Bowen Ratio in Western São Paulo State, Brazil

Elaine C. Barboza, Antonio J. Machado

Abstract—This paper discusses micrometeorological aspects of the urban climate in three cities in Western São Paulo State: Presidente Prudente, Assis and Iepê. Particular attention is paid to the method used to estimate the components of the energy balance at the surface. Estimates of convective fluxes showed that the Bowen ratio was an indicator of the local climate and that its magnitude varied between 0.3 and 0.7. Maximum values for the Bowen ratio occurred earlier in Iepê (11:00 am) than in Presidente Prudente (4:00 pm). The results indicate that the Bowen ratio is modulated by the radiation balance at the surface and by different clusters of vegetation.

Keywords—Bowen ratio, medium-sized cities, surface energy balance, urban climate.

I. INTRODUCTION

THIS paper contributes to an understanding of surface energy balance in cities in tropical regions, which have received less attention than cities at other latitudes. Changes on the natural land surface imply destruction of a preexisting microclimate. Alterations to the urban surface cover affect the amount of stored energy (ΔQs) because of changes in radiative and convective fluxes brought about by the different radiative and thermal properties of the materials used.

Convective fluxes of sensible and latent heat are traditionally estimated [1] using observations made from micrometeorological towers or tethered balloons above the urban canopy layer in a portion of the boundary layer known as the inertial sublayer. In these strata convective flows have a much more regular temporal variability, allowing a more consistent estimate of convective fluxes [2] and, consequently, indices derived from these, such as the Bowen ratio (β).

However, estimates based on the inertial layer provide a generic characterization of the city and do not take into account specific local characteristics.

We propose a methodology for estimating β in the lowest stratum of the boundary layer between the ground and a height of several meters.

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II. METHOD

A. SURFACE ENERGY BALANCE

The residual energy balance method involves estimating the stored energy flux (ΔQS) from the energy balance equation for the urban canopy:

$$\Delta Q_S = (Q*+Q_F) - (Q_H + Q_E + \Delta Q_A) \qquad (1).$$

The net radiation flux ($Q*$) is observed directly with an NR-LITE-2 net radiometer from Kipp & Zonen (KZ). Sensible (Q_H) and latent (Q_E) heat fluxes are expressed as a function of the vertical temperature and humidity gradients close to the surface and are given by Eqs. (2) and (3):

$$Q_H = C_a K_H \left(\overline{\frac{\delta \overline{T_S}}{\delta z}} \right) \qquad (2),$$

$$Q_E = L_V K_V \left(\overline{\frac{\delta \overline{\rho_V}}{\delta z}} \right) \qquad (3),$$

where $C_a = 1200 \ Jm^{-3}K^{-1}$, $L_v = 2.5 \times 10^6 \ J \ kg^{-1}$ and $K_H \cong K_V \cong 25.10^{-10} \ m^2 s^{-1}$. The vertical temperature and humidity gradients close to the surface are estimated from the air temperature (T) and humidity (ρ) using an HC2S3 temperature and relative humidity probe from Campbell Scientific Inc. (CSI). The vapor density (ρ_V) is calculated directly from the vapor pressure, which, like all the other data, is measured with a CR3000 automated data acquisition system (CSI). The surface temperature (T_s) is estimated from the long-wave radiative flux observed with a PG4 pyrgeometer (KZ) using an emissivity of 0.9.

According to the energy balance proposed by [3], two simplifications can be made: the effect of anthropogenic heat (Q_F) can be ignored as its magnitude is one order less than the fluxes described in Eq. (1) [4], and heat advection (ΔQ_A) can also be ignored. As these are the main sources of error when estimating β, the variation in air temperature, wind speed and oscillations in the weather [5, 6] during the period when observations are made are evaluated.

β can therefore be expressed as:

$$\beta = \frac{Q_H}{Q_E} \qquad (4).$$

Observations made with a CSAT3 sonic anemometer (CSI) were used to analyze in detail the daytime evolution of the

World Academy of Science, Engineering and Technology
International Journal of Environmental and Ecological Engineering
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three wind components (V) and the turbulent sensible heat flux by the eddy correlation technique.

B. STUDY AREA

The town of Presidente Prudente (22°07'47"S, 51°24'31"W) is located on the South American continent in the state of São Paulo. It is one of 47 towns in an area encompassing the lower and middle Paranapanema valley known as *Oeste Paulista* (Western São Paulo State) and is approximately 600 km from the Atlantic Ocean (Fig.1a). It is around 425 m above sea level, covers an area of approximately 562 km^2 and has more than 200,000 inhabitants [7]. Briefly, the climate can be described as dry in winter, from May to September, with a humid summer from October to April. The urban form contrasts strikingly with the surrounding rural area. This contrast in land cover can also be observed within the urban area in the mixture of built-up blocks and town squares. In addition to Presidente Prudente, we investigated the towns of Assis and Iepê (Table 1). Together, these three towns occupy an area of 1,618 km^2 and have a population of 310,000 and a fleet of 100,000 automobiles.

Presidente Prudente suffers from chronic environmental problems, most notably air pollution caused by fires at dumps and by the earth being trampled by cattle. The town is located around 450 m above sea level, 150 m above the bed of the Parapanema river and 100 m below the Assis plateau (Fig. 1b). It lies to the north of the former and to the west of the latter (Fig. 1b).
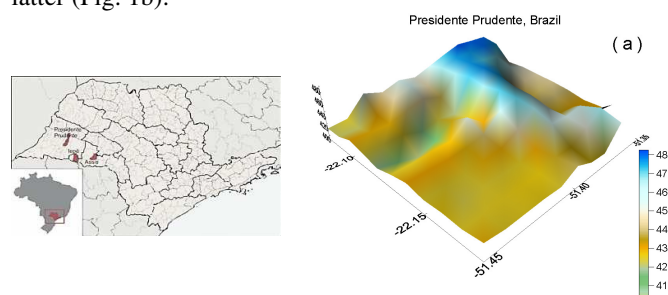

Fig. 1 Location of the state of São Paulo in Brazil showing Presidente Prudente, Assis and Iepê. Geographic coordinates and altitude of Presidente Prudente (a).

Tab. 1 Description of the urban and rural locations studied. Land use classes are based on [8].

Characteristics	Presidente Prudente	Assis	Iepê
Land use class	Suburban – Do3	Suburban – Do5	Rural
Area (km^2)	563	460	595
Population	207,610	95,144	7,628
Number of vehicles	70,290	29,110	1,690

C. DESCRIPTION OF THE LANDSCAPE

The first step in the spatial distribution analysis in Presidente Prudente was to identify the type of land cover. The landscape can be described by assessing the spatial distribution of vegetation in the open spaces and the distribution of land cover in the surrounding built-up areas as represented by cross-sectional views (Fig. 2). The different environments were classified according to visual estimates of the amount of vegetation and the predominant type of land cover.
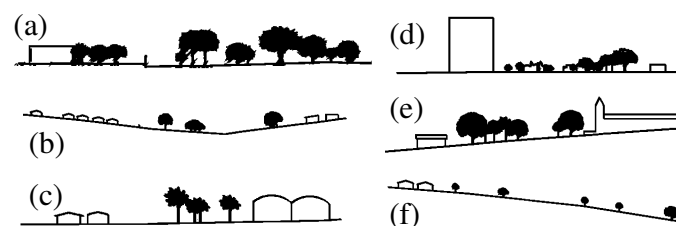

Fig. 2 Cross sections: Cerejeiras Square (a), COHAB (b), Assis (c), Santuário Square (d), Iepê (e) and Jd. Itapura (f).

D. OBSERVATIONS

Mean values of air temperature, air humidity, T_S and Q^* observed at one-minute intervals and mean values of the three orthogonal wind components (u, v, w) observed at one-second intervals were recorded. Observations were made in six locations between June and October 2012.

The stored energy flux (ΔQ_S), which corresponds to the net heat flux stored in the urban canopy, represents all the energy storage mechanisms inside this volume, i.e., the air, trees, built volume and ground [9]. All the observations used to estimate the energy balance were made at the top of urban structures and street furniture in public roads and squares in the towns of Presidente Prudente, Assis and Iepê between June and October 2012 (Fig. 3 and Table 2). Of the six observation points shown in Table 2, four (Cerejeiras, COHAB, Santuário and Itapura) are in Presidente Prudente and two in Assis and Iepê.
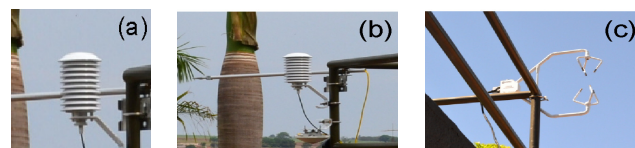

Fig. 3 Micrometeorological sensors installed on an urban structure: temperature and relative humidity probe (a), net radiometer (b) and sonic anemometer (c) located 3 m above the ground.

Tab. 2 Observations in Presidente Prudente, Assis and Iepê, from June 11th to October 31st, 2012. Altitudes are in relation to sea level.

Location	Lat. (S)	Lon. (W)	Altitude	Frequency
Cerejeiras	22°07'47"	51°24'31"	458 m	1 min
COHAB	22°06'49"	51°25'31"	395 m	30 sec
Assis	22°40'14"	50°24'59"	585 m	20 sec
Santuário	22°07'33"	51°22'55"	508 m	1 min
Iepê	22°39'39"	51°04'30"	426 m	1 min
Itapura	22°07'59"	51°22'05"	406 m	1 min

World Academy of Science, Engineering and Technology
International Journal of Environmental and Ecological Engineering
Vol:9, No:10, 2015

III. RESULTS

A. DIURNAL EVOLUTION OF Q^*, Q_H, Q_E, ΔQ_S AND β

A first approximation of the fluxes gives an indication of the diurnal pattern of evolution. In all the investigations, the lowest values for the Bowen ratio on days with a clear sky were always observed at the start of the day, and sensible heat flux (Q_H) gradually became more important than latent heat flux (Q_E), so that the values for β (open circles in Fig. 4) increased. The difference between the environments analyzed is therefore not directly related to the values obtained but to the moment when this relationship between the fluxes changes.
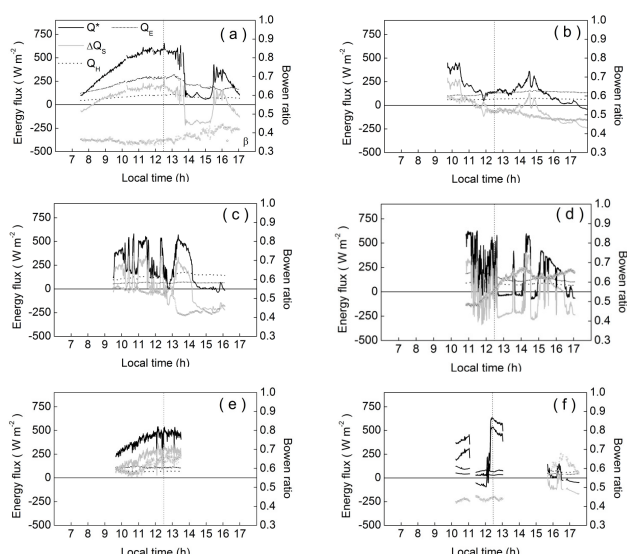

Fig. 4 Diurnal evolution of the components of the energy balance on (a) October 25th in Jd. Itapura, (b) October 10th in Iepê, (c) September 19th in Santuário de NSª Aparecida, (d) August 29th in Assis, (e) August 2nd in COHAB and (f) June 15th in Cerejeiras Square.

The variability of Q^* reflects the effect of shading by the tree canopy or cloud cover. In parks with grass, the flux Q_H is much more significant than Q_E, and the difference becomes more pronounced toward the end of the morning, with β increasing rapidly from 11:00 am and tending to stabilize around midday.

The records for Largo do Santuário in the morning are similar to those for Cohab, indicating a certain degree of similarity between the patterns on dry grass and those on stone paving. However, the variations observed in the afternoon are due more to changes in sky conditions than to the presence of the vegetation itself. The rain at the end of the experiment confirmed that there had been an increase in the humidity and a decrease in the temperature of the air during the period when observations were made. Just after 1:00 pm the values for β are close to those observed at the start of the day in Cerejeiras Square, which has many trees.
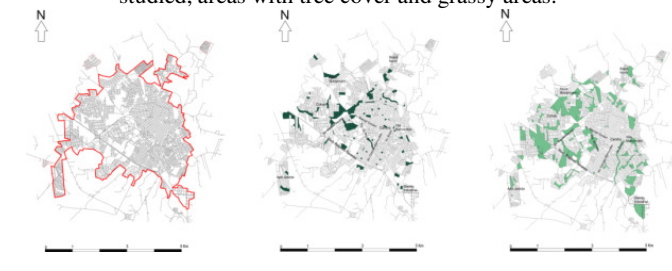
The results in Fig. 4a show that in Presidente Prudente most of the energy flux available at the surface during the day is transferred to the atmosphere in the form of latent evaporation heat. The β ratio varies from 0.3 to 0.4 after the convective activity.
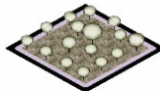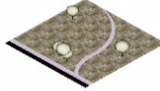
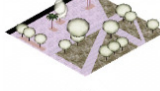### B. DIFFERENT CLUSTERS OF VEGETATION AND THE DIURNAL EVOLUTION OF β

The diurnal evolution of β is different for each of the environments analyzed. These different patterns are the result of the particular way the fluxes Q_H and Q_E vary in response to the different land cover characteristics.

Three clearly different surfaces and five distinct types of urban spatial composition were identified. These are shown in Table 3 together with the mean typical three-hourly values for β for each of them. Surfaces with dense tree cover (C1) account for only 7.3% of the urban fabric. Grassy areas with irregular tree cover (C2) account for an area approximately three times greater (21.7%). The urban surface accounts for 71% of the land cover and can be divided into areas where the only vegetation is that along the side of roads (C3), areas where there is irregular tree cover with a preponderance of impermeable or semipermeable surfaces (C4) and areas where there is regular tree cover also on surfaces with low permeability but without any standard form predominating (C5).

Tab. 3 Spatial distribution of the different types of land cover in Presidente Prudente. From left to right: The extent of the urban fabric studied, areas with tree cover and grassy areas.

	Type of land cover	β 9:00 am	B 12:00 am	β 3:00 pm	β 6:00 pm
C1	Green area.	0.43	0.44	0.57	0.6
C2	Sparse tree cover.	0.57	0.65	-	-
C3	Tree cover on paved area.	-	0.56	0.63	0.63
C4	Irregular tree cover on mixed surface	0.55	0.54	0.43	-
C5	Regular tree cover on mixed surface	0.59	0.52	0.48	0.47

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International Journal of Environmental and Ecological Engineering
Vol:9, No:10, 2015

C. COMPARISON OF THE RESIDUAL ENERGY BALANCE AND EDDY CORRELATION METHODS

A comparison of small eddies and a large eddy is shown in Fig. 5. The large eddy was observed in Iepê. The surface energy balance depends on the removal of heat by Q_H (Fig. 5a, below) as a result of the intra-urban breeze (Fig. 5b).

The intention in analyzing the flux Q_H determined by the eddy correlation method is to show that the fluctuations in β in an urban environment can be much more drastic and brutal (Fig. 5, 102 Wm^{-2}) than those observed when the residual energy balance method is used. However, these fluctuations are transitory and can only be observed with the CSAT3. In practice they go unnoticed by an inattentive observer as they occur on a much smaller timescale than human activities.
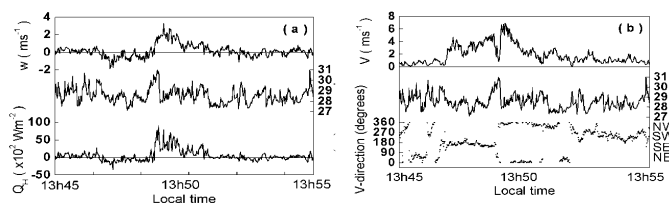

Fig. 5 Comparison of a major turbulent cycle in the midst of small vortices represented by vertical heat flux (a) and by the intra-urban breeze (b).

IV. DISCUSSION AND FINAL CONSIDERATIONS

An observational experiment was carried out to estimate β and the components of the surface energy balance. The values estimated in cities in Western São Paulo State typically varied from 0.3 to 0.7, values similar to those normally observed on grassy areas [10].

The figures for the turbulent fluxes Q_H and Q_E appear to agree with other values found in the literature. In COHAB specifically, these fluxes were lower than in the other areas studied and were slightly below 100 Wm^{-2} around midday. This type of land cover, with large grassy areas, paved roads and sparse tree cover, leads to reduced values of evapotranspiration typical of the dry season. Similar observations were made in urban areas in central Europe [11].

The variability of $Q*$ is affected by tree clusters, which reduce the intensity of solar radiation and increase emission of long-wave radiation. Careful management of urban vegetation can also help increase the vapor density of the air and consequently increase the flux Q_E and reduce β. These effects can clearly stabilize extreme local weather conditions.

ACKNOWLEDGMENTS

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