 degrees for directions and 5% for wind speed.

Figures 12 and 13 show both portable weather station – Vantage PRO 2 Davis and HOBO U30. Figure 13 exemplifies the temperature and humidity sensor positioned at one of the points, representing the kind of installation used for the whole measuring campaigns. Figure 14 shows an example of a point with HOBO Pro V2 U23-001 Sensor.

Figure 9 – **Data logger with 10 digital canals and data transmitter Ethernet**

Source: Onset Brazil (2014).

Figure 10 – **anemometer precision of 5 degrees and resolution of 1.4 degrees**

Source: Onset Brazil (2014).

Figure 11 – **Temperature and humidity Sensor – THB-M002. Temperature precision ± 0.2°C - Humidity precision ± 2.5% with shield**

Source: Onset Brazil (2014).

Figure 12 –**Portable weather station Vantage PRO 2 Davis**

Figure 13–**Portable weather station HOBO U30**

Figure 14 –**HOBO Pro V2 U23-001 Sensor**

The collecting field campaigns occurred from June 09 to July 07 of 2013, period within which 2 subsequent days that presented two different wind directions (southeast and northwest) were selected for analysis. This selection assured that the horizontal movement of the humidity on the plume could be detected according to the performance of both directions on the urban fabric. To determine the time and space scale and relate them to the microclimatic behavior of LCZs, the meso and macroclimate characteristics of the region were firstly analyzed. According to Peel, Finlayson and McMahon (2007), the study area is under a Aw climate, representing a high-altitude tropicalclimate with mild and dry winters, warm and rainy summers. The average air temperature in the winter is close to 18 °C, while in the summer reaches 30 °C. The annual average of relative air humidity in this area is approximately 70%, reaching humidity levels below 20% during the driest months. The prevailing wind during the winter months occurs from a southeasterly direction, especially at night. The wind from the northeast direction is also quite frequent and mainly predominant under the dominion of the Atlantic Tropical Mass, causing periods of stable and dry atmosphere throughout the winter. Therefore, the data analysis was carried out according to the detection periods characterized by stable atmospheric behavior, clear skies, light winds and intense horizontal global irradiance.

Mapping the microclimatic variables

We mapped the microclimatic information by using geostatistical tools provided by the Surfer 11 software, Golden Software (2013), mainly to make it easier to interpret the results and to identify the variation of air temperature and absolute humidity in the urban environment. This software is also largely used to map heat island and graphically express urban climate data, according to Yaoa *et al.* (2015), Lin *et al.* (2012) and Ugeda Junior (2011). One of these tools made available by this software is the kriging interpolation method, which consists on a regression method widely used for spatial analysis. The principle of this interpolation process is that the value of a given point is weighted by the values of the neighboring points, so that the predicted point value is more similar to the nearest points than to the values of the farthest points. Thus, it represents a suitable method for the purpose of this research. The data collected in the nine points, including points 1 and 2, were interpolated using the kriging method to estimate the range values between them and, then trace the contours that characterize the variation of temperature and humidity in the urban central area. The winds on the analyzed days were plotted using the WR Plot computer program (LAKES…, 2014), which graphically charts the direction, frequency and intensity of the wind speed variations. AutoCAD software helped to prepare the maps, as well as the contour maps generated by Surfer 11, overlapping on the vector files.

Results

It can be observed in Figures 15 and 16 that on 30th June, 2013 the wind blew from a northwesterly direction and on 1st July, 2013 the prevailing direction became southeasterly. In both cases, the wind speed remained close to 1m/s and the sky was clear, achieving approximately 600 W/m² of horizontal global irradiance on these days, according to values measured on Point 9, which is quite intense. Thus, the weather conditions remained favorable to record the effects of urban climate during these two days under different wind direction conditions.

The northwest wind crosses the urban space in the north of the city, which is characterized by low humidity and reaches Points 7 and 8 before reaching the water surface area. Thus, it seems that the warmest time on 30th June, 2013 was at 16h, when air temperatures peaked at 32 °C. On 1st July, 2013, even considering the action of a slightly cooler air mass, the difference between the temperatures at points 7 and 8 tended to move away, registering differences close to 2 °C (Figure 17).

The absolute humidity variation chart (Figure 18) shows that Point 9, located southwards from the banks of the reservoir, recorded the highest values for almost the whole evaluation period. Points 6 and 8 are exposed to the humidified wind action, which easily penetrates through the urban canyon and is distributed by the pedestrian level. Only the absolute humidity values recorded at Point 7 decreased, reaching a minimum value of 11.91 g/m³ in the afternoon on 1st July, 2013, while the absolute humidity values increased in all the other points.

Figure 15 – **Wind direction on 30th June, 2013**

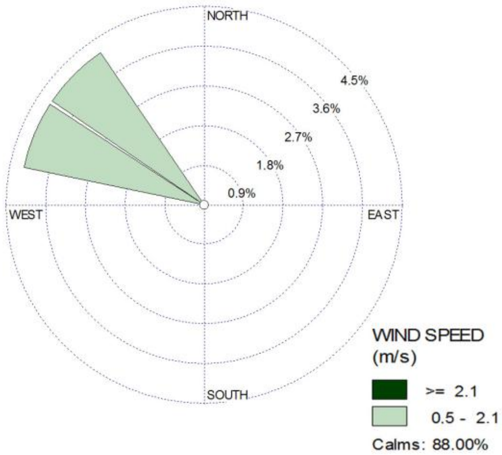


Figure 16 – **Wind direction on 1st July, 2013**

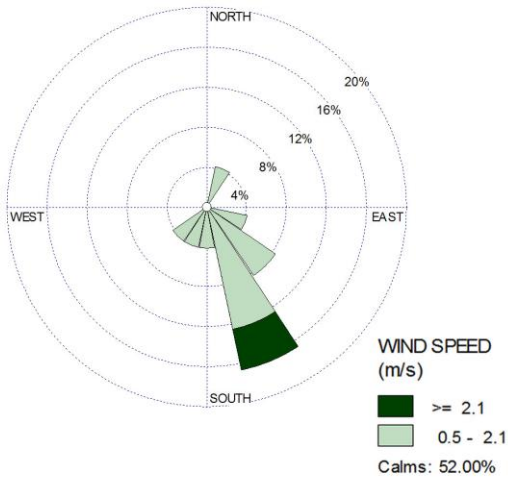


Figure 17 – **Air temperature range x wind direction between 30th June and 2nd July, 2013**

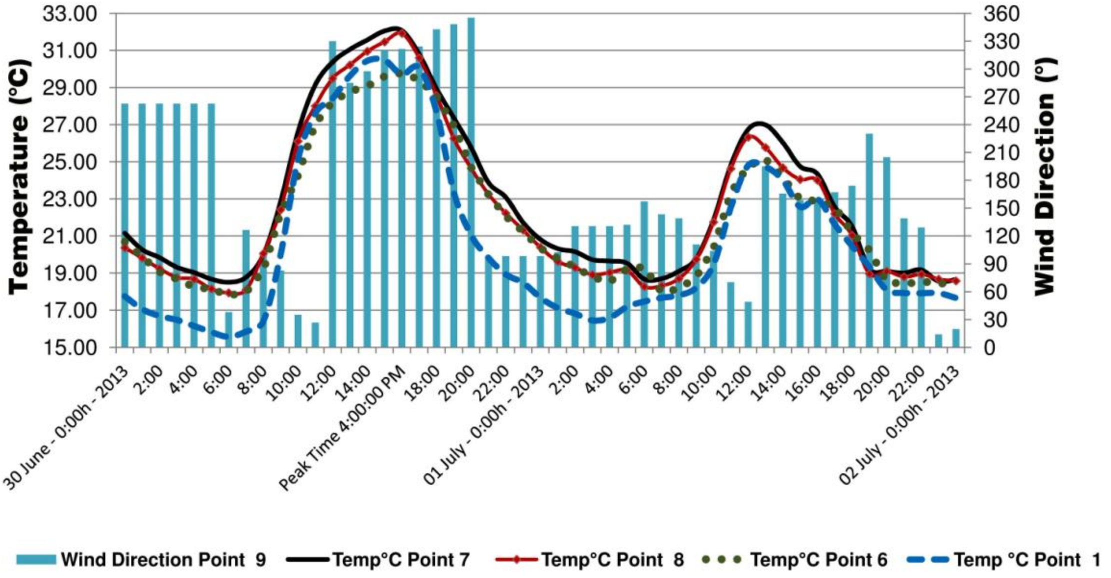
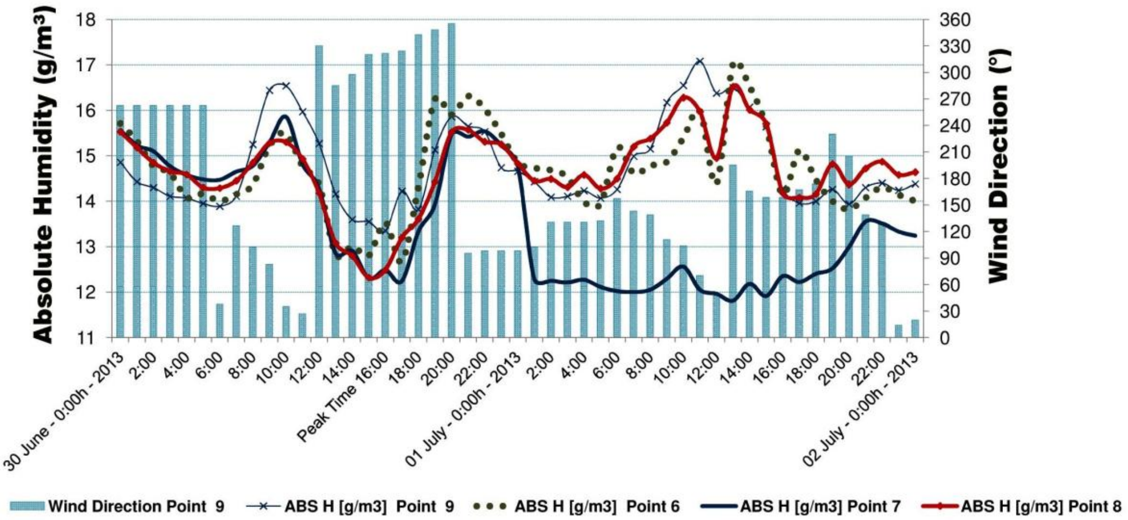


Figure 18 - **Absolute humidity range x wind direction between 30th June and 2nd July 2, 2013**



This absolute humidity variation behavior shows that the urban setting in which Point 7 is situated, despite being just 100 meters away from the bank, does not favor the humidity action from the water body. This urban canyon is oriented in an east-westerly direction at a very high level in relation to the level of the water body, therefore, the penetration of the humidity plume in this environment causes little effect on the air temperature attenuation (Figures 17 and 18). The high taxes of impermeable surfaces, 95.2% on Point 7 and 94% on Point 8 contribute to the high differences on the temperature and humidity levels.

The street in which Point 8 was established is located in a north-southerly direction and, therefore, is more subject to the action of the humidity plume carried by a southeasterly wind to the urban environment. Thus, there is a difference of up to 4 g/m³ in the warmest hours on 1st July. The air temperature and absolute humidity variation maps of the seven LCZs are shown in Figures 19 to 22, simultaneously showing microclimatic the differences between urban fraction. The maps were drawn up on 30th June at 16h with a northwest wind action direction, and subsequently, on 1st July at 14h with the wind action from a southeasterly direction.

By observing the temperature contours maps, there is a distinct difference between the northern and southern areas of the city. The central area receives some influence from the dam's humidity, when the wind blows from a northeasterly direction, mainly in the urban canyons towards to the Northeast - Southwesterly direction. However, the southeasterly wind, although more frequent, has difficulties in penetrating more deeply into the urban environment.

The absolute humidity contour maps clearly show the dry wind effect from the Northwest on 30th June and the significant humidity plume on the urban environment on 1st July, under a wind condition from a southeasterly direction (Figures 21 and 22).

Higher values of humidity can be observed on the previous day in Points 3, 4 and 5, which were located in the urban centre, and there is a shift of the humidity plume position on the central area on the following day.

Figure 19 – **Air temperature (°C) variation map on June 30, 2013 16h - Northwest Wind**

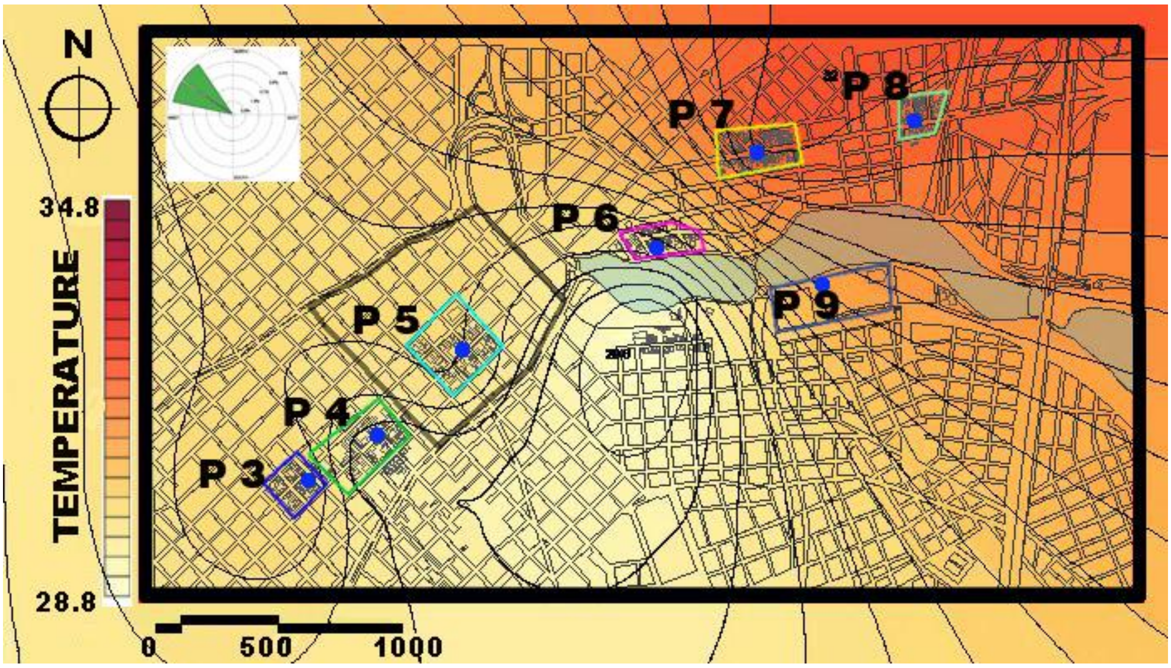


Figure 20 - **Air temperature (°C) variation map on day 1st July, 2013, at 14h – Southeasterly Wind**

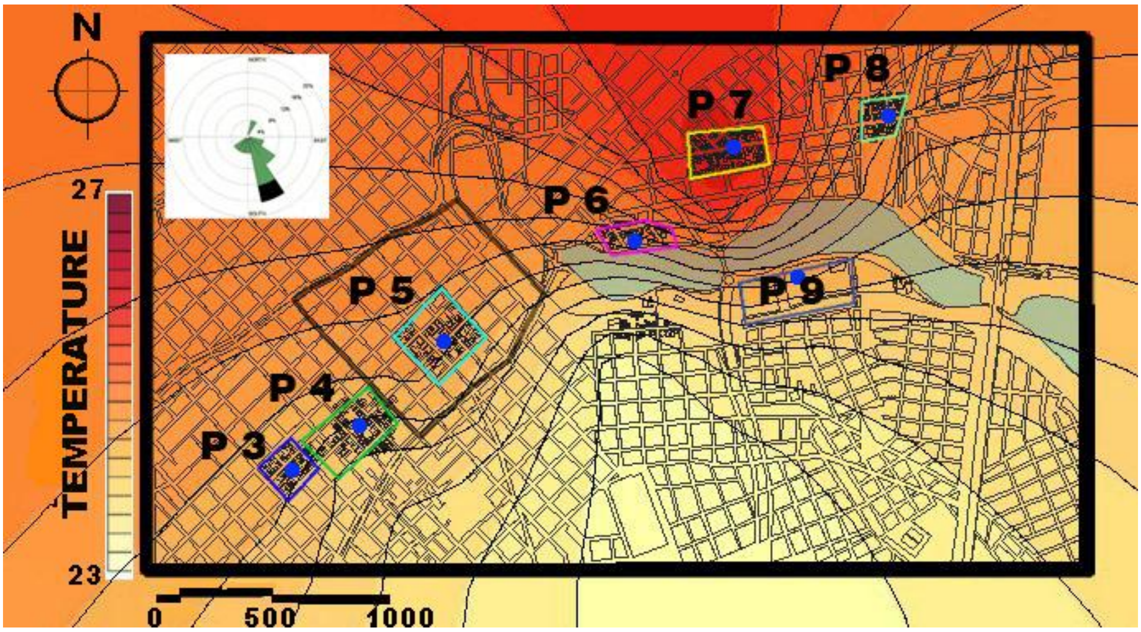


Figure 21 - **Absolute humidity (g/m³) variation map on 30th June, 2013, at 16h - Northwest Wind**

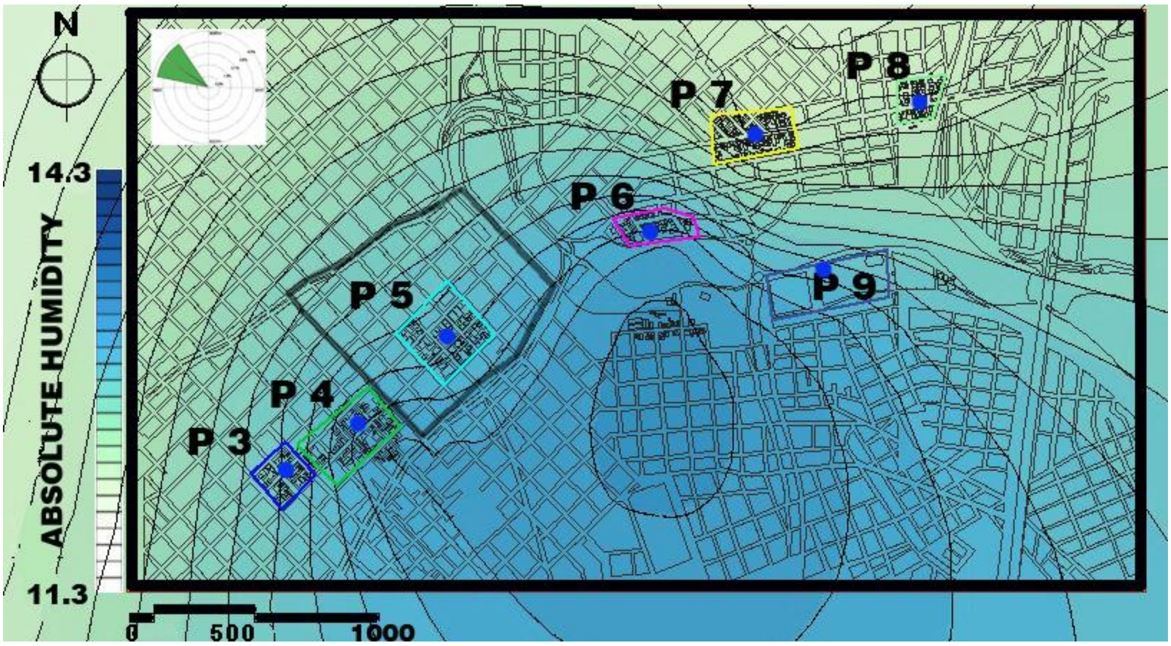
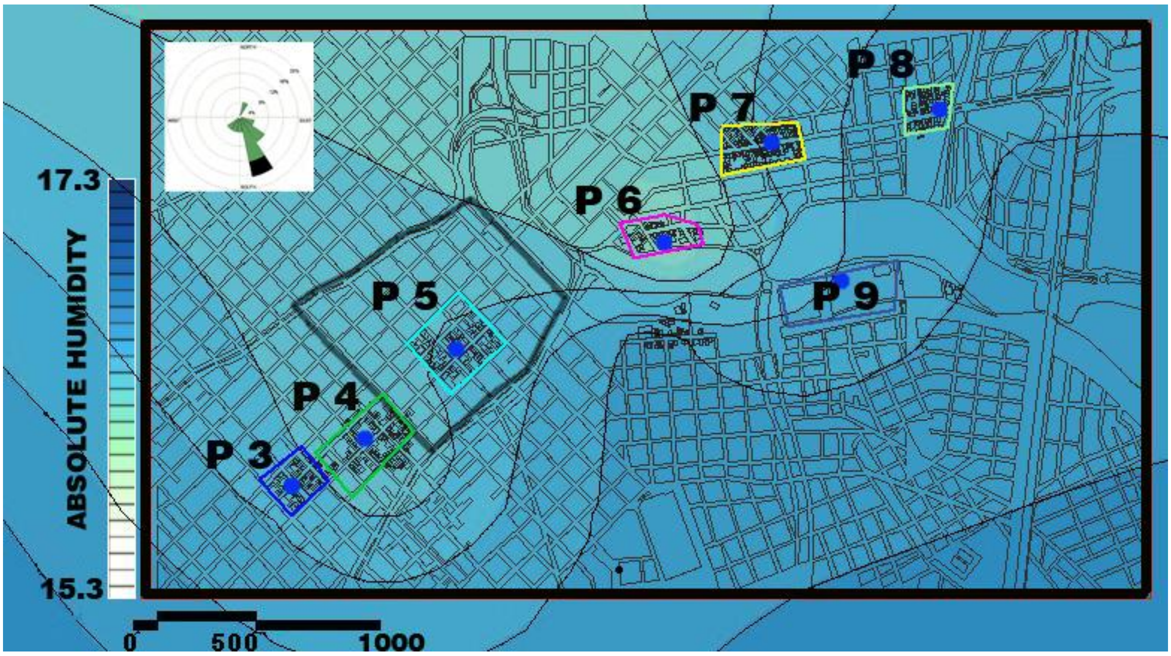


Figure 22 - **Absolute humidity variation map on 1st July, 2013, at 14h – Southeasterly Wind**



This study demonstrates that the humidity plume tends to be distributed in the spaces that offer the least resistance. The east-west urban canyons and the Northeast - Southwest density direction of the buildings hinders the combined action of the wind and droplet spreading of the water surface into the urban fabric.

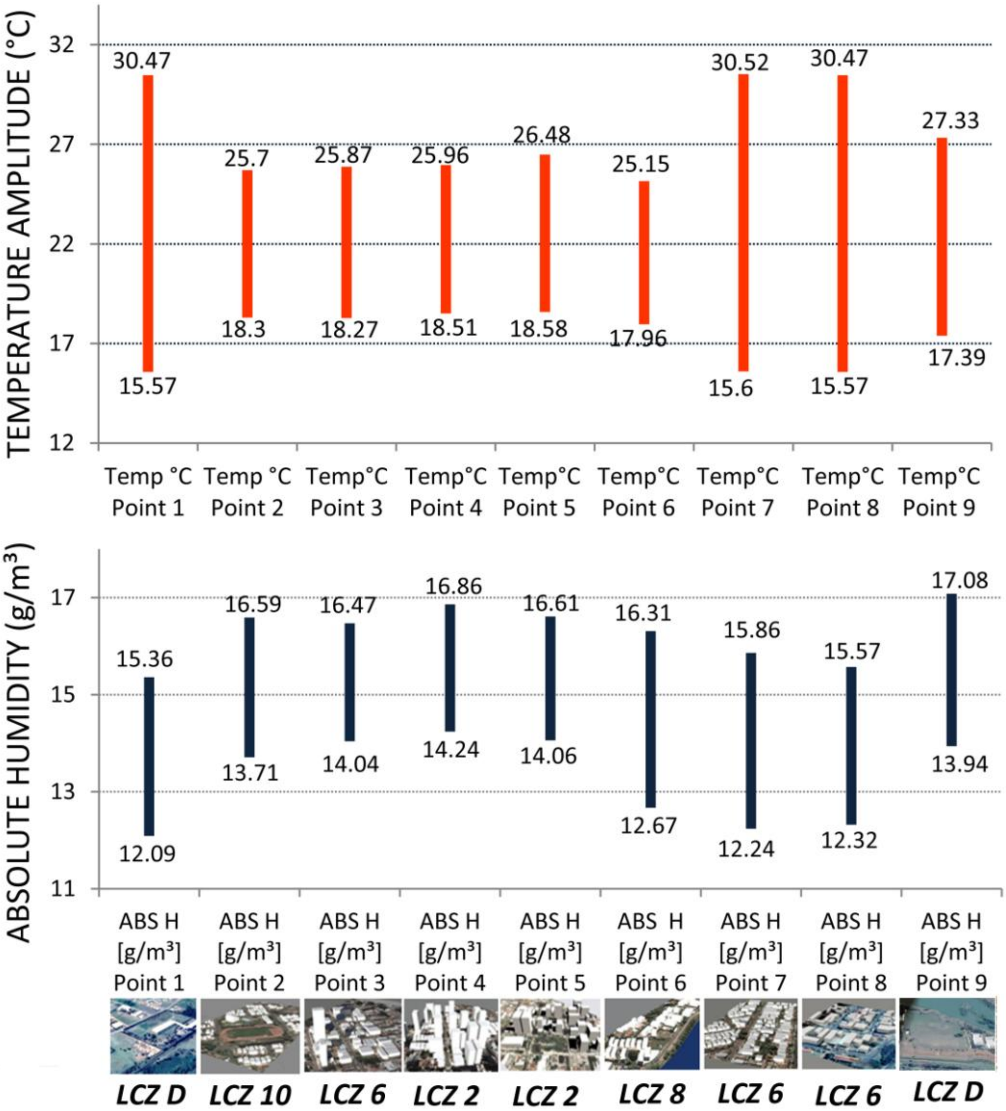
As the wind blows in a southeasterly direction, the humidity values tend to be higher in the city centre and in the north, although the physical barrier of the buildings, situated in the Northeast - Southwesterly direction together with the topography make it difficult to influence the denser areas of the suburb north of the city. The thermal range next to the water body proved to be smaller, depending on the urban setting. Therefore, the farther from the water body, the greater the need to use vegetation, shading, buildings, humidity channeling or other resources to maintain the air temperature and humidity stability of appropriate levels for humans' well-being.

According to Figure 23, Points 7 and 8 – LCZ 6 Open Midrise – presented the highest thermal amplitude of all points and the lowest index of absolute humidity. Point 1 –LCZ D Low Plants – which is situated at a suburban area, presented also high thermal amplitude and low index of absolute humidity. Although Point 9 having the same classification as Point 1 – LCZ D Low Plants – it has presented lower thermal amplitude and higher absolute humidity index, due to its proximity to the water body.

Discussion

The high air temperature and air humidity differences observed in the southern and northern areas of the city are mainly a consequence of the effect of evaporative cooling. However, the occurrence of water evaporation and the distribution of intra-urban air humidity are mainly related to the predominant climatic characteristics of a region, the configuration of the built and vegetated environment and the availability of local water resources. So, that the interaction among this set of factors contributes to the thermal behavior of the urban space.

Figure 23 – **Thermal amplitude and Humidity Variation according to the LCZ**



As São José do Rio Preto city is located at a continental region with a high-altitude tropical climate, the relative humidity in the driest winter months may often reach levels below 20%. Then, although the region has water resources and wind potential, the urban network does not take advantage of this natural potential to ensure the thermal quality of the urban space. The daily air temperature range in dry climates is usually high due to low humidity content and, the greater the amount of water in the atmosphere, the lower the thermal variation throughout the day. It is important to note that during the night, the wettest areas of a city tend to lose less heat than dry ones.

A comparison can be made between other results pointed out in the literature and those obtained here, helping on improving methods for urban climate studies.

According to the classification of four elements, namely the water surface area, geometry, city centre location and proportion of constructed environment, Sun and Chen (2012) investigated the intensity and efficiency of urban cooling caused by 197 water bodies in Beijing, China. The results indicated significant impacts on the microclimate in the vicinity of each water body and showed the need for planners to consider issues related to the potential for cooling in cities with strong urbanization.

Theeuwes, Solcerová and Steeneveld (2013) presented that the temperature effect of a lake on the city differs for various distributions of the same amount of water over the city. One large lake has a strong effect on its surroundings, while several smaller lakes influence a higher percentage of the city. In the case of São José do Rio Preto, the waterbody was dammed in a concentrated area which is privileged in terms of green infrastructure, so, the thermal effects could be detected in a limited surrounding area. Also, the form of the water surface, the relief, the prevailing winds and the resistance of the built environment on the humidity penetration through the urban space are the main aspects that influenced the highest difference of air temperature, reaching differences of 4 °C in between the LCZs.

Hathway and Sharples (2012), during the spring, detected a lower air temperature difference of 1.5 °C in an area near the Don River in Sheffield, England, when comparing it to a more distant area. This difference was quantified based on the variation of the environmental conditions, the urban form and the distribution of the humidity favored by the shape of the river. The authors emphasize that the unfavorable thermal conditions in occupied central and densely urban areas can be reduced by introducing humidity in the air, taking advantage of the action between the wind and river water and from the territory occupation.

Therefore, humidity can either encourage the creation of cooler environments during the day or create stuffy environments at night if there is too little wind. It depends on the kind of climate the city is located in. As Gough and Hu (2016) reported, the main causes of the occurrence of urban heat islands include the reduction of evaporation and evapotranspiration due to the excess of impermeable surfaces, reduced vegetation and lower reflectivity of the albedo. Points 7 and 8 – LCZ 6 – were the sites presenting the highest air temperature and the lowest index of humidity along all period of measurements. They show 95.2% and 94% of impermeable surface and 0.69 and 0.72 of FVC, respectively, allowing heat gains and favoring a high intensity of evaporation. These kind of environment, however is restricted to a few quarters from the lake, having low capacity of keeping the air humidity, mainly because of the impermeable prevailing pavement, which does not retain water.

Points 3 and 4 – LCZ 6 and 2 – area composed by 91.3% and 100% of impermeable surface and FVC of 0.70 and 0.35, respectively. Although they are farther from the water body and present plenty impermeable surface, these kinds of environments had shadows from buildings acting on the pedestrian level during the measuring period, so, the solar heat gains are lower than points 7 and 8 – LCZ 6.

The urban infrastructure establishes complex geometries that intercept energy and alter airflow, increasing the available energy to heat the urban surface (OKE, 1978). Therefore, it is crucial that planners know the benefits and limitations of different passive cooling strategies, in order to make comfortable and healthy environments, assuring the optimization on the investment in green sustainable infrastructures.

Conclusion

The monitoring process of air temperature and humidity variation in the LCZs and their mapping, showed the importance of considering urban water bodies as an urban planning strategy. Built environment configurations significantly influence on the distribution of humidity through urban spaces affecting the thermal urban environment.

The presented results are based on the horizontal air mass movement analysis in the urban canopy layer under the influence of a water surface, according to the variation of the built environment.

Water supply and distribution in the atmosphere through water bodies presence and from vegetation evapotranspiration may provide more stable urban thermal behavior, while the humidity content may bring more suitable urban air.

The study of the interaction between winds, water bodies and built space clarifies the high potential of microclimatic control through passive and natural resources available. The physical concepts and the thermal combination of the effects of urban evaporative cooling and the horizontal distribution of air masses demonstrate a high potential for application on urban spatial interventions.

It is noteworthy that moisture present in the valleys hardly penetrates the urban fabric located at the higher levels. The relief and density of the buildings of the urban centre, mainly those located in a Northeast - Southwesterly direction, contribute to a decrease in both, the blowing wind and distribution of humidity. These factors prevent the dynamic interaction between the wind potential and the dam's humidity from reaching the higher and more arid areas of the city´s suburbs, located in the north.

Thus, the near thermal amplitude of the dam presents smaller values and as the environment becomes more arid and urbanized, a greater thermal amplitude can be observed. This fact must be taken into account to outline strategies that create microclimates and ensure the quality of the constructed space as a whole. Inserting humidity by damming rivers and streams can be a feasible strategy for urban planning. It can improve the conditions of the urban thermal environment of continental regions with predominantly hot and dry climates.

Despite the scientific advances, man has limited action on the natural phenomena that could really keep the intra-urban layer air at the ideal levels of quality. However, from the point of view of urban design, several factors can be managed, modified and controlled by human action in order to obtain gains for the quality of life.

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