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# Observational evidence of the urban heat island of Manaus City, Brazil

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**ABSTRACT:** This work examined observationally the Urban Heat Island (UHI) of Manaus city, Brazil. For this, data collected from two different sites, in an urban area and from a region of forest about 30 km from city, for the period of 2000–2008, were used. The results show that the urban environment creates a local increase in temperature and a decrease in relative humidity. The annual average observed between the urban and forest sites can reach differences of temperatures around 3 °C and relative humidity close to 1.7%. An interesting feature of the UHI of Manaus is associated with a diurnal cycle that differs from other studies for different locations in the world, with two peaks of highest intensity, one at 0800 LST and one between the 1500 and 1700 LST. It also highlighted that the urban area tends to heat first and more slowly and cool down later and faster than the forest, which explains the distinct behaviour of the diurnal cycle of the UHI. The obtained knowledge of the Manaus UHI allows the implementation of policies and methodologies that aim to improve the quality of life and comfort of large urban cities, such as those studied.

KEY WORDS urban heat island; temperature; Amazon; urbanization

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## 1. Introduction

The urbanization process produces significant changes in land surface and atmospheric properties, such as the energy partitioning between urban and adjacent areas, thus creating a new urban climate, which can be understood as a local perturbation of the regional climate (Oke, 1987; Oke *et al*., 1992). A clear indicator of the effects of an urban area on the local climate is the formation of a so-called Urban Heat Island (UHI). The term UHI is defined, by Arya (2001), as the increase in surface and air temperatures over an urban area, in relation to neighbouring rural or suburban regions. The intensity of the UHI depends on many factors, such as (Roth, 2000): (1) mechanical effects produced by the friction caused by buildings (acting as a momentum sink) and an increase in the energy transfer from large to small vortices (transformation of average kinetic energy to turbulent kinetic energy), and, (2) thermal effects induced by temperature differences of the buildings, shading effects, variation in the incident radiation on the streets of the urban canyons and reduction of latent heat fluxes, which leads to altered sensible heat fluxes to the atmosphere. According to Oke (1988), the greatest urban area heating results from a combination of factors that alter the local energy balance, such as building thermal properties, urban surface roughness, anthropogenic heat sources and other factors which contribute to a decrease in evapotranspiration.

The impact of the urbanization effect on local climate has been estimated through comparisons of meteorological data at urban and rural stations, far from urban centres, but which demonstrate similar climatic characteristics (Maitelli and Wright, 1996; Montávez *et al*., 2000; Kim and Baik, 2005; Comarazamy *et al*., 2007; Miao *et al*., 2008; Sajani *et al*., 2008). Other methods, which consider the collection of data at various locations in an urban area (Montávez *et al*., 2000; Wong and Yu, 2005), as well as remote sensing (Lee, 1984; Gallo *et al*., 1993a,b) for the estimate of surface temperature and the use of observational surface data combined with meteorological reanalysis data (Kalnay and Cai, 2003) have also been used for studies of this nature.

The city of Manaus, centred at 3° 8′S and 60° 1′W and with an average elevation of 21 m above mean sea level, is located in the state of Amazonas, Brazil, approximately in the central part of the largest tropical forest in the world, the Amazon rainforest, with a population of approximately 1 802 000 inhabitants (IBGE, 2010). Preliminary analysis performed from satellite images show that the urban area of Manaus increased by approximately 194 $km^2$ in 1998 to 242 $km^2$ in 2008, which could influence the UHI intensity and consequently the thermal comfort for the city population.

The climate of the region is characterized by two seasons, dry and wet, which are defined in relation to precipitation behaviour. According to Silva Dias *et al*. (2002) and Marengo (2005), the rainy season occurs from December to May and the dry season from June to November. The distinction between dry and rainy seasons is principally related to the position of the Inter-tropical Convergence Zone (ITCZ), which is positioned to the south during the summer months, intensifying convective activity in the region.

A recent observational analysis for the period between 1961 and 2008 for the city of Manaus (Souza and Alvalá, 2010), found that the average air temperature is $26.78 \pm 0.70$ °C. During the wet (dry) season, the month of October (March), was the hottest (coldest), with the mean temperatures equal to $27.8 \pm 0.41$ °C ($26.11 \pm 0.60$ °C). The maximum (minimum) air temperatures are observed during September (July), with values of $33.36 \pm 0.78$ °C ($22.9 \pm 0.61$ °C). For precipitation data, the annual mean accumulated precipitation is $2277 \pm 104$ mm $year^{-1}$, with April (July) showing the highest (lowest) rainfall values of $322.7 \pm 76$ mm $month^{-1}$

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($55.4 \pm 33$ mm month$^{-1}$). Considering the definition of dry and rainy periods, the average precipitation (accumulated) during the rainy season is $279.3 \pm 27$ mm month$^{-1}$ (1675.8 mm), while in the dry season the average (accumulated) is $100.17 \pm 31$ mm month$^{-1}$ (601 mm). An evident relationship is noted between the minimum average temperature and the city's rainy season, which occurs during March, in the rainy quarter (February to April). This relationship is due to the presence of cloudiness during this period, which directly influences the surface radiation balance through radiative cooling, leading to a reduction in surface sensible heat fluxes and, consequently, to a cooling of the atmosphere. These results are in accordance with the ones observed by, among others, Machado (2000).

Kayano and Moura (1986), Molion (1987) and Rao and Hada (1987) showed that the annual variation in surface air temperature is influenced by the variability in dynamic mechanisms that generate convection, cloud formation, and rain. Many of these dynamic mechanisms are associated with tropical sources of latent heat. Phenomena such as the El Niño/Southern Oscillation (ENSO) directly influence the Walker cell, intensifying convective activity in the Amazon region, and thus convective cloud formation.

Considering studies already conducted for the area of interest, Maitelli and Wright (1996) showed the presence of the UHI of the city of Manaus, analysing a dataset collected in urban, forest and pasture areas for a period of 14 months, from February 1991 to March 1992. The authors found differences of 2.25 °C between the urban and forest areas, with the city region presenting between 3 and 6% less humidity than the forest, making clear the presence and magnitude of the UHI of the city of Manaus.

In this context, considering that urban areas can significantly modify local scale weather and climate, and that little is known about the behaviour of the UHI in tropical regions, the present work analyses the UHI intensity of Manaus, Brazil, considering a longer period of data, evaluating the differences in temperature and relative humidity between urban area and the forest adjacent to city in order to highlight the UHI phenomenon, and to quantify its intensity.

## 2. Data and methodology

Five surface datasets for different periods were considered in the present study. For the urban area analysis, four datasets that include hourly measures of mean, maximum and minimum temperature, relative humidity, and wind intensity and direction were used. These data were collected at the automatic weather station of the National Institute of Meteorology (INMET) (3.129 °S: 59.948 °W) and in the Ponta Pelada Airport (PP) (3.146 °S: 59.995 °W), for the period 2000–2008. Also, for June 2008 the data were also collected at the automatic weather station of the Eduardo Gomes Airport (EG) (3.033 °S: 60.044 °W) and National Institute for Amazonian Research (INPA) (3.095 °S: 59.989 °W). The stations of INMET, PP and INPA are located in the Manaus urban area and station EG is located in the Manaus suburban area (Figure 1).

A third dataset was obtained from the INPA station, located in a forest area approximately 30 km distant from the urban area (ZF2-K34) (2.610 °S: 60.210 °W). This dataset includes observations every 30 min at six different levels, between 5 and 50 m high, of air temperature and relative humidity for the period 2000–2008, which were organized in order to facilitate comparison with the urban area data. Whereas the first level of observation of temperature (5 m) used in this paper is inserted in the canopy, temperature and wind data collected at 50 m will also be analysed.

Considering that a direct method of investigating the UHI effect is by analysing the difference in meteorological variables, principally temperature and humidity, between a city region and more distant rural areas little affected by the intense urbanization, as noted by Hua *et al*. (2008), in this study data were analysed from the three stations mentioned above. Thus, for a more detailed analysis of the UHI of Manaus, the value of its intensity (UHII) was calculated for the period of 2000–2008, considering the definition also used by Maitelli and Wright (1996), in which the intensity is given by:

$$\mathrm{IICU} = \frac{1}{D}\left[\sum_{d=1}^{d=D}(T_{u,d} - T_{r,d})\right] \quad (1)$$

where $d$ is the day number of the year, $D$ is the number of days, $T_u$ is the temperature in the urban area and $T_r$ is the temperature in the rural area.

## 3. Results and discussion

In the first stage, values of UHII were calculated with relation to the daily values of mean, minimum and maximum temperature and relative humidity observed below the canopy. The monthly means of the UHII for the period of 2000–2008 are shown in Table 1. From the general analysis of the values presented in Table 1 notice that, with relation to the mean surface air temperature, the city was 1.74 °C warmer, with January (September) presenting the lowest (highest) values of UHII (1.41 and 2.12 °C, respectively). The values of UHII for the maximum daily temperature show an even warmer urban area, with observed differences of 2.98 °C between the city and the forest and minimum (maximum) differences during January (October). The same behaviour is observed for the minimum daily temperature, with a difference of 0.84 °C. A seasonal behaviour is still noted from this difference, accompanying the dry and rainy seasons, in agreement with what was previously presented. As highlighted by Murphy *et al*. (2011) and Chow and Roth (2006), during the rainy season, the presence of cloudiness tends to reduce the surface incident solar radiation, decreasing the quantity of heat stored in the urban area. Additionally, the greater soil humidity in forest areas increases the heat storage capacity, which will consequently reduce the temperature difference between the forest and the city.

Wienert and Kuttler (2005) showed that there is a close relationship between the intensity of UHI with latitude, where at low latitudes the average intensity observed is about 4 °C, which increases toward high latitudes with average of about 6.1 °C. The authors explain these variations by the increase of anthropogenic heat in high latitudes and also by the differences in surface energy balance between these regions.

Another important observed characteristic of the formation of the UHI are the differences in the relative humidity between urban and non-urbanized areas. Therefore, relative humidity data were also used for the calculation of the UHII. For the period 2000–2008, it was noted that the city is 1.67% dryer than the forest. During February, in the rainy season, it is observed that the city is 3.44% dryer than the forest area. Liu *et al*. (2008) highlighted that the principal factors that affect the relative humidity distribution in urban areas are the

 

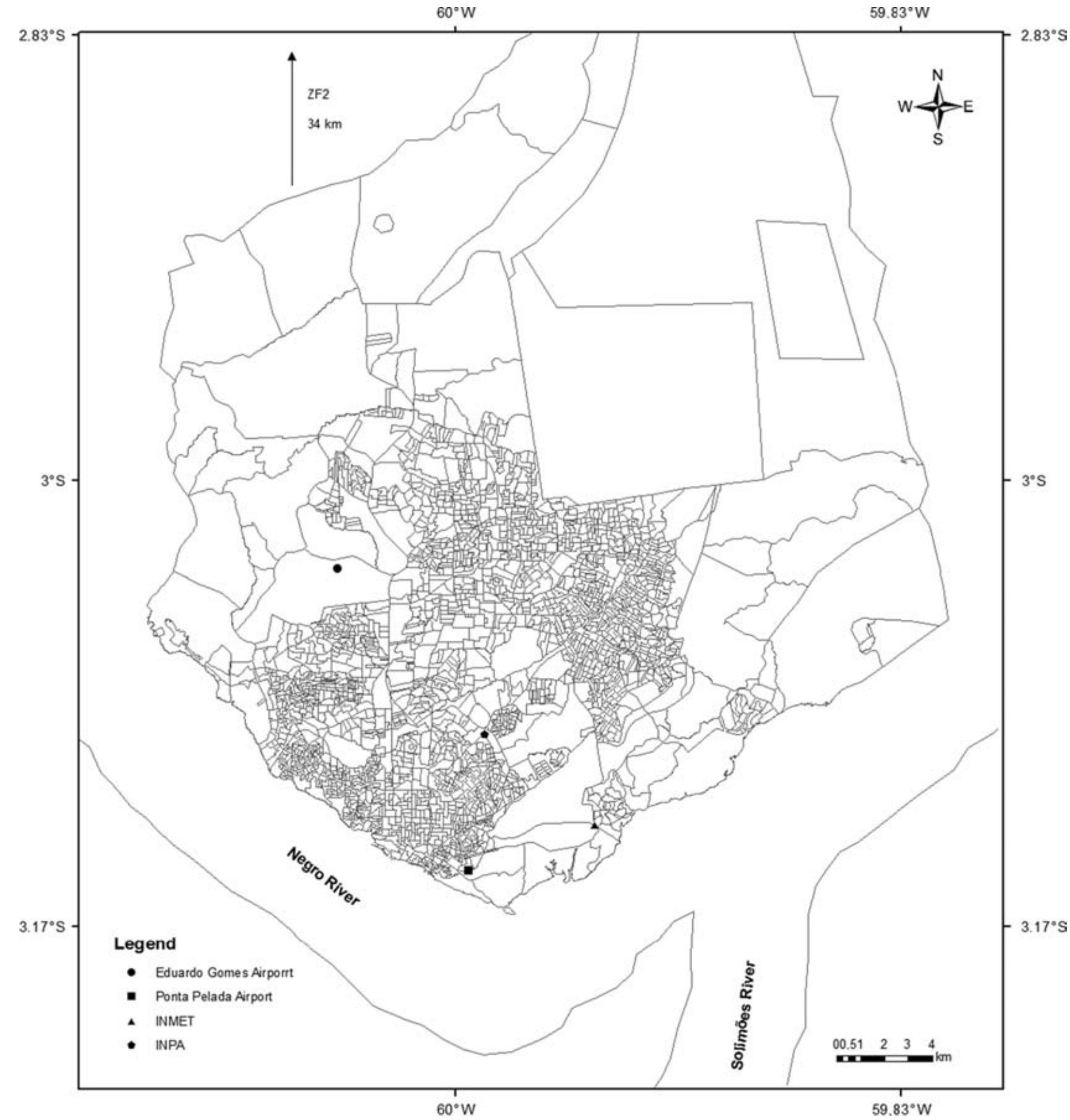


Figure 1. Urban area of Manaus and location of the meteorological stations.

Table 1. Differences between city and forest for mean, minimum and maximum temperature and relative humidity observed in the city of Manaus, Brazil, from 2000 to 2008.

| | $T_{urb} - T_{for}$ (°C) | | | $RH_{urb} - RH_{for}$ (%) |
|---|---|---|---|---|
| | MEAN | MIN | MAX | |
| January | 1.41 | 0.56 | 2.46 | −2.40 |
| February | 1.43 | 0.48 | 2.83 | −3.44 |
| March | 1.52 | 0.62 | 2.67 | −1.75 |
| April | 1.87 | 0.99 | 3.14 | −2.29 |
| May | 1.58 | 0.75 | 2.73 | −3.17 |
| June | 1.99 | 0.75 | 3.22 | −1.23 |
| July | 1.68 | 0.73 | 2.85 | −0.22 |
| August | 1.54 | 0.68 | 2.75 | 1.28 |
| September | 2.12 | 1.27 | 3.28 | −0.49 |
| October | 2.08 | 1.32 | 3.59 | −1.63 |
| November | 1.77 | 0.94 | 2.90 | −2.35 |
| December | 1.93 | 1.05 | 3.36 | −2.38 |
| | 1.74 | 0.84 | 2.98 | −1.67 |

turbulence caused by surface roughness and heating of the urban area, the reduction in evapotranspiration due to land use changes, emission of water vapour from industrial sources and transpiration, and the removal of vapour by precipitation or aerosols. It is worth noting that relative humidity is a variable strongly controlled by air temperature, but it can still contribute significantly to the understanding of processes related to the UHI.

Using the obtained values of differences between temperature and relative humidity, the UHI of Manaus can be identified. With the objective of evaluating in more detail the UHI of Manaus, the temperature and wind diurnal cycles for the city and forest were evaluated for the period 2000–2008 (Figures 2 and 3, respectively). It is observed, for the temperature diurnal cycle in different levels, that the hour of maximum temperature occurs at 1400 Local Standard Time (LST, = UTC – 3 h), at INMET and INPA stations, and at 1500 LST at the PP station, with an average difference between the city and the forest equal to 2.22 °C within the canopy and 1.43 °C for temperature values collected above the canopy. It is noteworthy that the average annual rainfall for the period 2000–2008 (2276.21 mm) was

 

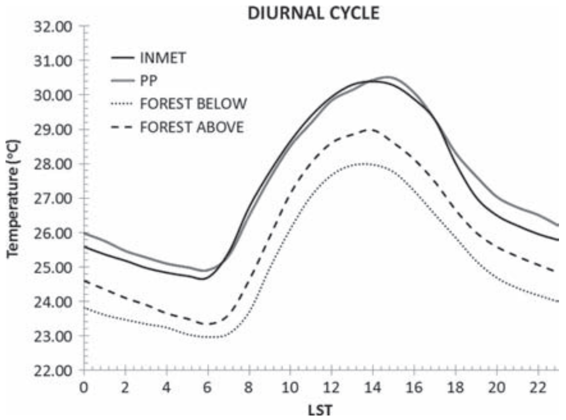


Figure 2. Diurnal cycle of mean temperature observed in urban and Forest area between 2000 and 2008.

almost equal to the historical average calculated by Souza and Alvalá (2010) for the period 1961–2008.

Analysing the behaviour of the wind for the stations in the urban area and the forest it is possible to notice that throughout all day the wind direction is from the southeast, varying in intensity during the day. The varying intensity of the wind in the urban area follows the same pattern as the ones observed for temperature, with maximum intensity at 1300 LST, 1 h before the maximum temperature. For the forest area it is observed that the wind has greater intensity at 1100 LST. The wind directions observed in the present study are in agreement with the study by Kayano (1979) and Oliveira and Fitzjarrald (1993).

Regarding the intensity observed for the urban area, the highest values near the time of greatest surface heating are directly associated with the temperature gradient formed between the urban area and the river, and then the consequent formation of the river breeze, which has seen the predominant southeast orientation river-continent in this region. Authors such as Martilli *et al*. (2003) and Freitas *et al*. (2007) show a direct relationship between the formation and intensification of the UHI with the formation and intensity of local atmospheric circulations, showing the direct relationship between UHII and intensity of the breeze, as well as the weakening of the land breeze during the night due to the presence of the UHI.

To analyse the UHII, an average of both the values observed for the two urban areas was considered. Subsequently, this was compared with measures for the forest areas, above and below the canopy (Figure 4). The observed values of UHII, which are greater than 1 °C (annual mean equal to 2.22 and 1.43 °C for below and above the canopy, respectively), corroborate the existence of the UHI of Manaus during all the day. Also, the presence of two maximum peaks was observed, for both annual cycle and dry and rainy seasons, which can be seen at different times. Thus, Figure 4 shows one peak at 0800 LST in all seasons for data collected below the canopy, as well as the second one observed in the evening, at 1600 LST for the annual mean and dry season, and at 1700 LST during the rainy season. Although the UHII analyses for temperature values above the canopy shows the same peak at 0800 LST for all seasons, there is a difference for the second peak, which occurs at 1600 LST for the annual mean, and at 1500 (1700) LST during the rainy (dry) season.

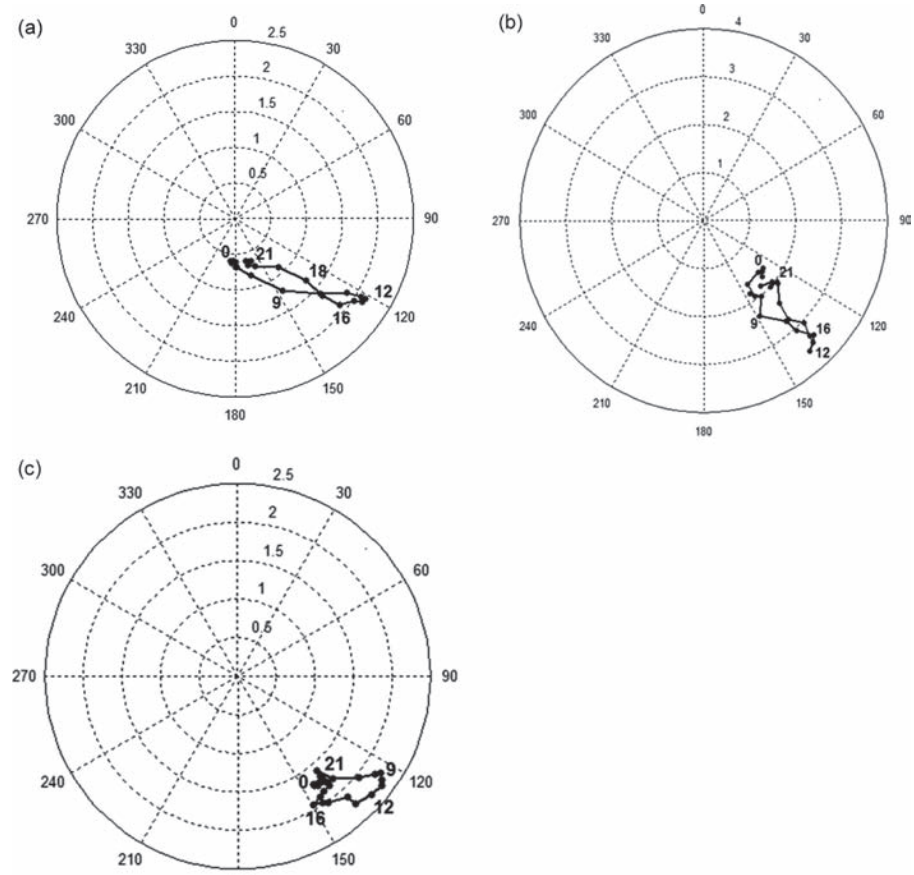


Figure 3. Observed diurnal cycle of the wind in the stations of (a) INMET, (b) PP and (c) ZF2 between 2000 and 2008.

 

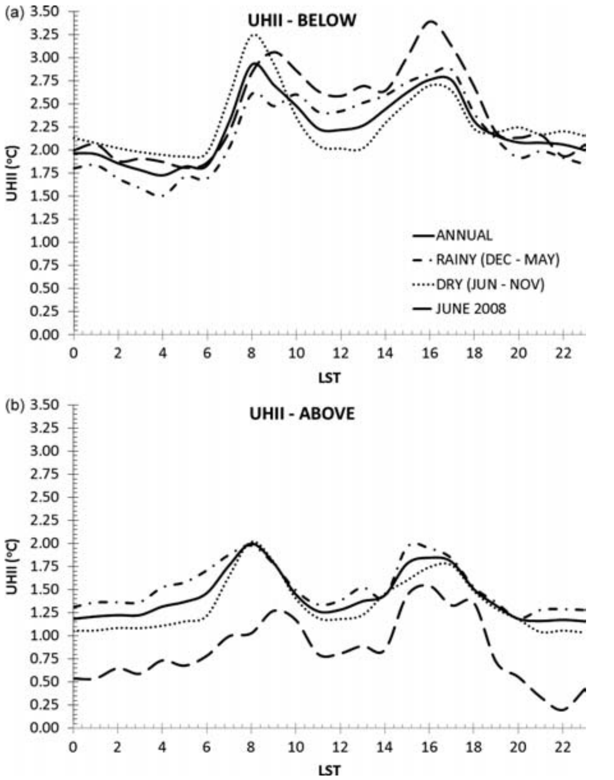


Figure 4. Diurnal cycle of the UHI intensity of Manaus city for the data observed (a) below and (b) above the canopy for the period between 2000 and 2008.

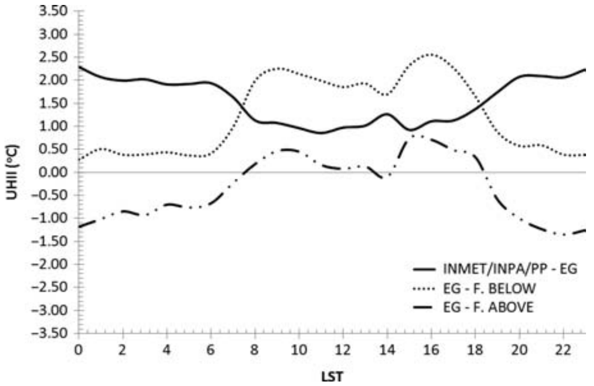


Figure 5. Diurnal cycle of the UHI intensity of Manaus city for the data observed below and above the canopy for the period of June 2008.

The results also show a distinct behaviour for the observed diurnal cycles during the dry and rainy seasons. For both seasons during the period 2000 and 2008, the average intensity of the UHI was 2.27 °C for the layer below and 1.33 °C for the layer above the canopy during the dry season and 2.17 °C for the layer below and 1.53 °C for the layer above the canopy during the rainy season.

Specifically for the observed data above the canopy, it is noted that during both the dry and rainy seasons the highest intensity of the UHI occurs at 0800 LST, whereas for the observed data below the canopy, during the rainy season, the greatest intensity occurs at 1700 LST. The highest observed intensity during the rainy season (1700 LST) is related to the lower temperature in the forest area during this period, principally due to the higher availability of water in the soil, which increases evaporation and evapotranspiration, as well as being directly associated with processes that lead to a cooling of the atmosphere in the forest area. The intense values observed during the dry season, at 0800 LST, are directly related to the energy availability and storage capacity of the urban surface, which heats more rapidly than the adjacent forest at the beginning of the morning.

Whereas for the study of UHII presented earlier only two stations in the urban area were used, a case study was performed for June 2008 using data from the INPA and EG stations. In this context the values of UHII were calculated as the difference between data observed in a densely urban area, the INMET, INPA and PP stations, and data collected at the EG station, a suburban area. The difference between data collected in the EG station and data observed in forested area, ZF2 station, was carried out to investigate the different patterns previously observed.

For June 2008 the UHII was initially calculated with respect to the difference between the average of temperature at the INMET, INPA, PP and EG stations (CITY), and data collected above and below the canopy at the ZF2 station in the forested area (Figure 4). A similar behaviour to that observed for the period of 2000–2008 is noted, with two maxima of intensity, one at 0900 LST and another at 1600 LST. The results of the UHII calculated as the difference between the average of temperature at INMET, PP and INPA stations, and data collected at station EG (Figure 5), also for the period June 2008, show a different behaviour from that observed for the UHII calculated with respect to data observed in the forest, where it is possible to observe that the highest UHII occurs in the night (0000 LST) and the lower intensity occurs at 1100 LST. Analysing the difference between the observed data at EG station and data collected on forest area, below and above the canopy, there is the same pattern observed between the forest and urban area shown in Figure 4, with two very clear maxima at 0900 LST and 1100 LST.

With regard to the study of UHII presented earlier, which only used data from two stations in urban areas, a case study for the month of June 2008 using data from stations INPA and EG was performed. The UHII for this period, was initially calculated with respect to the difference between the average data collected at stations INMET, INPA, PP and EG (CITY), and data collected at the station in the forest (ZF2), above and below the canopy (Figure 4). It is noteworthy that the stations EG and INPA are located in wooded areas and with little urban impact. A similar behaviour to that observed for the period 2000–2008 was noted, with two maxima of intensity, one at 0900 and another at 1600 LST. The results for the UHII on the difference between the average data INMET, PP and INPA, and data collected at the station EG (Figure 5), also for June 2008 show a different behaviour from that observed for the calculated UHII with respect to data observed in the forest, where it is possible to observe that the highest UHII occurs in the evening (0000 LST) and lowest intensity occurs at 1100 LST. Analysing the difference between the observed data at the station and EG collected data at the forest, below and above the canopy, there is the same pattern observed between forest and urban area shown in Figure 4, with two very clear maximum at 0900 and 1100 LST.

Similar to the methodology considered by Lee and Baik (2010), for a better interpretation and understanding of the behaviour of the UHII diurnal cycle for the entire period (2000–2008), the heating/cooling rates for the urban area and forest, above and below the canopy, during the entire annual period and dry and wet seasons were calculated (Figure 6(a)

 

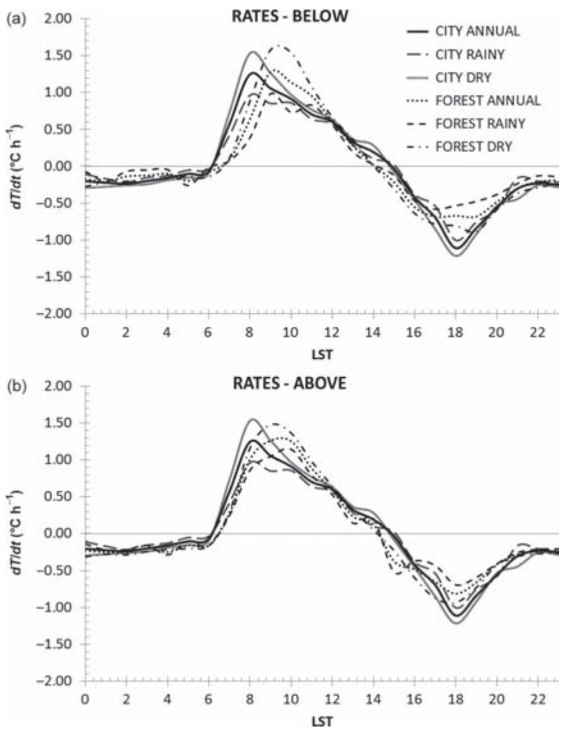


Figure 6. Diurnal cycle of the heating/cooling rates between data observed at a urban area and data observed (a) below and (b) above the canopy for the period from 2000 to 2008.

and (b)). The maximum heating rate is found during the early morning at 0800 LST (1.25 °C h$^{-1}$) for the city, and at 0900 LST for the forest (equal to 1.28 °C h$^{-1}$ below and 1.26 °C h$^{-1}$ above the canopy). On the other hand, the maximum cooling rate for the urban area is found at 1800 LST (−1.25 °C h$^{-1}$), while for the forest region is found at 1700 (1800) h (LST), which value is equal to −0.68 °C h$^{-1}$ (−0.81 °C h$^{-1}$) below (above) the canopy. This behaviour makes it clear that the city begins to warm up earlier and more slowly, and cool down later and more quickly in comparison to the forest, mainly due to urban surface properties, such as albedo, which may explain the two peaks found for the UHII (Figure 4).

Analysing the heating/cooling rate values for the rainy and dry seasons, it is noted that significant differences are observed in the maximum values, both below and above the canopy. For the rainy season, the spread of the maximum heating/cooling rate values between the city and the forest is much lower than the ones observed during the dry season, which leads to a decrease in the intensity of the UHI. The major effect which leads to smaller rates during the rainy season is the decrease of the incident solar radiation due to the presence of cloudiness. Concerning the variability of heating/cooling rates for the urban and forest mentioned above, these differ from the ones observed by Lee and Baik (2010), who found a higher difference between heating and cooling rates for the rural area than for the urban area of Seoul, although the results are similar when compared with those for the rainy and dry seasons. Also, it was found that during the days without rain, the heating and cooling values are less intense for both regions.

The heating/cooling rates for June 2008 (Figure 7) were also calculated for the average temperature calculated at densely urban stations, the data observed at EG and ZF2 station. Initially, it is possible to observe that the rates for the EG station exhibit a characteristic of rural areas, the same pattern

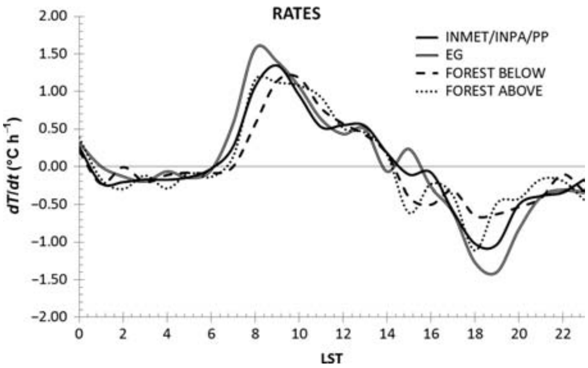


Figure 7. Diurnal cycle of the heating/cooling rates between data observed at a urban area and data observed below and above the canopy for the period of June 2008.

observed in rural stations by Lee and Baik (2010). Note that suburban area heats up faster and earlier than densely urbanized areas, and that these cool at about the same time but with cooling rates higher for suburban area than for the other stations in urban areas. This behaviour makes clear the influence of the urban canopy, primarily related to characteristics such as albedo and emissivity, on the intensity of the UHI of Manaus. Regarding the rates observed in the forest area similar behaviour to that observed for the whole period from 2000 to 2008 is noted.

Considering the pattern observed for UHII in the city of Manaus, there is a different pattern to that observed for other regions of the world where UHI is analysed with respect to adjacent forest. A characteristic UHII pattern is noted in other studies of UHI in relation to densely urbanized areas with suburban areas, as observed by Oke (1987). Studies for other locations around the world, such as Granada, Spain (Montávez *et al.*, 2000) and Seoul, South Korea (Lee and Baik, 2010), have shown the greatest value of UHII occurs during the night time. Maitelli and Wright (1996) and Rodrigues da Silva *et al.* (2009) found a diurnal cycle, with only one peak, near 1400 LST, for the cities of Manaus, State of Amazonas, and Campina Grande, State of Paraiba, which are located in tropical areas of Brazil.

## 4. Conclusions

The characteristics of the urban heat island (UHI) of the city of Manaus, Brazil, from 2000 to 2008, were evaluated from hourly temperature and relative humidity data. The comparisons between the forest and urban areas show clearly the presence of the UHI of Manaus. The urban area of Manaus city was warmer and drier than the adjacent forest during the entire year, with higher and lower intensity during the dry and rainy seasons, respectively. The results show that there are differences in the UHI diurnal cycle of Manaus, and the ones obtained from other studies of UHI. Thus, two peaks of highest intensity were observed, one at 0800 LST and the other between 1500 and 1700 LST. When analysing the UHI intensity with respect to the dense Manaus urban area with the suburban area it is noted that the greatest intensity occurs at night, at 0000 LST, similar to that outlined by Oke (1987), which defines the UHI as a night time phenomenon

It was observed that the urban heat island intensity (UHII) is directly related to the heating and cooling rates observed in the forest and urban areas. It was noted that the city tends to heat first and more slowly and cool later and more rapidly than the forest, following the sunset and sunrise, respectively. The results also showed that the suburban areas of Manaus tend to heat faster and more intensely than densely urbanized areas, a characteristic directly related to albedo and emissivity of the city.

The two maxima of UHII observed for comparisons between urban and forest are possibly related to the forest's energy storage capacity, as highlighted by von Randow *et al*. (2004), since the tropical forest is completely different if compared with the rural areas analysed in the studies mentioned above. Another justification for this pattern could be related to the liberation of heat from automobile and industrial sources, not evaluated in this work.

The results also make clear the influence of the UHI in the intensity and formation of local atmospheric circulations over the study area. It was observed that when the UHI has its maximum with respect to the suburban areas, the wind flow related with the river breeze has less intensity and it isn't possible to observe the formation of the land breeze. The temperature differences between urban and forest areas, as evidenced by UHII calculated for the period 2000–2008, also shows a direct influence on local atmospheric circulations between forest and city.

The obtained results stress the presence of the UHI of Manaus and its influence on the local microclimate. The knowledge of the dynamic characteristics of the atmosphere associated with the formation and presence of the UHI can also help to elucidate and detail this phenomenon, which is still little-studied for tropical regions, principally in densely forested areas. It is noteworthy that a denser observation network in both urban area and its surroundings will allow a better description of the UHI phenomenon, evidenced in this work. However, this paper presents observational results of great value for policies related to urban development, especially with issues related to urban comfort.

In this context, as a continuity of the present work, a modelling study, considering high resolution simulations with a mesoscale meteorological model coupled with an urban canopy scheme, is being implemented, with the objective of studying the physical mechanisms related with the UHI of the city of Manaus, Brazil.

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