Urban versus green areas: a heat stress evaluation

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1 Introduction

The evidence with regards to climate change and global warming keeps mounting, with the UN forecasting that by 2100 global temperatures will increase by three degree Celsius (Grinsted et al., 2010). The temperature increase will further intensify the heat excess already experienced by urban settlements all over the world (Stone et al., 2012). This heat comes in the form of heat waves, which are concentrated in inner urban, high-density environments compared to nearby suburban areas where the built form and population densities are lower. The difference is explained by changes in the surface characteristics that alter the partitioning of surface heat fluxes (Castleton et al., 2010; Parizotto & Lamberts, 2011). As urbanisation occurs, natural vegetation and surfaces are replaced by impervious concrete and asphalt. Changes in land use also contributes significantly to urban heat island UHI during night time (Coseo & Larsen, 2014). These changes alter thermal energy fluxes and reduce evapotranspiration by reducing the surface moisture levels. The changes in original land surfaces, airflow limitation in dense urban environment and heat produced by the occupation of buildings and human activities contribute to the urban heat island (UHI) effect that accounts for higher urban temperatures when compared to rural areas (Doick et al., 2014; Laaidi et al., 2012; Stone, 2007). Surface temperatures around buildings in inner-city areas have been found to be 4 degrees Celsius higher than suburban areas (Laaidi et al., 2012). In 2018, 55% of the global population lived in cities, a figure that is predicted to increase to 68% by 2050 (United Nations Department of Economic and Social Affair, 2018). This scenario indicates a trend to worse thermal conditions in urban environments.

Adverse health outcomes and deaths related to heat exposure have been evidenced worldwide (Anderson et al., 2013; Gasparrini et al., 2015; Hondula & Barnett, 2014; Ye et al., 2012). In a 2003 European heat wave, over 30,000 deaths were recorded (WHO, 2004). It has been predicted that each one degree Celsius increase in temperature doubles the risk of mortality (Vandentorren et al., 2006). Those most at risk are the elderly, the young and those with reduced mobility who are more severely affected by extreme temperatures (Anderson et al., 2013; McGeehin & Mirabelli, 2001; Zanobetti et al., 2012). The outcome is that hospitals and medical services experience peaks in demand for their services during hot periods (Anderson et al., 2013). With the aged population increasing globally, as people survive to older age, the risk of increasing heat-related mortality grows. Other factors, which influence human health, are gender, socio-economic conditions, residence area, the way of life, housing, health problems and behavioural adaptation to heat (Vandentorren et al., 2006). In addition, health of young and elderly are more severely affected by high temperatures (Zanobetti et al., 2012).

The response of the human body to heat exposure has extreme relevance in terms of health promotion. When undertaking light activities or under cool environmental conditions, metabolic heat is transferred from human skin to the environment through a convective and radioactive process. However, during heavier working conditions or warmer environments, the human body increases its dependency on evaporative cooling, and thus all factors that affect evaporation, such as air velocity and humidity have a relevant role on heat stress (Budd, 2008).

Heat stress is an important factor to be assessed since it can affect the labour productivity and health of the individual, as well as diminishing tolerance to other environmental hazards (Epstein & Moran, 2006). It is a combination of physical and environmental parameters that comprise the total heat load input to the human body (Webber et al., 2003). In the quantitative evaluation of heat stress, WGBT was adopted by ISO 7243 (2017) and is the basis of the publication authored by the American Conference of Government Industrial Hygienist (ACGIH) "Permissible heat exposure threshold limits values" (TLV) that refers to conditions of repeated exposure without adverse health effects. As stated by (Budd, 2008), the existence of well-established limit values that help to interpret readings of WBGT in working, military and occupational contexts comprises one of the main strengths of this index. The second one is the combination of temperature, relative humidity, wind speed and solar radiation, which includes crucial components of the outdoor climate.

Green areas have shown importance in the improvement of thermal conditions in urban environments. Cohen et al. (2012) reported the importance of urban parks in reducing summer heat stress. The addition of green spaces in urban areas could reduce land surface temperatures, mitigating urban warming and providing cooling benefits towards human health improvement (Cheung & Jim, 2019; Kotharkar & Bagade, 2018; Zhang et al., 2018; Gunawardena et al., 2017; Klemm et al., 2015; Akbari et al., 2001; Rosenfeld et al., 1998). A study performed by Lee et al. (2016) evaluated that trees are more significant than grasslands in attenuating heat stress under different spatial scales.

Planting trees comprises an effective green infrastructure strategies aiming to attenuate urban temperatures (Lanza & Stone, 2016). According to Lin et al. (2017) pocket parks were cooler than their surrounding urban streets and thus, helped to mitigate UHI at micro scale. Trees and green spaces have shown to be an important strategy in mitigating UHI due to their strong potential regulating urban air temperatures (Doick et al., 2014). Even though the low albedo characteristics, vegetated surfaces can absorb a large part of the incoming solar radiation, maintaining lower temperatures than paved surfaces, due to evapotranspiration process (Snir et al., 2016). The vegetation showed relevance in the energetic control of the city reducing the incoming solar radiation in urban spaces (Gómez et al., 2004; Liu et al., 2018). Consequently, according to Shiflett et al. (2017), in vegetated areas it was observed a reduction in surface temperatures during daytime and air temperature at night.

Due to the urbanization process, as well as the high number of industries in the metropolitan region, serious environmental problems have arisen, such as water and air pollution, and urban heat islands. The urban density has also a relevant role in establishing different microclimates in the city, blocking dominant winds, trapping heat, and absorbing solar radiation. Aiming to point out the effects of urbanization on the thermal stress, this paper presents a heat stress comparison between two different neighbourhoods in Rio de Janeiro, Brazil. These localities differ markedly in their spatial structure in terms of building density and vegetation cover. The outdoor heat stress is evaluated by Wet Bulb-Globe Temperature (WBGT) Index, which considers the combined effect of air temperature, relative humidity, solar radiation and wind speed.

2 Methods

This paper assessed the influence of urbanization in heat stress comparing simultaneously outdoor WBGT between an urban and a suburban area in Rio de Janeiro city named São Cristovão and Barra de Guaratiba, respectively. The following topics present all the relevant information concerned with the present study.

2.1 Climate and Geographic characteristics

Rio de Janeiro the capital of the state of Rio de Janeiro is the second most populous municipality in Brazil and is located 23°S and 43°W. Temperature varies spatially according to the type of vegetation or land use, elevation and distance from the coast. Along the shore the regular breeze moderates the temperature. The city is also often reached by cold fronts coming from the south most frequently during autumn and winter and Amazon forest, resulting in weather changes. The city presents a tropical climate with dry and mild winters and springs, and very wet and warm summers and autumns. Temperatures higher than 40°C may be eventually reached over the year, but are more often during the summer, leading to apparent temperatures higher than 50°C due to the combination of high relative humidity levels and low winds (INMET, 2019)

According to INMET, the average annual temperature is 23.8°C. The lowest daily averages occur in July (18.4°C) and the highest (32.2°C) in February. The average annual relative humidity is about 79%, ranging from 77% in July and August to 80% in December and in March to May, which comprise humid characteristics basically all over the year. The wind patterns are not regularly distributed along the year. In terms of monthly wind speeds, the lowest and the highest averages occur from April to July and from August to November, respectively (Rio de Janeiro, 2002). The averages of global solar radiation reaches the highest levels during February (~ 6.5 kW/(m².day)) and the lowest between June and July (~ 4 kW/(m².day)) (Instituto de Energia da PUC, 2016).

Besides the aforementioned general climate characteristics, it is important to point out that in a local scale, neighborhoods' climate characteristics may vary due to different geographic factors such as: urban density; rate and type of vegetation; and proximity to forests or seashore.

According to Figure 1, São Cristovão is located in the vicinities of Guanabara Bay and comprises an urban dense area. It is an old neighborhood where the onset of the urbanization occurred through the industrial production from 1940's. The urbanization process occurred with no planning actions resulting in a dense building mass and a lack of green areas. Oppositely, Barra de Guaratiba (simply named as Guaratiba) is a coastal neighborhood situated in the west zone of Rio de Janeiro city, surrounded by mangroves and mountains covered by dense rainforest vegetation. It can be considered as a suburban area comprised mostly by single residences, where buildings are scarcer and the presence of green areas is well distributed throughout the region. The proximity to the shore and the lower urban density is expected to make the wind effect more pronounced.

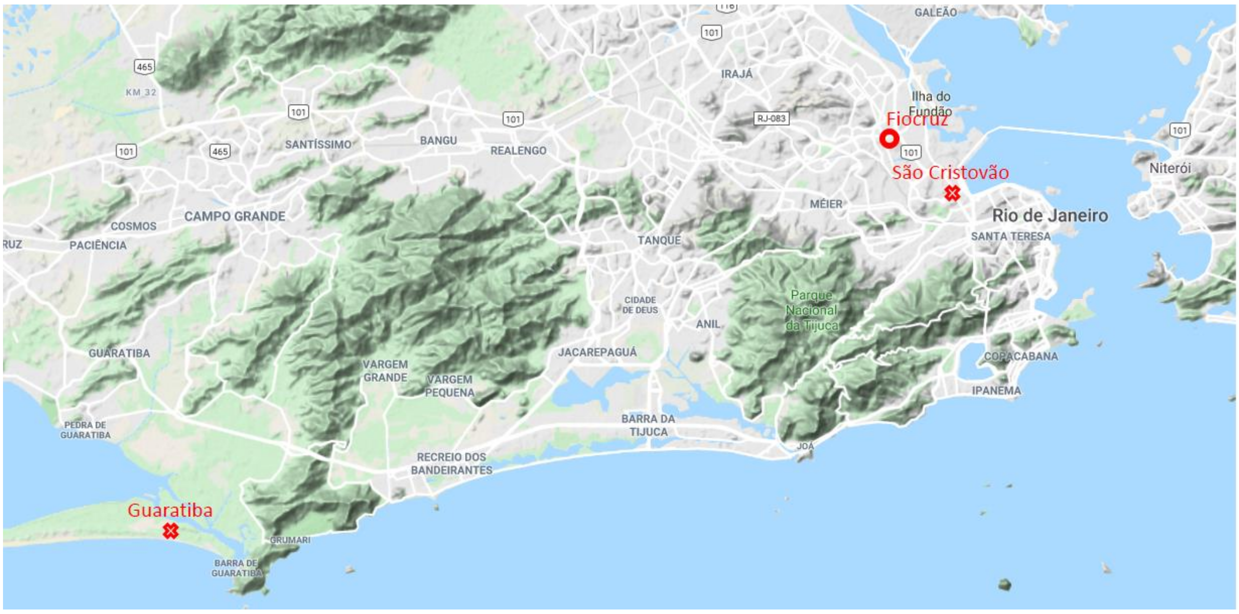

Figure 1 – São Cristovão and Guaratiba location (red crosses), and the local of solar radiation measurements (red circle).

2.2 Data collection

Registers of relative humidity, temperature, and wind speed were achieved in Alerta Rio Meteorological System data basis, freely available on web. This meteorological system comprise thirty-three stations scattered throughout the city of Rio de Janeiro that provide data every fifteen minutes in real time. The solar radiation data was collected at the rooftop of Helio Peggy Pereira building in Oswaldo Cruz Foundation campus (Fiocruz), located in Manguinhos neighbourhood (Figure 1) in the metropolitan region of Rio de Janeiro. The selected equipment for this purpose was the Hukseflux LP02 pyrometer, which measures the solar radiation in W/m² received by a plane surface from a 180° field of view angle. The data was collected every fifteen minutes during the whole year of 2016. Considering the lack of solar radiation data in the meteorological database provided by Alerta Rio system, the solar radiation collected at Fiocruz was extrapolated to São Cristovão and Guaratiba sites. The distances between the data collection site and these neighbourhoods were about 4 km and 39 km, respectively.

2.3 Heat stress assessment

Based on ISO 7243 the WBGT index is determined for outdoor conditions as:

$$WBGT = 0.7\,Tnwb + 0.2\,Tg + 0.1\,Ta$$

Where *Tnwb* is the natural wet bulb temperature, *Ta* is the air temperature, and *Tg* is the globe temperature. *Tnwb* and *Tg* are calculated by methodology proposed by Liljegren et al. (2008) that takes into account diffuse and direct components of solar radiation. The calculation of *Tnwb* requires an iterative process of complex equations which is performed by an excel spreadsheet comprising Visual Basic macros given climatic variables of solar radiation, temperature, relative humidity and wind speed. The methodology for calculation of *Tnwb* and *Tg* proposed by Liljegren et al. (2008) is summarized as described below:

Tnwb is solved iteratively through the following equations (1) and (2):

$$Tnwb = Ta - \frac{\Delta H}{Cp}\frac{M_{H2O}}{M_{air}}\left(\frac{Cp\,\rho\,\partial}{k}\right)^{0.56}\left(\frac{e_w - e_a}{P - e_w}\right) + \frac{\Delta F_{net}}{A}\frac{1}{h} \quad (1)$$

$$\therefore \quad h = \frac{k}{D}\,0.281\left(\frac{VD}{\mu}\right)^{0.6}\left(\frac{C_p\mu}{k}\right)^{0.44} \qquad e_w = e_{sat}\,T_{nwb} \qquad e_a = RH\,e_{sat}\,T_a$$

$$\frac{\Delta F_{net}}{A} = 0.95\,\sigma\left[\frac{1}{2}\left(1 + (0.575\;e_a^{0.143}\right)Ta^4 - Tnwb^4\right] + 0.6\,S\left[0.2\left(1 + \frac{D}{4L}\right) + 0.8\left(\frac{D}{4L}\right) + 0.45\right] \quad (2)$$

Tg is solved iteratively in the following equation:

$$T_g^4 = \frac{1}{2}\left(1 + 0.575\;e_a^{0.143}\right)T_a^4 - \frac{h}{0.95\,\sigma}\left(T_g - T_a\right) + \frac{S}{\sigma}\,0.525 \qquad (3)$$

Where: *ΔH* - heat of vaporization; M_{H2O} - molecular weight of water vapour; M_{air} - molecular weight of air; Cp - specific heat at constant pressure; ρ – air density; ∂ – diffusivity of water vapor in air; k – thermal conductivity of the air; D – wick diameter (psychrometer); A - surface area of the wick; e_{sat} - saturation vapour pressure; RH – relative humidity; P – barometric pressure; V – wind velocity; μ - Air viscosity; h - convective heat transfer coefficient; σ - Stefan-Boltzmann constant; S – solar radiation; L – wick length.

In the aforementioned equations, *Tg* represents the inputs and outputs of heat in the environment, due the combined effect of air temperature, radiant heat and cooling effect of the wind. *Tnwb* reflects the evaporation rates and it is regulated by relative humidity, radiation levels and wind. The calculation of outdoor WBGT as a function of relative humidity, air temperature, wind speed and solar radiation is performed through the methodology proposed by Liljgreen et al. (2008) for outdoor environments that presented a very good agreement with measured data (Grundstein et al., 2015; Lemke & Kjellstrom, 2012).

Many regulatory bodies recommend WBGT threshold limit values (TLVs) to evaluate the heat stress in human health for different workload rates. As presented in Table 1 the present work adopted the preconized limits by ISO 7243 “Hot Environments - Estimation of the Heat Stress on Working Man”

Table 1 – WBGT threshold limit values (TLVs) for different workload rates (Watts - W) according to ISO 7243. * WBGT in brackets refer to sensible air movement.

Workload/activity	WBGT
Resting	33°C
Light	30°C
Moderate	28°C
Heavy	25°C (26°C*)
Very heavy	23°C (25°C*)

It is worth mentioning that encompassing different human tolerance to heat since acclimatization lies on physiological adaptations that occur after constant exposure to hot environments is not a simple task (Armstrong & Maresh, 1991). A constant exposure to heat makes an individual more resistant to heat stress comprising a greater sweat rate along with increased heart function, fluid balance and skin circulation (Grundstein et al., 2015). The magnitude of these physiological changes lies on the duration, intensity, and frequency of human heat exposure. In general terms, the resistant to heat exposure varies geographically.

Even though heat illness may occur more often in hotter climates due to higher levels of heat exposure, it is noted that people in cooler regions may be more vulnerable to hot spells because they are not acclimatized to extreme conditions (Grundstein et al., 2015). Thus, it is important to highlight that in order to provide guidance the specified WBGT limits above in the Table 1 will be adopted in the evaluation of heat stress in outdoorenvironments from both Guaratiba and São Cristovão localities

The outdoor WBGT from both neighbourhoods was calculated as described in the aforementioned equations from 01/01/2016 to 31/12/19, according to the registers of temperature, relative humidity, wind speed and solar radiation every 30 minutes, comprising 17569 data points.

3 Results

The comparison of the outdoor environmental factors and the heat stress levels, in terms of WBGT, from both urban and suburban localities is presented in the following figures. The results present clearly the effect of the urbanization process in the worsening of thermal aspects of densely populated areas.

3.1 Long-term simultaneous comparison

The environmental parameters and the calculated outdoor WBGT in both São Cristovão (WBGT(SC)) and Guaratiba (WBGT(G)) neighbourhoods are compared simultaneously by the line graphs depicted in the Figure 2. The wind velocities in Guaratiba were higher than the observed in São Cristovão. Even though being influenced by the temperature levels, the relative humidity levels in Guaratiba were often higher than São Cristovão because of the higher density of vegetation cover. Oppositely, the lack of the vegetation in São Cristovão tends to provide to this neighbourhood a dryer characteristic, and higher temperatures.

The temperature in both neighbourhoods presented a straight relationship to the solar radiation levels. Higher temperatures occurred during higher levels of solar radiation. Guaratiba's temperature was lower than the observed in São Cristovão, presenting generally similar levels during the maximum temperature peaks, but significant lower levels along the minimum peaks.

The heat stress evaluation in terms of WBGT had particularities due to the combination effect of the aforementioned environmental parameters. Considering an annual perspective, it is also evident the influence of the solar radiation in WBGT. From April to October (autumn to winter) low levels of solar radiation coincide with decreasing WBGT in both locations, whereas the opposite occurs in summer and spring months. The WBGT patterns were similar to temperature in both Guaratiba and São Cristovão neighbourhoods. However, compared to temperature the WBGT(BG) flattened and shifted downwards, whereas WBGT(SC) stretched vertically and shifted upwards. In summary, in terms of heat stress São Cristovão showed to be significantly unhealthier than Guaratiba, reaching WBGT levels related to higher risk zones as classified in Table 1. Besides the slightly lower temperature, this trend may be explained by the higher wind speeds observed in Guaratiba , that improve the thermal conditions due to the cooling potential effect of the winds.

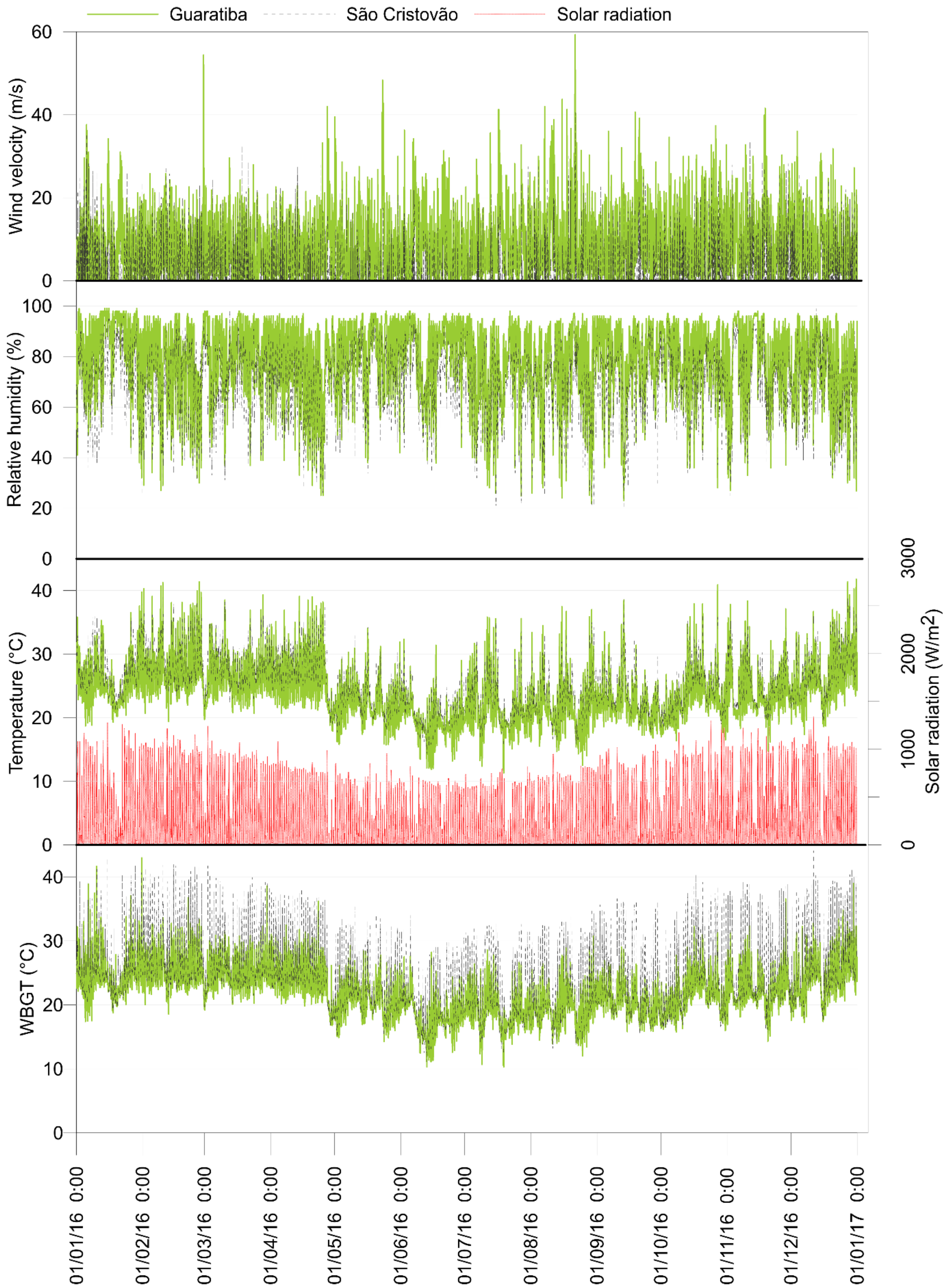

Figure 2 – Annual conditions of RH, temperature and WBGT over time and the respective relative frequency. The lower

The simultaneous differences in temperature and WBGT between São Cristovão and Guaratiba showed the evidence of better thermal conditions experienced in Guaratiba. Comparing the simultaneous differences between temperature and WBGT, São Cristovão showed to be significantly warmer than Guaratiba up to 12.6°C of temperature and 16.2°C of WBGT.

To provide a better analysis the aforementioned results are complemented and discussed considering a statistical analysis, which takes into account the relation among all parameters that comprise the heat stress evaluation, through the WBGT parameter.

3.2 *Statistical analysis*

The following histograms depicted in Figure 3 describe statistically the environmental parameters as well as the calculated WBGT of São Cristovão and Guaratiba neighbourhoods. In this same figure, the corresponding boxplots indicate the maximum, minimum, median, and the first and third quartile of all the distributions.

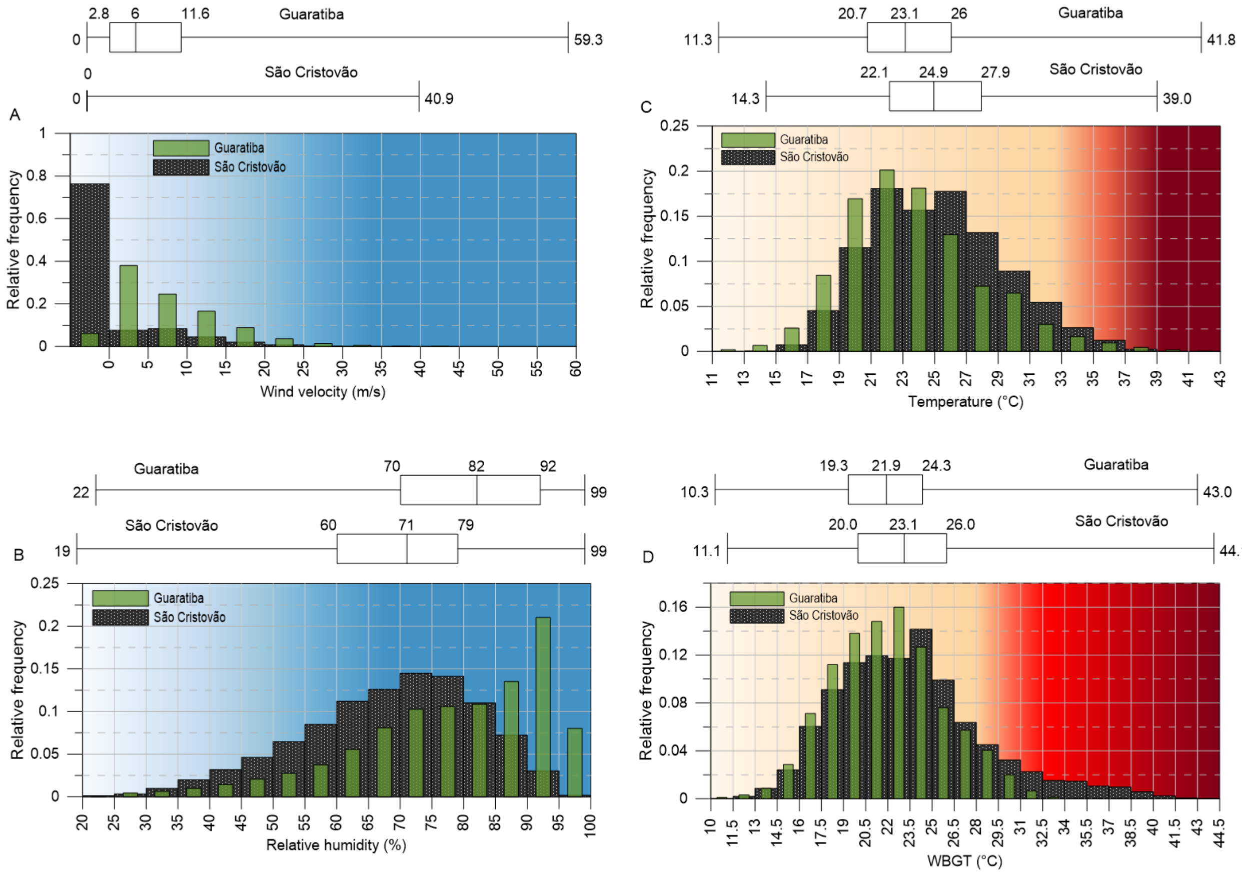

Figure 3 – Guaratiba and São Cristovão histograms and boxplots of wind velocity, relative humidity, temperature and WBGT.

Regarding the wind velocity Figure 3A evidenced the differences between the two localities. The maximum wind velocities in São Cristovão and Guaratiba reached 40.9 and 59.3 m/s, and the means were respectively 2.0 and 8.0 m/s. A stagnant condition occurred 75% of the time in São Cristovão, whereas Guaratiba presented this same condition only about 5%, having the wind effects much more pronounced mostly due to the low building density. Comparatively to São Cristovão, in Guaratiba 75%, 50% and 25% of the occurrences comprised, respectively, wind velocities up to 11.6, 6.0 and 2.8 m/s.

As depicted in Figure 3B the levels of relative humidity (RH) in Guaratiba was higher than São Cristovão. For both localities, the maximum RH reached 99%, whereas the lowest RH levels were 22% for Guaratiba and 19% for São Cristovão, having respectively the highest relative frequencies occurred in the ranges between 90-95% and 70-75. In Guaratiba 75%, 50% and 25% of the occurrences referred to RH ranges up to 92%, 82% and 70%, respectively, whereas for São Cristovão these occurrences comprised 79%, 71% and 60%.

In Figure 3C the variation between the maximum (41.8°C) and minimum (11.3°C) temperatures was wider in Guaratiba, than the respective values registered in São Cristovão (39.0°C and 14.3°C). However, the relative frequencies above 39°C and bellow 15°C were insignificant in Guaratiba, whereas higher relative frequencies of temperatures from 25°C were observed in São Cristovão, indicating a distribution towards higher temperature levels. In São Cristovão 25%, 50% and 75% of the occurrences referred to temperature ranges up to 22.1°C, 24.9°C and 27.9°C, respectively, whereas for Guaratiba these occurrences comprised temperatures up to 20.7°C, 23.1°C and 26.0°C.

WBGT(SC) was higher than WBGT(G) according to all statistical parameters (Figure 3D). The highest frequencies for Guaratiba and São Cristovão occurred for WBGT ranges 22.0-23.5°C and 23.5-25.0°C, respectively. WBGT levels higher than 31.0°C were negligible for Guaratiba, whereas these ranges for São Cristovão had a frequency of about 8% (~29 days). WBGT(G) varied from 10.3°C to 43.0°C and WBGT(SC) ranged between 11.1°C and 44.1°C. The better thermal characteristics in Guaratiba are evidenced by the occurrences of lower WBGT ranges comparatively to São Cristovão. WBGT(G) frequencies of 25%, 50% and 75% occurred for ranges up to 19.3°C, 21.9°C and 24.3°C, whereas WBGT(SC) these same frequencies corresponded to ranges up to 20.0°C, 23.1°C and 26.0°C.

Besides the higher temperature levels, the main reason for the worse heat stress conditions observed in São Cristovão lie in stagnant air conditions. Comparatively to São Cristovão, even though the higher RH in Guaratiba could offset the lower temperature patterns, the higher wind velocities exerted a major role in decreasing WBGT(G).

Aiming to evaluate to what extent Guaratiba presents a better thermal environment conditions, Figure 4 presents a histogram of the simultaneous differences of temperature and WBGT classified in 2.5°C ranges. Both parameters indicated that São Cristovão is significantly warmer than Guaratiba (80% of the time in terms of temperature and 74% of the time in terms of WBGT). In relation to the WBGT parameter, the temperature differences occur in lower level ranges. The temperatures in São Cristovão were higher than 5°C only 3% of the time, whereas similar ranges of WBGT had a frequency of 10%, which corresponds to about 36 days over the year.

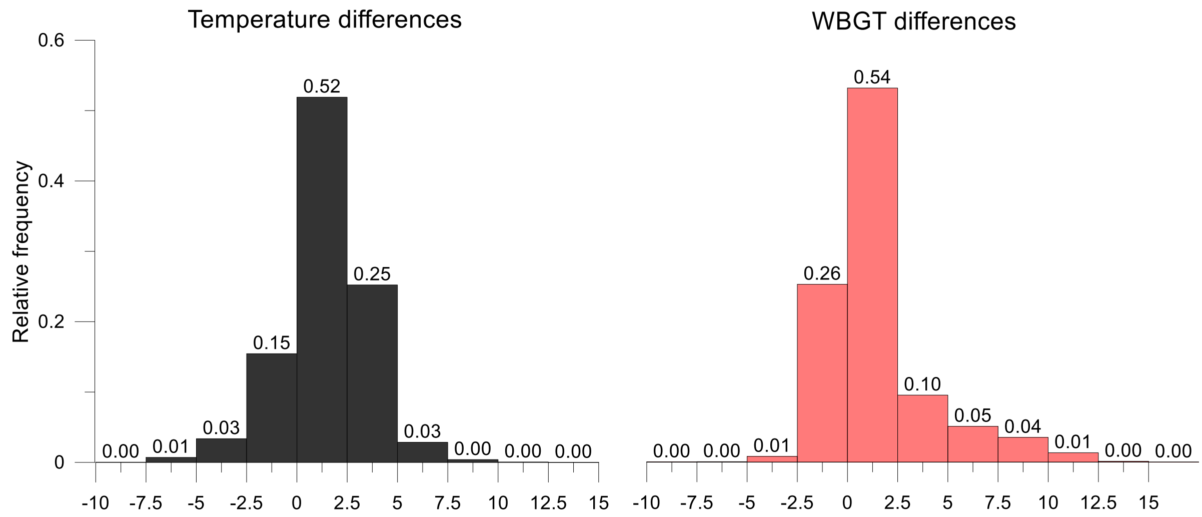

Figure 4 - Relative frequency of WBGT and Temperature differences (São Cristovão minus Guaratiba).

As presented in Table 2 z-test is carried out considering a confidence interval of 95% to evaluate whether the levels temperature and WBGT observed in São Cristovão and Guaratiba are statistically different or not. Z values higher than the critical, as well as p-values lower than 0.05 indicate significant differences between temperature and WBGT means.

Table 2 – Temperature and WBGT statistical z-test analysis.

	Temperature		WBGT	
	São Cristovão	Guaratiba	São Cristovão	Guaratiba
Number of observations (data points)	17569		17569	
Mean	25.20	23.71	23.48	22.00
Variance	17.34	19.01	25.23	14.03
z critical (p=0.05)	1.960		1.960	
Z	32.735 (p = 0.00000)		31.126 (p = 0.00000)	

According to the results presented in the Table 2, the values found for z are significantly higher than the z critical, showing that both temperature and WBGT between São Cristovão and Guaratiba are statically different, meaning worse thermal conditions experienced in São Cristovão.

3.3 Heat stress analysis

Aiming to evaluate the heat stress and the health related risks between São Cristovão and Guaratiba, Figure 5 compares outdoor thermal conditions of both localities for different performing activities, according to WBGT thresholds presented in Table 1. This figure describes for the two neighbourhoods the number of the days over the year of 2016 categorized according to allowed activities.

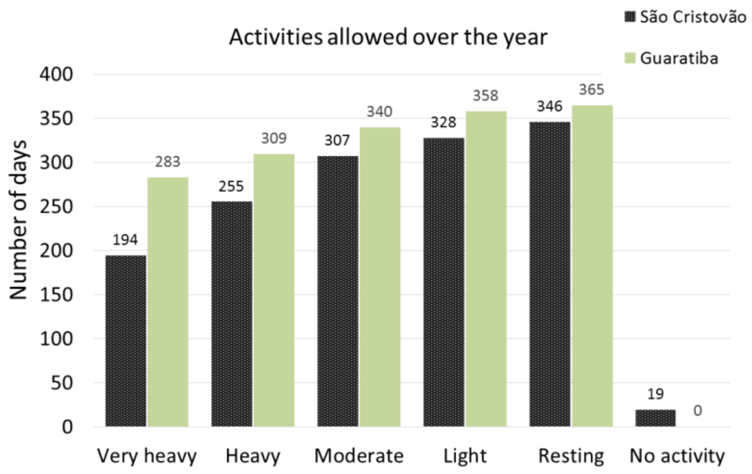

Figure 5 – Number of days in which activities can be performed according to different workloads.

Guaratiba presents a higher allowance for all activities, indicating a significant better thermal condition compared to São Cristovão. Over the year, very heavy activities are allowed in São Cristovão and Guaratiba 194 and 283 days, respectively, meaning a restriction equivalent to 171 days in São Cristovão, and 82 days in Guaratiba. The heavier the workload, the higher the difference between the numbers of days in which activities can be performed in São Cristovão and Guaratiba. These differences increases from 9 days, for resting, to 89 days in the case of very heavy activities. It is also important to highlight that São Cristovão exhibit as a worst-case scenario a total restriction of 19 days to any activity.

Additionally, a heat stress analysis was evaluated under extreme warm conditions. With this purpose, February was selected as the worst-case scenarios, comprising 29 days of analysis. As depicted in Figure 6 Guaratiba presented significant better thermal conditions when compared to São Cristovão.

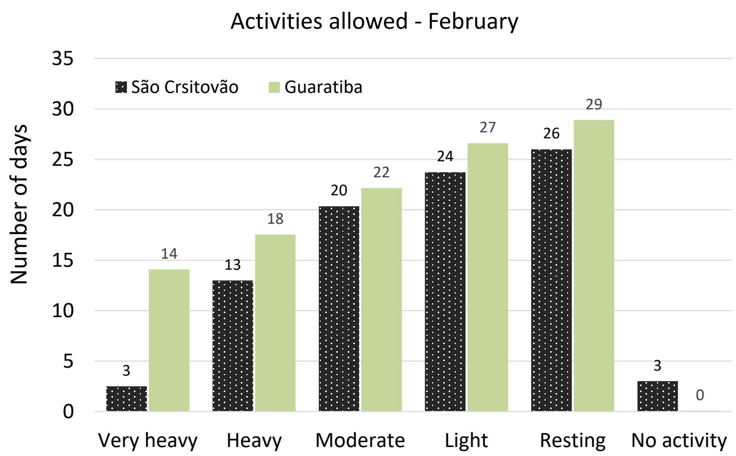

Figure 6 - Number of days in which activities can be performed according to different workloads

Very heavy activities were allowed in Guaratiba 14 out of 29 days, whereas in São Cristovão it was reduced to only 3 days. Extreme thermal conditions, in which no activity is allowed, occurred during 3 days in São Cristovão, and had no occurrences for Guaratiba. Table 3 summarises the comparison between these two localities, presenting the percentage of the time in which outdoor activities can be performed according to different workload rates.

Table 3 – Worst case scenario (February) - Percentage of time in which activities can be performed according to different workloads rates.

Workload/activity	São Cristovão	Guaratiba
Very heavy	9%	49%
Heavy	45%	60%
Moderate	70%	76%
Light	82%	92%
Resting	90%	100%
No activity	10%	0%

The allowance for all activities in Guaratiba was significantly higher than São Cristovão regarding to very heavy activities. Almost half of the time very heavy activities could be performed in Guaratiba, whereas these activities were restricted to only 9% of the time. The extreme thermal conditions in São Cristovão could be highlighted when 10% of time there was a restriction to any activity.

4 Discussion

Comparatively to Guaratiba, São Cristovão presented the temperature patterns towards higher ranges of mean, median, first and third quartiles. In terms of mean temperatures (Table 2), São Cristovão showed to be 1.5°C warmer than Guaratiba. Stone et al. (2012) presented similar differences between urban and rural areas, mostly due the presence of vegetation and less dense urban environments. According to Su et al. (2012) urban dense areas tend to be warmer than surrounding rural areas. Similar studies have also highlighted the effect of vegetation in promoting better thermal conditions in urban environments (Cheung & Jim, 2019; Liu et al., 2018; Lin et al., 2017; Snir et al., 2016; Lanza & Stone, 2016; Lee et al., 2016).

Considering the relative proximity between these localities (~ 40km) the incoming solar radiation levels reaching São Cristovão and Guaratiba can be assumed similar, and thus, the higher temperatures observed in São Cristovão occur due to the different land cover types, since the built densities in Guaratiba and São Cristovão correspond to 782 and 11975 m²/ha, respectively. As pointed out by Su et al. (2012) in urban environments the relationship between land cover and temperatures provide significant implications for a group of people more vulnerable to high temperatures, suggesting that the vegetation play a significant role in temperature attenuation. Lee et al. (2016) evidenced the influence of trees and grasslands in attenuating urban temperatures. However, the results showed that trees are more efficient than grasslands. Gómez et al. (2004), Coseo and Larsen (2014), Doick et al. (2014), Lanza and Stone (2016), Gunawardena et al. (2017), Zhang et al. (2017), Cheung and Jim (2019), also highlighted the effect of trees and green spaces in mitigating urban temperatures.

The lack of vegetation areas, the higher urban density makes São Cristovão more susceptible to heat islands, considering that urban surfaces have a high percentage of areas made in asphalt concrete that increases substantially the surface temperatures, as well as the overlying air layer. According to Akbari et al. (2001) besides the lack of vegetation, heat islands occur due to the low reflectance of solar radiation by mostly urban surfaces. The fraction of the incoming solar radiation reflected from a surface depends on its albedo.

According to Dimoudi and Nikolopoulou (2003) and Imhoff et al. (2010), the albedo is an important parameter that regulates the heat gain from solar radiation and have an important role in the thermal aspects of vegetated and built surfaces. Higher albedo provides better thermal conditions, since they reduce the convective heat fluxes from cooler surfaces. A relationship presented by Akbari et al. (2001) shows that an albedo increase from 0.1 to 0.5 decreases the pavement temperature from 49°C to 32°C. The albedo of the urban environment varies considerably due to the different types of buildings, pavements, as well as adoption of mitigation strategies such as cool roofs or green roofs (Berardi et al., 2014; Georgescu et al., 2014). Snir et al. (2016) compared the average albedo for vegetated and non-vegetated ground surfaces over mid-day hours. Albedo of concrete (0.32) and bare soil (0.39) surfaces are slightly higher than vegetated ground surfaces (average of 0.22). However, according to these authors, due to the cooling process provided by evapotranspiration the vegetated surfaces absorb large part of the incoming solar radiation, and thus offset their lower albedo characteristics. As a result, lower surface temperatures occur in vegetated surfaces when compared to paved surfaces.

The relative humidity (RH) depends on the temperature levels. For a given air moisture content, the lower the temperature the higher the RH. Both São Cristovão and Guaratiba are located close to the tropical zone of Rio de Janeiro where the humidity is relatively high. The first neighborhood is located about 900m from Guanabara Bay, while Guaratiba is on the shore and a few meters from the ocean. Even though having lower temperature levels as depicted in Figure 3, the RH in Guaratiba was substantially higher than the observed in São Cristovão mostly due to higher vegetation coverage in the former neighborhood. As pointed out by Cheung and Jim (2019), trees may increase humidity and offset partially the reduction of temperature promoted by vegetation. However, the RH effects might not be the most relevant parameter to justify the heat stress differences observed the WBGT levels between São Cristovão and Guaratiba.

The wind effect was significantly different between these two localities. São Cristovão presented stagnant conditions most of the time, whereas Guaratiba comprised higher frequency of windy conditions. The wind effect superposed to the lower temperature levels in Guaratiba had a significant role in the better WBGT levels observed in this neighborhood. Similar studies corroborated the findings of the present work. Kotharkar and Bagade (2018) reported that urban heat islands are more intense under absent windy conditions. Gómez et al. (2004) also presented high WBGT levels in urban environments due to low wind effect. Coseo and Larsen (2014) and Zhang et al. (2017) reinforced that under low wind conditions air temperatures are significantly influenced by surface temperatures. Additionally, in dense urban environments high buildings hinder air circulation (wind effect) and trap thermal energy, resulting in increased air temperatures.

Besides the high building density, São Cristovão as well as many neighborhoods in the city of Rio de Janeiro did not take into the consideration the street orientation according to most frequent wind direction during its planning process. This fact concur to the findings pointed out by Doick et al. (2014) that both wind strength and direction have a significant role in attenuating urban temperatures. Oppositely, Guaratiba due to the low building density enhances the wind effect in attenuating heat stress. According to Gunawardena et al. (2017), under high wind speeds the forced convection regulates the heat transfer, increasing the sensible heat loss regardless the temperature gradients. In humid environments, windy conditions are also favorable since the airflow advects away accumulated saturated air promoting increased surface heat loss through evapotranspiration (Santamouris, 2014).

Guaratiba was significantly better in terms of heat stress when compared to São Cristovão, having lower WBGT levels 73% of the time, mostly due to the combination of lower air temperatures and higher wind speeds provided by the low built density characteristics as well as the significant presence of vegetation. Gómez et al. (2004) observed the lower WBGT levels in the districts with the highest vegetation coverage. Similarly to Guaratiba, these authors found the best thermal comfort condition during the summer for the seafront district. Klemm et al. (2015) also reported more thermal comfort conditions in vegetated streets. Snir et al. (2016) described the relevant role of the grass covered ground surface in attenuating thermal stress under hot summer conditions, since vegetated surface simultaneously reflects less short-wave radiation, and absorbs sunlight releasing latent heat through evaporation, rather than sensible heat. As a result, surfaces temperatures and the emissions of long-wave radiation are lower.

As for the outdoor conditions, Guaratiba showed to be safer in terms of health-related risks associated with heat stress categorized according to different workload activities as presented in Table 1. Extreme thermal conditions are observed in São Cristovão leading to circumstances that recommended a total restriction to any activity during 19 days over the year. Under these outdoor conditions, was recommended to avoid sun exposure and the search for shaded places. Gómez et al. (2004) also evidenced the perception of heat stress in dense urban environments with narrow streets. Lee et al. (2016), Lanza and Stone (2016) and Lin et al. (2017) highlighted the effect of trees and grasslands in attenuating heat stress in cities. The alleviation of heat stress zone comprise heat sink areas that comprise vegetated urban areas (Kotharkar and Bagade, 2018). Under tropical climate such as the São Cristovão and Guaratiba the combination of high temperatures and relative humidity levels comprise stressful thermal conditions especially during the summer. However, the wind conditions in Guaratiba, as well as the lower temperature ranges promote to this locality healthful thermal conditions.

5 Conclusion

The singular evaluation of temperature does not reflect comprehensively the effects of heat stress in human health. Thus, the use of thermal stress indices is preferred since it comprises the combined effect of temperature, relative humidity, wind speed and solar radiation. Comparatively to Guaratiba, the heat stress conditions observed in São Cristovão are more severe mostly due to the combined effect of higher levels of temperature and lower wind speeds. Even though the lower relative humidity levels, the worse thermal conditions experienced in São Cristovão lie in the combination of higher temperatures and mostly stagnant air conditions.

Vegetation has played a significant role controlling urban heat fluxes, by absorbing part of incoming solar radiation. The urban planning of tropical regions that combine high temperatures and relative humidity levels must comprehend simultaneously higher albedo building materials, significant spaces provided for vegetated areas, building spaces that allow the wind flow, as well as streets orientation according to most frequent wind direction.

Under conditions where urban environments have already established without taking into account the aforementioned measures, the solution might comprise the increase of green areas and/or the use of building material with low thermal conductance and reflective characteristics.

This study can contribute to the implementation of municipal public policy for many neighbourhoods in several Brazilian cities that need to increase area of vegetation to mitigate the heat flux and improve the conditions of well-being, especially in areas of large urban settlements.

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