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CHANGES IN LAND COVER AND USE AFFECT THE LOCAL AND REGIONAL CLIMATE IN PIRACICABA, BRAZIL

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Abstract: Land use and changes in land cover play an important role in local and regional climatic conditions, especially in tropical regions. Piracicaba, a city in southeastern Brazil, has an economy that is based primarily on sugar cane cultivation. The seasonality of this crop means that there are marked annual fluctuations in land use and cover in this municipality. In this work, we investigated the seasonal variation in urban heat-islands and local climatic variations by using remote sensing data, geographic information system (GIS) and atmospheric modeling. The urban heat-islands were analyzed by using Landsat 7 (Enhanced Thematic Mapper+) images for the sugar cane crop (January to March) and non-crop (August to November) periods, and these images were subsequently converted to land surface brightness temperature. The average temperature in the non-crop period was 3.5°C higher than in the crop period, which suggested that heat-island intensity may be linked to the seasonality of sugar cane cultivation. In order to examine the influence of urban areas on regional temperature changes and heat fluxes, numerical simulations were done with the Brazilian Regional Atmospheric Modeling System (BRAMS). Overall, the results obtained suggested that local and regional climatic dynamics were related to land use and changes in land cover.

Keywords: Climate change; land use and land cover; numerical simulations; sugar cane seasonality; urban heat-islands

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INTRODUCTION

There is a general consensus that anthropogenic activities can significantly change the global climate. Several studies have suggested that human activities such as urbanization, agricultural systems, pollution and desforestation have accelerated important climatic changes (Carnaham *et al.*, 1990; Pratz, 2005).

One of the most discussed effects of urbanization is the increase in local and regional temperature (Perez *et al.*, 2001). On a micro-scale, the most important phenomenon in climatic change is the "urban heat island" (UHI) (Stohlgren *et al.*, 1998). Heat islands are a thermal anomaly in which one location has a higher temperature than another. Thus, in urban areas, there are UHIs in which the air temperature is higher than in rural areas (Pinho *et al.*, 2000; Weng, 2002; Weng *et al.*, 2004). Urban Heat Islands (UHIs) vary in scale and severity among seasons and from year to year (Pinho *et al.*, 2000; Weng, 2000). Several factors can affect the onset and intensity of UHIs, including geographical location, climatic conditions, city area and population, and the size of green areas (Kalnay *et al.*, 2003; Kim *et al.*, 2005).

The phenomenon of UHI has been studied for decades and it is now known that urban land cover and use affect the overall energy balance in a city (Voogt *et al.*, 1997; Pinho *et al.*, 2000). Thus, Lu *et al.* (2005) reported a significant difference in temperature between green areas and other regions of a city. Urban Heat Island (UHI) studies have traditionally linked city land cover and use to its temperatures. While this is generally true for large cities (Carnaham *et al.*, 1990), the extent of land cover and use in areas surrounding medium size and small cities can also greatly affect the heat island. For example, small and medium size cities in desert areas usually generate cold UHIs (Garcia-Cueto *et al.*, 2007).

Thermal infrared data have been used to measure the surface temperature over larger areas (Lu *et al.*, 2005). These studies suggest that urban areas affect heat flux and, consequently, temperature. However, studies of meso-scale climates support the existence of strong perturbation in thermal emittance in urban areas (Chen *et al.*, 2006; Garcia-Cueto *et al.*, 2007), which suggests that urban areas can directly affect regional temperature (Lu *et al.*, 2005).

Piracicaba, a medium size city located in southeastern Brazil, has an economy based primarily on sugar cane cultivation. During the crop period, the rural area is completely devoted to sugar cane cultivation and creates a large green belt around the city. However, in the inter-crop period, the rural area is transformed into bare soil and results in a drastic shift in land cover and use. In fact, this bare area may act as a desert around the city in inter-crop periods, thereby affecting the energy balance in rural and urban areas.

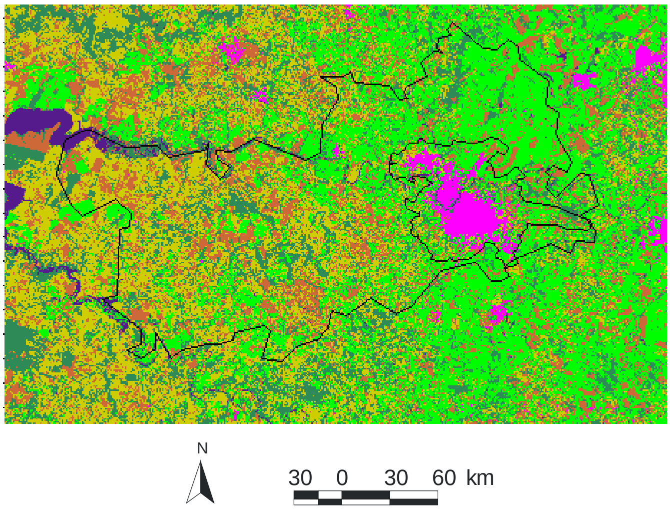

Fig. 1 Composite image of land use in Piracicaba. The urban area is in pink (6%), the sugar cane crop is in green, grasslands are in brown and cerrado (savanna) in dark green. The larger area enclosed by the black line represents the city limit whereas the smaller area represents the official urban area.

The aim of this study was to investigate the consequences of major changes in land cover and use on the local and regional climate of Piracicaba, and to relate the dynamics of sugar cane cultivation to the morphology, seasonality and intensity of UHIs, in addition to analyzing the changes in land cover by using the Brazilian Regional Atmospheric Modeling System (BRAMS).

METODOLOGY

Study Area

Piracicaba is a tropical, medium size city (356,000 inhabitants) located 47º38' W, 22º42' S in São Paulo state, southeastern Brazil. The urban area represents 6% of the total municipality and accounts for more than 90% of the population (**Fig. 1**). The city's climate is classified as "tropical humid", with a dry period in the austral winter. The average temperature of the warmest month is > 22ºC and in the colder month it is < 18ºC. Meteorologically, frontal systems and the South Atlantic Convergence Zone (Kodama, 1992) prevail during the summer whereas cold fronts are common during the winter. The economic activity is based on sugar cane and, in the crop period, more than 46% of the city's area is used to grow sugar cane (**Fig. 1**). However, in the inter-crop period, this percentage decreases to 13%. Sugar cane is harvested during the inter-crop period and around 39% of the area is dominated by bare soil. The inter-crop period normally occurs during the dry season.

ETM+ Images

We analyzed the Landsat Enhanced Thematic Mapper Plus (ETM+) image (Row/Path: 220/76) for representative days of each season: 8 January 2003 (austral summer), 13 May 2002 (austral fall), 17 August

2002 (austral winter) and 29 November 1999 (austral spring). These days were characterized by stable atmospheric conditions with clear skies. The Landsat images were rectified using the software ENVI 4.0 and the data was resampled by using the nearest neighbor algorithm for all bands, including the thermal band. The resulting RMSE (root mean square error) was < 0.5 pixel. The higher-resolution aerial photographs used were also rectified and resampled with the ERDAS IMAGINE 8.5 software.

We initially identified the primary land uses by using an official map. The following categories were selected (a) urban area, (b) sugar cane area, (c) bare soil, (d) forestry area, (e) water (rivers) and (f) grass. Satellites Bands 3, 4 and 5 were then classified using the "supervised classification" method of software ENVI 4.0. We used the algorithm Maximum Likelihood Classification (MAXVER) to classify the images. The ETM+ thermal band gray levels were subsequently transformed into land brightness surface temperatures (LST) by using the software IDRISI 3.2 (Coltri, 2006).

In order to describe the UHI morphology, we first detected UHIs based on the thermal band images, i.e., pixels where the surface temperature was greater than the surrounding areas. We then chose the UHIs with the ten highest and ten lowest temperatures to investigate whether land cover could intensify the phenomenon. Thereafter, high-resolution aerial photos were used to describe the UHI morphology and search for urban structures that could enhance a heat island.

The influence of seasonality was assessed by first identifying all of the UHI quarters of all seasons and then computing the temperature difference between the rural and urban areas (referred to hereafter as *Tr-u*) (**Eq. 1**):

$$Tr\text{-}u = TUHI_{urban} - T_{rural} \quad (1)$$

where $TUHI_{urban}$ is the warmest UHI in the city and T_{rural} is the coldest place in the rural area, in ºC.

Mesoscale Model and Simulation Setup

The regional model used in this study was Brazilian Regional Atmospheric Modeling System (BRAMS, http://www.cptec.inpe.br/brams) which is a new version of the RAMS (Maréca *et al.*, 2006) adapted for the tropics, and it is a multipurpose numerical prediction model designed to simulate the atmospheric circulation spanning from hemispheric scales down to large eddy simulations of the planetary boundary layer. Among the additional possibilities of BRAMS compared to RAMS version 5.04 are the ensemble version of shallow cumulus and deep convection parameterization (Maréca *et al.*, 2006; Gevard *et al.*, 2006), new 1 km vegetation data for South America, a heterogeneous soil moisture assimilation procedure (Artaxo *et al.*, 2001) and SIB2.5 surface parameterization.

A BRAMS simulation was done to analyze the impact of urbanization on air temperature (*tempc*) and sensible (*h*) and latent (*le*) heat fluxes. The calculation of air temperature requires knowledge of the ratio between heat fluxes (Rosolem, 2005). The Bowen ratio, which reflects the ratio of energy fluxes from one medium to another by sensible and latent heat, respectively, varies between urban and rural areas. The latent heat flux, which represents the energy related to water evaporation and sensible heat, is directly related to the heating surface. The temperature pattern reflects the behavior of this Bowen ratio. In urban areas (or where there is bare soil or deforestation) the water deficit increases as the soil dries and this leads to a decrease in the latent heat fluxes (Rosolem, 2005).

For a simulation, two types of land cover and land use were chosen. In the first case, a natural scenario covered with primary vegetation was used, with two types of land use being considered, namely, a savanna-like vegetation classified as mixed woodland, and water. In the second case, an urban area was used as the natural scenario. The difference between these two simulations allowed us to estimate the influence of the urban area on temperature and heat flux on a meso-scale. Three periods and their corresponding average atmospheric variables were defined:

1. Daytime – from 12:00 to 18:00 h (local time)
2. Night-time – from 00:00 to 06:00 h (local time)
3. All periods.

BRAMS can also be used to generate different classifications of land use in the same cell; this can be helpful in assessing the interaction between the type of land use and the overlying atmospheric column (Artaxo, 2005). In this study, the analyses were done using the 2 meter air temperature (2*mtempc*).

RESULTS AND DISCUSSION

UHI Analyses

The warmest UHIs in the summer were observed in areas where there were large buildings and no green areas. Typically, these UHIs were characterized by the presence of asphalt and cement roof tiles, both of which are usually associated with UHI formation (Lombardo, 1985; Ichinose *et al.*, 1999). There was a positive correlation between the amount of asphalt and number of buildings and the increase in local temperature (Oke, 1979; Weng, 2005). The cement roof tiles have a high reflectance that affects the overall energy balance and results in a positive relationship with the increase in temperature (Ichinose *et al.*, 1999). In contrast, urban blocks with green areas had UHIs with lower temperatures (Oke, 1979), probably because trees and vegetation can cool the air by absorbing water through their roots and evaporating it through leaf pores. This process uses heat from the air to convert water contained in the vegetation into water vapor.

Evapotranspiration alone can account for reductions of 1−5ºC in the summer peak temperatures (Macpherson & Person, 2002). Although this process adds moisture to the air, the cooling effect of vegetation usually outweighs any undesirable gain in humidity.

The average temperatures of the ten warmest and ten coldest UHI block were 36.2 and 31.3ºC, respectively. The difference between the warmest and coldest block was 4.85ºC. The thermal amplitude in the city was 10ºC. Similar results have been reported for larger cities such as São Paulo (Lombardo, 1985) and Beijing (Lu *et al.*, 2005). However, the Piracicaba UHI profile did not follow the traditional UHI profile in which downtown is generally warmer than surrounding areas. This difference may reflect the existence of a large river and a large green area in the downtown region of Piracicaba. The river and green area cause an oasis effect that reduces the downtown air temperatures.

Based on the thermal infrared images, the following average temperatures were estimated for seasonal UHIs: 37.2ºC (spring), 33.4ºC (summer), 21.4ºC (fall) and 24.7ºC (winter). Thus, the spring UHI was, on average, 3.8ºC hotter than the summer UHI. Interestingly, the winter UHI was 3.3ºC higher than the fall UHI. These results can be explained by the seasonality of sugarcane cultivation. Indeed, UHIs in the sugar cane crop period were, on average, 3.5ºC colder than those in the intercrop periods (**Fig. 2**).

This result can be explained by the extent of rural land cover since in the intercrop period a large portion of the rural area is bare soil (**Fig. 1**). In the winter image, 34% of the city's area was classified as bare soil, whereas 15% of the city was bare soil during this season. In the spring 39% of the city was bare soil, whereas the proportion of bare soil declined to 20% in the summer. In the crop period (summer and fall), more than 31% of the total area was covered with sugar cane, whereas in the intercrop periods, the corresponding values were 22 and 12% in the winter and spring, respectively. In medium and small cities, the climate surrounding the city directly influences the microclimate of the urban area and, consequently, the UHIs (Chen *et al.*, 2006; Garcia-Cueto *et al.*, 2007); the pattern seen in Piracicaba fits this model. In the intercrop period, a large proportion of the rural area is bare soil. In this case, the albedo is different than that of land covered by sugar cane and the energy balance is disturbed. As a result, the soil thermal inertia is modified and the sensible heat flux that emerges from the ground intensifies the atmospheric heating. This heat is advected by wind to urban areas and the new heat flux heats the city. The heat flux differs between bare and vegetated soil (Pielke *et al.*, 1990), possibly because the latter constrains the increase in the surface and air temperatures, thereby balancing the energy that enters and exits the system. In some situations, this heat flux is modified in the rural area

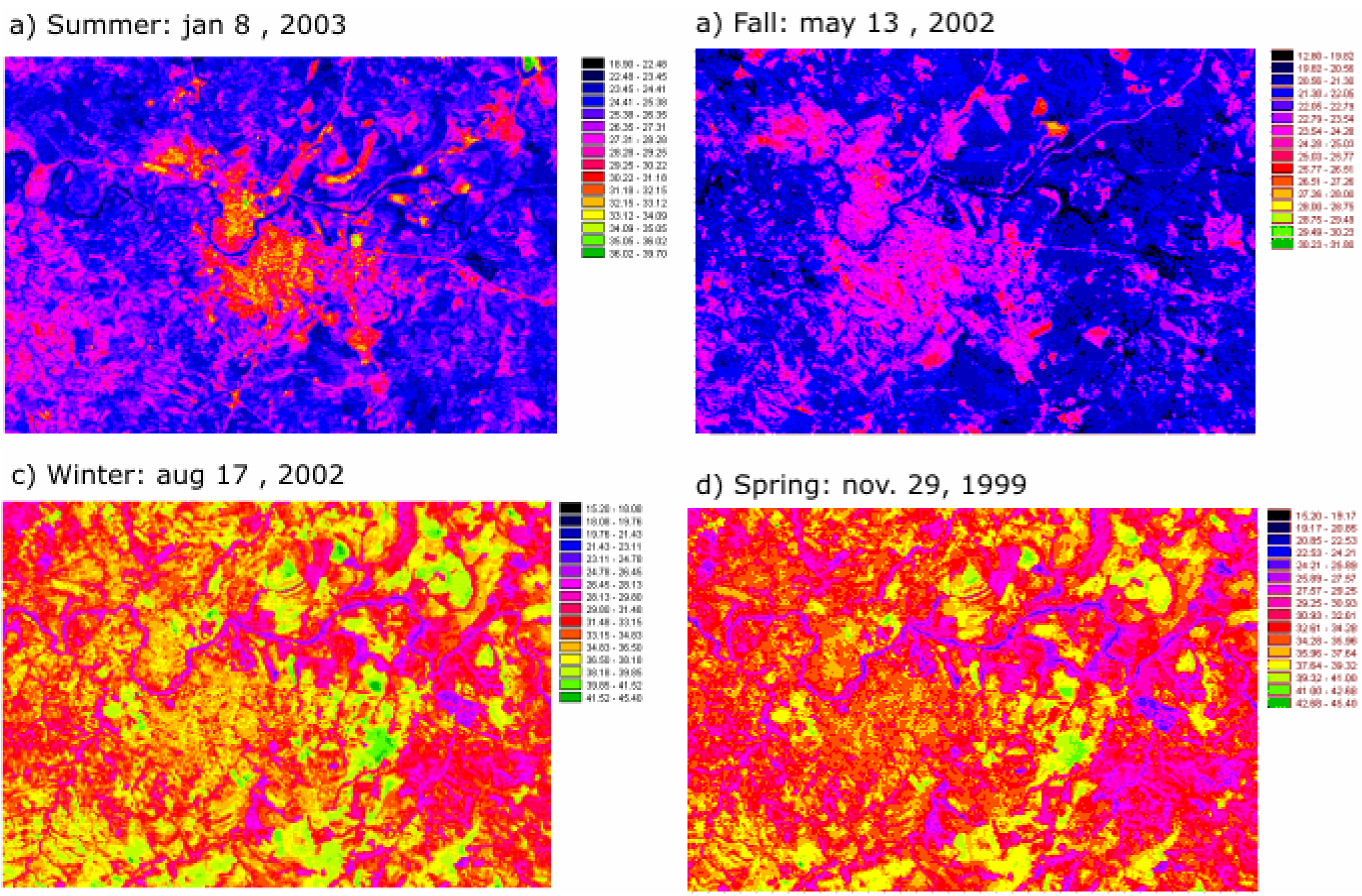

Fig. 2 Brightness temperature (°C) derived from LANDSAT Band 6. (a) summer, (b) fall, (c) winter and (d) spring. The blue colors represent cold temperatures and the yellow, green and red colors represent warm temperatures.

so that the city becomes colder than the surrounding, as in the case of desert cities (Jaregui, 1997; Garcia-Cueto *et al.*, 2007).

The seasonal differences in temperature between rural and urban UHIs were 16.8ºC in the summer, 4.4ºC in the fall, 9.2ºC in the winter and 13.8ºC in the spring. The temperature difference in the summer was higher than in other studies (Stohlgren *et al.*, 1998; Chen *et al.*, 2006; Pinho *et al.*, 2000; Kim *et al.*, 2005), whereas the fall temperature difference was lower than reported for other urban areas (Lombardo, 1985).

The difference in the intercrop period (spring and winter) was also lower than in the summer, probably because the rural area became warmer than the urban area. In the fall, the combination of meteorological conditions (colder temperatures) and the fact that the rural areas were almost totally covered by sugar cane explained why the UHIs were less intense. In contrast, the temperature differences were usually greater during the summer, when the sky in Piracicaba is generally clear and the days are very warm.

Simulation Analyses - BRAMS

Figure 3a shows the differences in sensible heat flux (*h*) for urban and non-urban areas. The average *h* in the non-urban area was 45 w/m², whereas in the urban area this average value increased to 80 w/m². The difference between the two simulations indicated an increase of 35–45 w/m² in the urban area, with a corresponding increase (15 w/m²) in the surrounding city. The increase in heat flux can be explained by the impermeable soil and lack of evapotranspiration in the urban area (Rosolem, 2005). At night-time, the decrease in *h* in the urban area was small (-1 w/m²) and not enough to affect the overall mean *h*. At night, radiation is lower and *h* generally decreases. Similar values were found in deforested areas that showed behavior comparable to that of urban areas (Rosolem, 2005).

This behavior reflects the influence of various factors in the regional climate, such as a decrease in the amount of cloud cover and, consequently, a decrease in rainfall (Ichinose *et al.*, 1999). Urban areas normally experience localized rainfall caused by UHI rather than regional rainfall that affects the vegetation, local agriculture and population (Lombardo, 1985; Ichinose *et al.*, 1999).

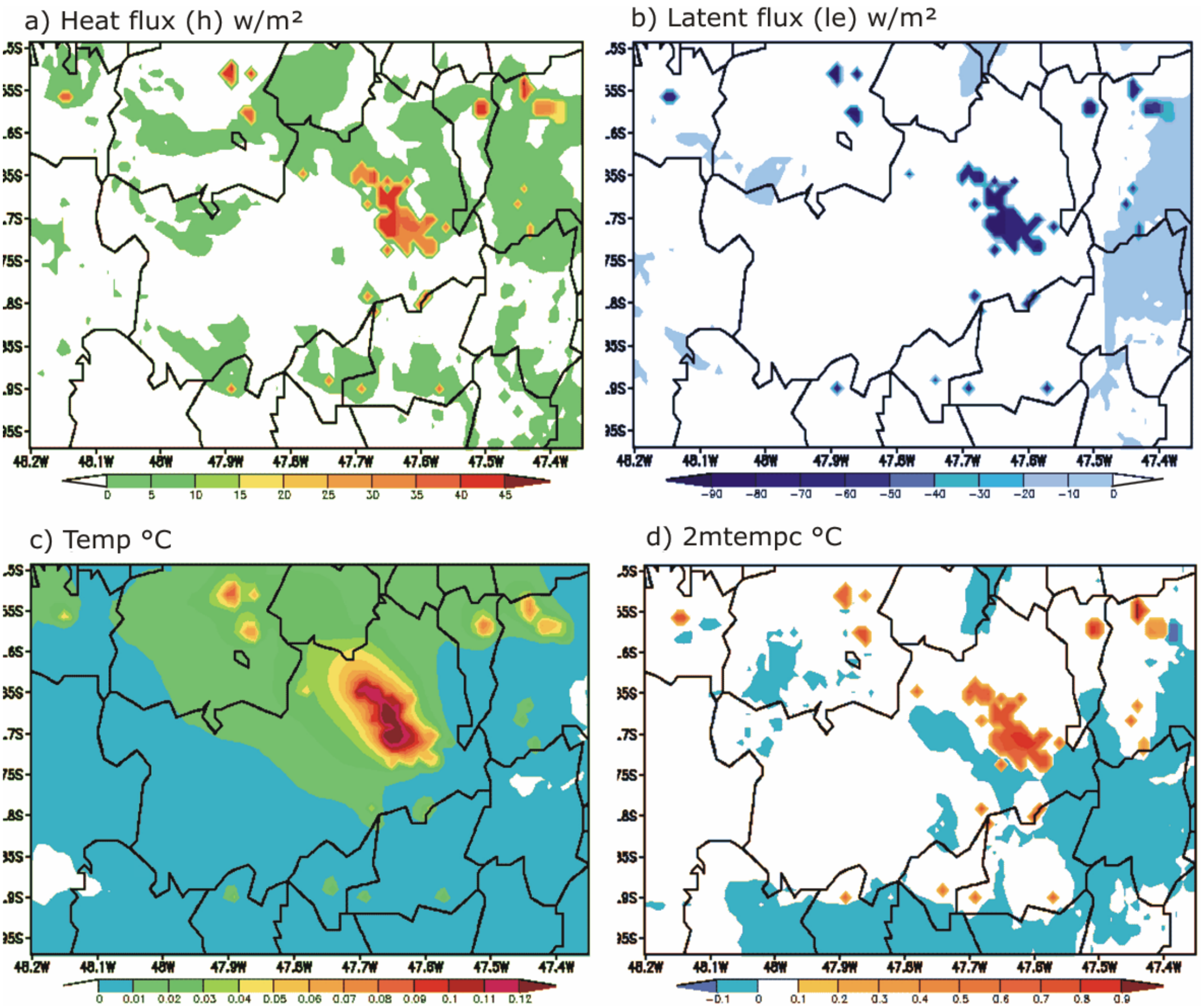

Fig. 3 Comparison of urban and non-urban simulations. (a) sensible heat flux (*h*), (b) latent heat flux (*le*), (c) temperature 48 m (*tempc*) and (d) temperature 2 m (2*mtempc*). Red colors indicate high values and blue colors indicate low values.

In Piracicaba, the intercrop period may worsen this scenario because the rural land cover during this period consists mainly of bare soil that behaves similarly to urban areas by reducing rainfall and soil humidity, and increasing the local and regional temperatures.

Figure 3b shows the difference in latent heat flux (*le*) between the two simulations; there was a decrease in latent heat flux during the periods studied (day, night and all periods). In the urban area, a decrease in the latent heat flux was related to the presence of mixed woodland. The urban area spatial distribution was < -60 w/m², and the mixed woodland value was 150 w/m². Rosolem (2005) suggested that, as with the increase in the sensible heat flux, a decrease in the latent heat flux can disrupt the Bowen ratio (*B*). Drastic changes in land cover and use can alter the pattern of heat flux within the perturbed areas (**Fig. 2**). Consequently, in large urban centers, the temperature within the city (downtown) is often higher than in the surrounding areas (Ichinose *et al.*, 1999). In addition, pollution in urban areas can also modify the Bowen ratio, in contrast to rural areas of bare soil where this factor is less important (Rosolem, 2005).

There was an increase in ground temperature when mixed woodland was replaced by urban areas (based on temperatures 48 m above ground) (**Fig. 3c**). The mean daily temperature rose by 0.5ºC in the urban area, with the effect being greatest in the afternoon, at the time of the maximum daily temperature (15:00 h local time), and weaker near the minimum daily temperature (06:00 h local time). In the afternoon, there was a marked decrease in *le* and an increase in *h* that created a dry, hot atmosphere (when compared with the morning period). This explains why the most important temperature changes occurred during the daytime. The temperature increase in the surrounding urban area was insignificant. This same pattern was reported for bare soil after deforestation by fire (Rosolem, 2005), indicating that a deforestation-like phenomenon also occurs in urban areas. In Piracicaba, this pattern is particularly relevant since sugar cane is harvested by using fire and the resulting soil behaves as typical deforestation soil (Maule *et al.*, 2001). These results indicate that the temperature pattern of the whole region is modified during the intercrop period. This situation is aggravated by the pollution generated by burning, which increases the air temperature even more.

Finally, the analysis of air temperatures 2 m above ground (**Fig. 3d**) showed that the temperature increase was greater than at 48 m above ground, although the pattern of changes was similar to the latter.

Figure 3 shows that during the entire period the temperatures 2 m above ground increased by 0.5–0.9ºC while the increase in the urban area was 0.9ºC. These results corroborate other findings presented above and explain the higher UHI values during the intercrop period in Piracicaba.

CONCLUSION

The results described here indicated that urban areas can affect micro- and meso-scale climates, with urbanization generally leading to an increase in temperature. On a micro-scale, urban area temperatures were higher than in rural areas throughout the year. However, the air temperature was affected by urban areas and by the surrounding land cover. The UHIs were more intense during the sugar cane intercrop period, when bare soil predominated around the city and affected heat fluxes. As a result, heat was transported to urban areas, with a resulting increase in UHI intensity. The temperature in urban areas also increased on a meso-scale. The numerical simulations showed that in urban areas the regional air temperature 48 m above ground increased by 0.12ºC, whereas 2 m above ground the air temperature was more disturbed and increased by 0.5–0.9ºC. Together, these results show that the effects of urbanization on local and regional climate are modulated by the land cover and use.

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