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Special Edition

Comparative study of energy balance in urban and forest areas in Central Amazonia

Estudo comparativo do balanço de energia em área urbana e florestal na Amazônia Central

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ABSTRACT

Data from two experimental sites in central Amazonia were used, one located in a forested region and the other in an urban region. The values of the radiation and energy balance components were measured at both sites. The observed components of the radiation balance in the forest, and urban areas were quite different. The city, the radiative (albedo and emissivity) and thermal (absorptivity) parameters of the surface produced greater reflection of solar radiation and emission of longwave radiation. Urban pollution reduced the incident solar radiation and increased the longwave radiation emitted by the atmosphere. The energy balance presented marked differences in the partition between sensible and latent heat flux between forest and city. In the forest, much of the available energy is converted into latent heat flux, due to the process of evapotranspiration. Whereas, in the city, energy is equally divided into sensible and latent heat fluxes.

Keywords: Energy balance; Turbulent fluxes; Urbanization

RESUMO

Foram usados dados de dois sítios experimentais na Amazônia central, sendo um deles localizado em região florestada e o outro em região urbana. Mediu-se os valores das componentes dos balanços de radiação e de energia em ambos os sítios. Observou-se que os componentes do balanço de radiação foram bastante diferentes quando comparados à floresta e ao Urbano. Acima da cidade os parâmetros radiativo (albedo e emissividade) e térmico (absortividade) da superfície produziram maiores reflexões da radiação solar e emissão da radiação de ondas longas. A poluição urbana favoreceu a redução da radiação solar incidente e o aumento da radiação de ondas longas emitidas pela atmosfera. O balanço de energia revelou diferenças acentuadas na partição entre o fluxo de calor sensível e latente entre a floresta e a cidade. Na floresta, grande parte da energia disponível é convertida em fluxo de calor latente, devido ao processo de evapotranspiração. Enquanto, na cidade, a energia é igualmente dividida em fluxos de calor sensível e latente.

Palavras-chave: Balanço de energia; Fluxos turbulentos; Urbanização

1 INTRODUCTION

Urbanization drastically modifies the radiative, thermal, hydrological, and aerodynamic properties of the surface (Roth, 2000; Oke *et al*., 2017). This modification directly affects the surface-atmosphere processes, resulting in complex and poorly understood microclimates, mainly due to the heterogeneity of urban surfaces (Barlow, 2014). The urbanization process conditions change the surface installing structures that retain more heat and contribute to local heating, which due to the effects of the thermal properties of materials, industrialization, and paved surfaces (Ayoade, 1986). Consequently, the phenomenon of the Urban Heat Island (UHI) occurs at the local scale, given by the anomalous warming in the urban area compared to rural areas (Oke *et al*., 2017).

Over the past four decades, the urban expansion of the city of Manaus (Central Amazon) has already caused changes in the local climate. Phenomena linked to urbanization, such as the UHI effect from surface heating (Carvalho *et al*., 2013) and air temperature (Souza; Alvalá, 2014), have already been verified. The impacts are already being felt in thermal comfort (Silva Junior *et al*., 2012) and in the wind circulation associated with the city-river temperature gradient (Souza *et al*., 2016).

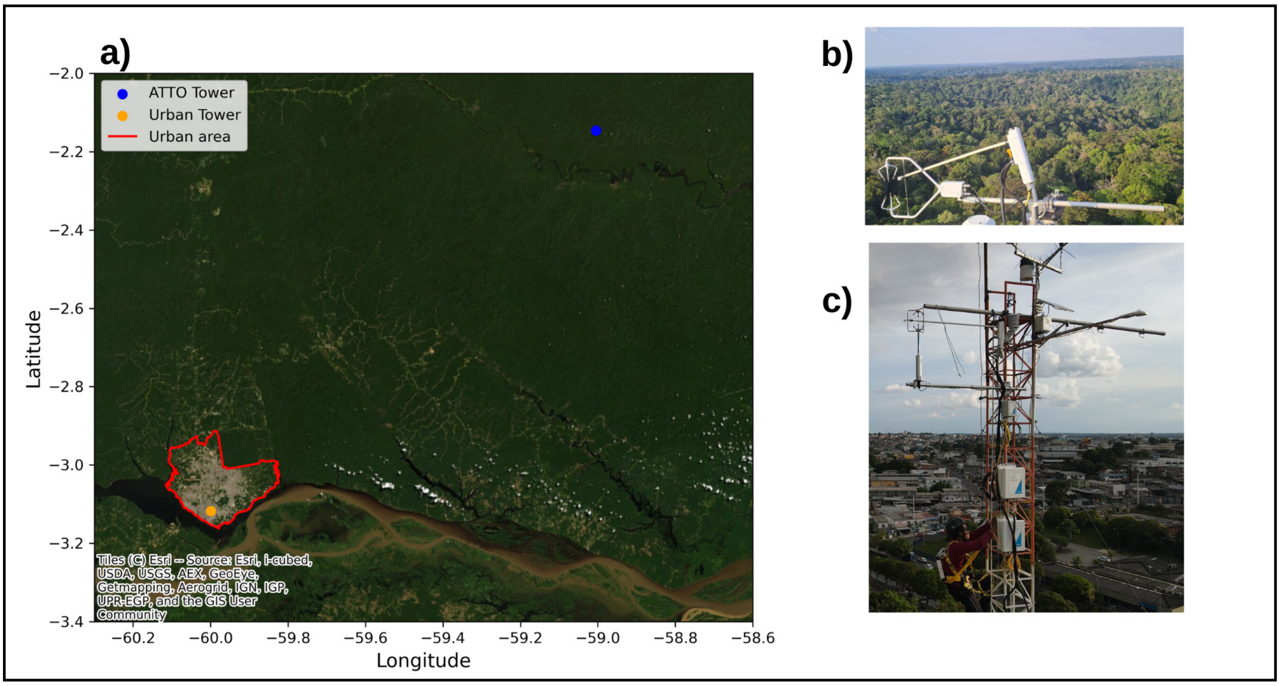
Studying changes in physical processes, such as energy balance in environments close to expanding cities, is relevant to understand the impacts on changes in land cover and to improve management of urban environments. Little is known about how a large urban area within the largest tropical forest interacts with actual climate change. Additionally, it is important to understand whether the forest is capable of mitigating local-scale phenomena, such as the Urban Heat Island effect. The present study aims to compare the radiation and energy balances of a forest region and an urban area in central Amazonia.

2 MATERIALS AND METHODS

The experimental sites were the Amazon Tall Tower Observatory (ATTO), in a region characteristic of Amazon rainforest, and the urban micrometeorological tower (Urban Tower) in the city of Manaus, Amazonas, both located in the central region of the Amazon. The urban micrometeorological monitoring in Manaus is in an area with high residential intensity in the urban region of Manaus (Figure 1c), located in the Petrópolis neighborhood, in the central-southern zone. The region has about 97% of built materials (asphalt, concrete, and industry) and only 3% of permeable areas (natural area and water bodies). The micrometeorological monitoring in the forest uses data from the Instant Tower (2° 08.64’S, 58° 59.99’W) of the ATTO project - (more information from the experimental site is described in Andreae *et al*. (2015)).

- **Instant Tower**: Data from the 3D sonic anemometer (Campbell Scientific CSAT3) and the water vapor analyzer (LICOR LI-7200RS) at the 80 m level were used.
- **Urban Tower**: The measurements used were from the 30 m level, consisting of a closed-path water vapor and carbon dioxide analyzer (LICOR LI-7200RS) and a 3D sonic anemometer (Gill Windmaster 3D)

Figure 1 – Location of the experimental sites



Source: Authors (2023)

Caption: Manaus urban area outlined in red and location of the experimental sites ATTO (blue dot and figure b) and urban (orange dot and figure c)

2.1 Estimation of turbulent fluxes

The turbulent fluxes of sensible heat and water vapor were determined using the Eddy Covariance technique (Moncrieff *et al*., 1997). High-frequency (10 Hz) turbulence measurements of vertical wind speed, temperature, and humidity were used to calculate the correlation between vertical velocity and atmospheric scalar variables of interest. Sensible and latent heat fluxes were calculated with EddyPro (LiCor 7.0.9) at 30-minute intervals. Common data processing and correction steps were applied to ensure the quality of the results [e.g., data with spikes (Aubinet *et al*., 2012) and data with the low-quality flag (2) were removed].

The analyzed data covers the period from October 26, 2021 to December 31, 2021. The observation period corresponds to the end of the dry season and the beginning of the rainy season and is characterized by a “La Niña” year, with above-normal precipitation patterns during these months. This behavior influences the data quality as well as the flux estimation.

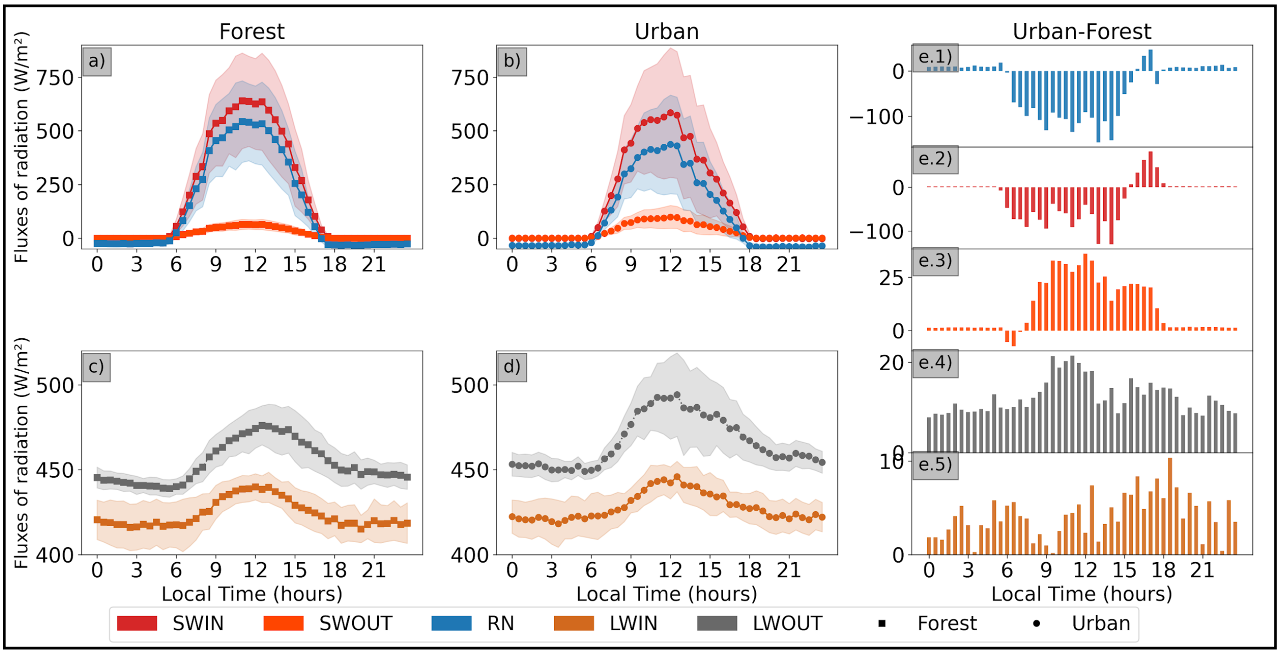
3 RESULTS

Figure 2 shows the average diurnal cycle of the radiation balance components for a forested and urbanized area. Slightly different values and behaviors were identified in the shortwave (SWIN and SWOUT) and longwave (LWIN and LWOUT) radiation components of the experiment sites. The curves of the average daily cycle of shortwave radiation components were smooth in the forest environment, while in the urban environment, there was an abrupt decrease in SWIN in the urban area at 13 LT (Local Time). The incident solar radiation was higher in the forest with a negative difference of up to 100 Wm^{-2} (Figure 2 e.2) and a positive difference for the reflected solar radiation (Figure 2 e.3), indicating greater reflection of solar radiation in the urban area.

The longwave components presented quite similar characteristics for forest and city surface. The hourly values of LWIN (Figures 2c and 2d) were similar between the sites. However, they were higher in the urban area, with daily maximums of 445 Wm^{-2} and 439 Wm^{-2} for urban and forest, respectively. The differences were more significant in the LWOUT component, with higher magnitudes in the urban area (maximum of 490 Wm^{-2}) than the forest (maximum of 475 Wm^{-2}) at 12 LT. Positive differences were observed in both LWIN and LWOUT components throughout the diurnal cycle (Figure e.4 and Figure e.5), indicating that the city modifies the radiation balance significantly in the longwave components.

The main differences in the values of the radiation components between the investigated environments may be associated with the different physical parameters (radiative and thermal) of the urban and forested surfaces. The higher albedo (not shown here) of the urban surface seems to result in greater reflection of solar radiation. The longwave radiation emitted by the urban surface is due to the combination of materials with high absorption capacity and surface emissivity. In addition, atmospheric pollution in the urban region helps increase in atmospheric longwave radiation and reduce the incident solar radiation (Nascimento *et al*., 2021), resulting in a lower radiation balance over the urban area.

Figure 2 – Daily mean cycle of radiation balance in Forested and Urban areas



Source: Authors (2023)

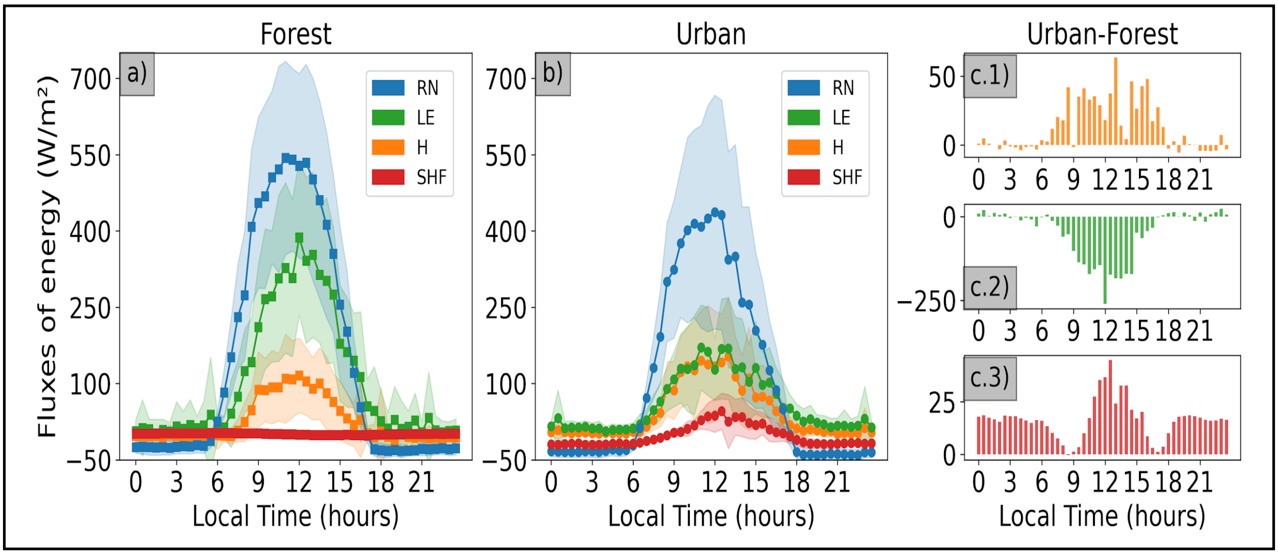
Caption: The incident shortwave radiation (Swin), reflected shortwave radiation (Swout), and net radiation (Rn) are shown in the upper panels (a and b). The incident longwave radiation (Lwin) and emitted longwave radiation (Lwout) are shown in the lower panels (c and d). The differences (Urban - Forest) of each component are illustrated in panel (e)

The daily mean cycles of energy balance components for the studied locations are presented in Figure 3. In the forest, the latent heat flux (LE) reaches a maximum of ~400 Wm^{-2}, while in the urban area, the maximum was only ~150 Wm^{-2}, both recorded at 12 LT. The behavior of the sensible heat flux was similar in both environments, with higher magnitudes in the city. The difference in heat fluxes between urban and forest was negative for LE (maximum of 200 Wm^{-2}, Figure 3 c.2) and positive for H (maximum of 50 Wm^{-2}, Figure 3 c.1). The soil heat flux (SHF) had higher magnitude in the urban area, with positive differences throughout the daily period (Figure 3 c.3).

It is well known that in the forest, most of the available energy is converted into latent heat flux, related to the process of evapotranspiration (Von Randow *et al*., 2004). In the city, energy was equally partitioned between sensible and latent heat fluxes for most of the day, but the curves diverged in the afternoon (14 LT) until sunset (18 LT), which demonstrated the dominance of latent heat in the radiation balance partitioning.

The sensible heat flux and soil heat flux were higher in the city, while the latent heat flux was higher in the forest. Differences were concentrated during the daytime. At night, anomalies were insignificant, except for SHF, due to the heat storage capacity of building materials in the city. The partitioning of available energy in the city was strongly modulated by the presence of outdoor water, according to precipitation events, soil moisture conditions, and possibly horizontal moisture transport.

Figure 3 – Daily average energy balance cycles for Forest (a) and Urban (b)



Source: Authors (2023)

Caption: The components of energy balance (RN), latent heat flux (LE), sensible heat (H), and soil heat flux (SFH) are represented by the colors blue, green, orange, and red, respectively. Anomalies of energy balance components are shown as bars in figure (c).

4 CONCLUSION

The main focus of the study was to analyze the radiation and energy balance over the city and the forest, comparing how the fluxes are modified and modulated from well-known forest patterns. The meteorological conditions were similar between the sites, and observed differences are attributed to the vegetation cover of the ground, because the city surface is impermeable. The results show that:

- The analysis of each component of the radiation balance provides information that justifies the differences in the available energy (RN). The radiative parameters (albedo and emissivity) and thermal (absorptivity) of the urban surface modulate the output of radiation, reflection of solar radiation, and emission of longwave radiation. Urban pollution and high cloud cover favor the reduction of incident solar radiation and the increase in longwave radiation emitted by the atmosphere, which leads to a reduction in RN in the urban region.
- The energy balance displayed marked differences in the partitioning between the sensible and latent heat fluxes in the two locations. In the forest, a large portion of the available energy is converted to LE due to the process of evapotranspiration. However, in the city, energy is equally divided into sensible and latent heat fluxes. The dominant LE in the city may be associated with horizontal moisture transport (from the forest and river) and above-average precipitation during the studied period.

The sensitivity of energy balance processes to precipitation events, such as soil moisture conditions during the studied period, indicates that water plays a predominant role in the energy balance, especially in the city. Further studies are needed to understand urban energy balance under different seasonal conditions.

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