ANTHROPOGENIC HEAT IN THE CITY OF SÃO PAULO, BRAZIL

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Abstract The main goal of this work is to describe the anthropogenic energy flux (Q_F) in the city of São Paulo, Brazil. The hourly, monthly and annual values of the anthropogenic energy flux are estimated using the inventory method, and the contributions of vehicular, stationary and human metabolism sources from 2004 to 2007 are considered. The vehicular and stationary sources are evaluated using the primary consumption of energy based on fossil fuel, bio fuel and electricity usage by the population. The diurnal evolution of the anthropogenic energy flux shows three relative maxima, with the largest maxima occurring early in the morning (~19.9 Wm^{-2}) and in the late afternoon (~20.3 Wm^{-2}). The relative maximum that occurs around noontime (~19.6 Wm^{-2}) reflects the diurnal pattern of vehicle traffic that seems to be specific to São Paulo. With respect to diurnal evolution, the energy flux released by vehicular sources (Q_{FV}) contributes approximately 50% of the total anthropogenic energy flux. Stationary sources (Q_{FS}) and human metabolism (Q_{FM}) represent about 41% and 9% of the anthropogenic energy flux, respectively. For 2007, the monthly values of Q_{FV}, Q_{FS}, Q_{FM} and Q_F are, respectively, 16.8 ± 0.25 MJ m^{-2} $month^{-1}$, 14.3 ± 0.16 MJ m^{-2} $month^{-1}$, 3.5 ± 0.03 MJ m^{-2} $month^{-1}$ and 34.6 ± 0.41 MJ m^{-2} $month^{-1}$. The seasonal evolution monthly values of Q_{FV}, Q_{FS}, Q_{FM} and Q_F show a relative minimum during the summer and winter vacations and a systematic and progressive increase associated with the seasonal evolution of the economic activity in São Paulo. The annual evolution of Q_F indicates that the city of São Paulo released 355.2 MJ m^{-2} $year^{-1}$ in 2004 and 415.5 MJ m^{-2} $year^{-1}$ in 2007 in association with an annual rate of increase of 19.6 MJ m^{-2} $year^{-1}$ (from 2004 to 2006) and 30.5 MJ m^{-2} $year^{-1}$ (from 2006 to 2007). The anthropogenic energy flux corresponds to about 9% of the net radiation at the surface in the summer and 15% in the winter. The amplitude of seasonal variation of the maximum hourly value of the diurnal variation increases exponentially with latitude.

Key words: Anthropogenic energy flux, energy balance, net radiation, São Paulo, urban climate.

List of symbols

A	Urbanized area (m^2)
a_{Fuel}	Fraction of vehicles by fuel type
C_{Electr}	Monthly consumption of electricity by stationary sources (GWh $month^{-1}$)
C_{Fuel}	Monthly consumption of fuel by vehicular or stationary sources (m^3 $month^{-1}$)
E_{DPC}	Energy flux released from daily consumption of electricity by stationary sources (MJ m^{-2} day^{-1})
EV_{Fuel}	Energy released by vehicles per distance traveled and fuel type (J m^{-1})
EV_T	Total energy released from fuel combustion of vehicles per traveled distance (J m^{-1})
f	Hourly fraction of the daily consumption of electricity by stationary sources
F_{DPC}	Energy flux released from daily consumption of fuel by stationary sources (MJ m^{-2} day^{-1})
FE	Fuel economy (m l^{-1})
F_t	Traffic fraction
g	Fraction of fuel consumption by stationary sources
Lat	Latitude (degree)
M	Rate of metabolic production of energy per person (W)
n	Number of persons or animals
n_D	Number of days in the month
NHC_{Electr}	Net heat released by the consumption of electricity by stationary sources (J KWh^{-1})

NHC_{Fuel}	Net heat released by fuel combustion per fuel type from vehicular or stationary sources (J kg^{-1})
$NWRP$	Number of residents (person)
$pcDVD$	Mean traveled distance of vehicles per person per day (m person^{-1} day^{-1})
ρ_{Fuel}	Fuel density (kg m^{-3})
ρ_{pop}	Population density (person m^{-2})
Q^*	Net radiation
Q_F	Anthropogenic energy flux
Q_F^{MAX}	Maximum hourly value of the diurnal evolution of Q_F
ΔQ_S	Heat storage
Q_H	Turbulent sensible heat
Q_{LE}	Turbulent latent heat
ΔQ_A	Heat advection
Q_{FM}	Anthropogenic energy flux released by human and animal metabolism
Q_{FS}	Anthropogenic energy flux released by stationary sources
Q_{FSE}	Anthropogenic energy flux released from the consumption of electricity by stationary sources
Q_{FSF}	Anthropogenic energy flux released from the consumption of fuel by stationary sources.
Q_{FV}	Anthropogenic energy flux released by vehicular sources
R^2	Coefficient of determination
WP	Number of nonresidents (person)

CET	Municipal Company of Transportation
CETESB	Environmental protection agency of the State of São Paulo
DETRAN	Department of transportation of the State of São Paulo
IAG	Institute of Astronomy, Geophysics and Atmospheric Sciences
IBGE	Brazilian Institute of Geography and Statistics
LPG	Liquefied Petroleum Gas
MRSP	Metropolitan region of São Paulo City
ONSE	National Operator of the Brazilian Electric System
SSE	State of São Paulo Energy and Sanitation Agency
UHI	Urban heat island

1 Introduction

In urban regions, the progressive substitution of natural surfaces by artificial materials and the continuous release of gas and particulate matter in the atmosphere contribute to environmental degradation and may change local patterns of weather and climate (Oke 1988; Arnfield 2003; Collier 2006; Mills 2007). One way of assessing the impact of urban occupation is to evaluate the energy balance at the surface. In this study, the energy balance is expressed as $Q^{*} + Q_F = Q_H + Q_{LE} + \Delta Q_S + \Delta Q_A$, where Q^{*} is the net radiation flux, Q_F is the anthropogenic energy flux, Q_H and Q_{LE} are the turbulent sensible and latent heats, ΔQ_S is the heat storage and ΔQ_A is the heat advection in the urban canopy (Oke 1988).

The anthropogenic energy flux is composed of three parts, $Q_F = Q_{FV} + Q_{FS} + Q_{FM}$, where Q_{FV}, Q_{FS} and Q_{FM} indicate, respectively, the anthropogenic energy fluxes released by vehicular sources (fuel combustion), stationary sources (electricity and fuel consumed by houses, industrial and commercial activities and for public lighting) and metabolism (human and animal).

There are basically two methods to estimate the anthropogenic energy flux: the method of residues and the method of energy inventory. The method of residues consists of estimating the anthropogenic energy flux in terms of the energy balance equation. In reality, this method requires the evaluation four out of six components of the energy balance equation at the surface. The energy inventory method is the most applied technique for estimating the anthropogenic energy flux in urban areas (Grimmond 1992; Kłysik 1996; Sailor and Lu 2004; Smith et al. 2009). This method requires information about the primary energy consumption of vehicles, industries and commercial and residential dwellings. The composition of the different forms of primary energy consumption between vehicular and stationary sources of the anthropogenic energy flux and the energy contribution due to human and animal metabolism vary according to city. In general, this information is obtained from statistical reports about the energy use of a particular city or country. The inventory method assumes that all primary energy usage is transformed into heat, which is released to the urban canopy. The delay between primary energy usage and its restitution to the system (urban canopy) as heat is assumed to be zero (Ichinose et al. 1999; Sailor and Lu 2004).

There are several ways to apply the energy inventory method (Grimmond 1992; Kłysik 1996; Sailor and Lu 2004). Sailor and Lu (2004) evaluated the contribution of vehicular sources in terms of the population density, energy used per vehicle and daily distance traveled by vehicle per person. Grimmond (1992) estimated the contribution of vehicular sources directly from the number of vehicles, road type and length, source area and energy usage per vehicle.

The objective of this work is to estimate the diurnal, seasonal and annual variations of the anthropogenic energy flux of the city of São Paulo, Brazil, using the energy inventory method. Here, the anthropogenic energy flux will be estimated based on the contributions of vehicular and stationary sources and the production of energy by the metabolism of the city's human population as proposed by Sailor and Lu (2004). This investigation is based on statistical information available from federal and state agencies concerning the primary energy consumption (fossil fuel, bio fuel and electricity) of the population from 2004 to 2007.

2 The city of São Paulo

The city of São Paulo (23°33'1"S, 46°38'2"W) is located about 60 km from the Atlantic Ocean and is approximately 700 m above mean sea level, as indicated the white line contour in Fig. 1. The city contains the largest industrial park in South America (Codato et al. 2008).

This study will focus the most urbanized area of São Paulo, which covers an effective area of 854 km^2. The city's 2007 population was 10,886,518, and it had 5,989,234 active vehicles (CETESB 2008; DETRAN 2008; IBGE 2008). The study region corresponds to the grey area within the city of São Paulo, as displayed in the satellite picture of Fig. 1.

According to Oliveira et al. (2002), the climate of São Paulo is typical of the subtropical regions of Brazil, being characterized by a dry winter from June to August, and a wet summer from December to February. The smallest daily values of temperature and relative humidity occur in July and August (16°C and 74% respectively), and the lowest monthly accumulated precipitation occurs in August (30 mm). The largest daily value of temperature and monthly accumulated precipitation occurs in February (22.5°C and 255 mm), while the maximum relative humidity (80%) is observed in two periods: December-January and March-April.

Hereafter, February and August will be used to characterize the climate conditions during summer and winter, respectively, in São Paulo. These months were chosen because they are more representative of the summer-winter contrast in terms of precipitation, as indicated in the climate description above.

3 Methodology

This work uses the energy inventory method to estimate the anthropogenic energy flux and its temporal variations based on hourly monthly, monthly and annual values of electric energy consumption and monthly and annual values of all fuel sold in the city of São Paulo between 2004 and 2007.

The energy inventory method used here consists of summing up the following:

- The energy fluxes released by all moving vehicles in the city of São Paulo considering the diurnal evolution of the number of vehicles in movement, the mean distance traveled, the fuel consumed in distance traveled and the energy released by fuel combustion (gasoline, hydrous alcohol and diesel oil) are used to estimate the hourly annual values of the anthropogenic energy fluxes released by vehicular sources.

- The energy released from the consumption of electricity and fuel (natural gas, liquefied petroleum gas and fuel oil) by stationary sources (residential, industrial and commercial activities and for public lighting) in São Paulo are used to estimate the hourly monthly values of the anthropogenic energy flux released by stationary sources.
- The energy flux released by the population's metabolism is used to estimate hourly annual values of the anthropogenic energy flux released by metabolic activity in the city of São Paulo.

Alternatively, the energy fluxes released by the fleet of vehicles in movement in São Paulo considering only the monthly consumption of fuel (gasoline, alcohol and diesel oil) sold in the city is also used to estimate the monthly and annual values of the anthropogenic energy flux released by vehicular sources. Most of the methodology used to estimate the diurnal, seasonal and annual variations of Q_F, described hereafter, is based on Sailor and Lu (2004).

3.1 Anthropogenic energy flux released by vehicular sources (Q_{FV})

The diurnal evolution of Q_{FV} can be evaluated using the expression:

$$Q_{FV} = pcDVD \;\; F_t \;\; EV_T \;\; \rho_{pop} \tag{1}$$

Where $pcDVD$ is the mean distance traveled by vehicles per person per day, F_t is the traffic fraction, EV_T is the total energy released from the fuel combustion of vehicles per traveled distance and ρ_{pop} is the population density.

To estimate EV_T representing the entire fleet of vehicles in a given city, it is necessary to account for the energy released by vehicles per distance traveled by type of fuel combustion (EV_{Fuel}) while considering the fraction of vehicles by type of fuel (a_{Fuel}), as indicated below:

$$EV_T = \sum_{Fuel} a_{Fuel}\ EV_{Fuel} \tag{2}$$

Where EV_{Fuel} is estimated by:

$$EV_{Fuel} = \frac{NHC_{Fuel}\ \rho_{Fuel}}{FE} \tag{3}$$

Where NHC_{Fuel} is the net heat released by the combustion of fuel, ρ_{Fuel} is the fuel density and FE is the fuel economy.

In general, the population of large conurbations shows a significant diurnal oscillation caused by population movements from the border cities toward the core city. According to Fulton (1984), the diurnal evolution of population density (ρ_{pop}) can be estimated for a given city in terms of:

$$\rho_{pop} = \frac{NWRP + WP}{A} \tag{4}$$

Where $NWRP$ is the number of residents, WP is the number of nonresidents, namely, those living outside the city that work or study in the city, and A is the urbanized area of the city.

There are two different ways to obtain the monthly values of Q_{FV} (both methods will be used here). One way is to use the integral of the diurnal evolution of Q_{FV}, given by expression (1), multiplied by the number of days in each month (n_D). The other way is by using the following expression:

$$Q_{FV} = \frac{\sum_{Fuel} NHC_{Fuel}\ \rho_{Fuel}\ C_{Fuel}}{A} \tag{5}$$

Where, C_{Fuel} is the monthly consumption of fuel by vehicular sources.

The annual values of Q_{FV} are estimated by adding all twelve monthly values in the year.

3.2 Stationary sources of anthropogenic energy flux (Q_{FS})

The Q_{FS} is estimated using the consumption of electricity and other sources of energy produced by the fuel combustion of natural gas, liquefied petroleum gas (LPG) and fuel oil. This estimation can be expressed as:

$$Q_{FS} = Q_{FSE} + Q_{FSF} \tag{6}$$

Where, Q_{FSE} and Q_{FSF} are the anthropogenic energy flux released from the consumption of electricity and fuel by stationary sources, respectively. These sources of energy are from houses and buildings used for residential, commercial and industrial activities. Public lighting in the urban region is also included.

The diurnal evolution of Q_{FSE} can be evaluated using the expression:

$$Q_{FSE} = E_{DPC}\quad f \tag{7}$$

Where, E_{DPC} is the energy flux released from the daily consumption of electricity by stationary sources and f is the hourly fraction of the daily consumption of electricity by stationary sources.

The energy flux released by the daily consumption of electricity by stationary sources (E_{DPC}) can be estimated using:

$$E_{DPC} = \frac{NHC_{Electr} \quad C_{Electr}}{n_D \; A} \tag{8}$$

Where NHC_{Electr} is the net heat released by the consumption of electricity by stationary sources, C_{Electr} is the monthly consumption of electricity by stationary sources and n_D is the number of days in the month.

The monthly values of Q_{FSE} can be estimated by integrating the diurnal evolution of Q_{FSE}, given by expression (7), multiplied by the number of days. Numerically, the monthly values of Q_{FSE} are equal to E_{DPC}, given by expression (8), because the daily consumption of electricity is constant, and the integral of f during a period of 24 hours is equal to 1.

By analogy with electricity, the diurnal evolution of Q_{FSE} can be estimated from the energy flux released by the daily consumption of fuel by stationary sources:

$$Q_{FSF} = F_{DPC} \quad g \tag{9}$$

Where F_{DPC} is the energy flux released from the daily consumption of fuel by stationary sources, and g is the hourly fraction of the daily consumption of fuel by stationary sources.

Correspondently, the energy flux released from the daily consumption of each type of fuel by stationary sources (F_{DPC}) can be estimated using:

$$F_{DPC} = \frac{\sum_{Fuel} NHC_{Fuel} \; \rho_{Fuel} \; C_{Fuel}}{n_D \; A} \tag{10}$$

Where NHC_{Fuel} is the net heat released by the consumption of fuel by stationary sources, and C_{Fuel} is the monthly consumption of fuel by stationary sources.

Similarly, the monthly values of Q_{FSF} can be estimated by integrating the diurnal evolution of Q_{FSF} given by expression (9) multiplied by the number of days in the month. Numerically they are equal to F_{DPC} given by expression (10) because the daily consumption of fuel by stationary sources is constant, and the integral of g during a period of 24 hours is equal to 1.

3.3 Human metabolism (Q_{FM})

The diurnal evolution of Q_{FM} is estimated by:

$$Q_{FM} = M \, \rho_{pop} \tag{11}$$

Where, M is the rate of metabolic production of energy per person (Oke 1988; Grimmond 1992; Sailor and Lu 2004).

The monthly values of Q_{FM} are estimated by the integral of diurnal evolution given by expression (11) multiplied by the number of days in the month. The annual values of Q_{FM} are estimated by adding all twelve monthly values in the year.

4 Diurnal variation of Q_F in the city of São Paulo

As indicated in the section above, to estimate the diurnal variation of Q_F is necessary to evaluate the mean distance traveled by vehicles (*pcDVD*), traffic fraction (F_t), total energy released by vehicles per distance traveled by type of fuel combustion (EV_T), diurnal evolution of population density (ρ_{pop}), hourly fraction of the daily consumption of electricity (f) and fuel (g) by stationary sources in the city of São Paulo

According to Lents et al. (2004), *pcDVD* in São Paulo in 2004 was 17,000 km. Considering that this mean distance traveled does not change much from one year to another, in 2007 the mean distance traveled by vehicles per day was 46.6 km, and the mean distance traveled by vehicles per person per day was 13,588 m person^{-1} day^{-1}. A similar extrapolation in time was calculated by Sailor and Lu (2004). In the *pcDVD* estimate for São Paulo, the number of vehicles is set to 3,174,294, and the population is set to 10,886,518 inhabitants, both values corresponding to 2007. It should be emphasized that the fleet of vehicles (3,174,294) in movement daily in São Paulo corresponds to 53% of the total number of registered vehicles in São Paulo during 2007 (5,989,234). This fraction (53%) is based on CET estimates (Roson 2008).

The traffic fraction F_t is estimated by considering that the number of vehicles in movement in the main streets is representative of the traffic in São Paulo at each hour of the day. Fig. 2 indicates the diurnal evolution of F_t based on the estimates of Lents et al. (2004) for São Paulo in 2004. Aiming to inventory CO_2 emissions, Lents et al. (2004) counted the number of vehicles in movement in the most representative regions of São Paulo. In this work, it is assumed that the F_t, observed by Lents et al. (2004) is valid for 2007. An equivalent extrapolation in time was also done by Sailor and Lu (2004) for American cities. The F_t, based on the observations carried out in 2004 (Fig. 2) matches the estimates provided by the Municipal Company of Transportation of São Paulo City in 2007 (Roson 2008). The later estimates were based on observations carried out in 15 major avenues of São Paulo during the rush hours (07:00 LT to 10:00 LT and 17:00 LT to 20:00 LT) in 2007. As a reference, the traffic fraction in the USA, based on observations performed in 99 cities over 19 states by Hallenbeck et al. (1997), is also indicated in Fig. 2. The F_t of the American cities shows a behavior similar to that observed in São Paulo.

Table 1 indicates the values of NHC_{Fuel}, ρ_{Fuel} and FE used to evaluate EV_T in São Paulo. The mean fuel economy corresponds to the mean values of fuel consumption of vehicles that use gasoline, alcohol and diesel oil. The values in Table 1 are consistent with those used to estimate the Q_F in other cities (Pirgeon et al. 2007). The contribution of motorcycles is particularly relevant because São Paulo has a fleet of 349,256 motorcycles in movement daily, corresponding to 53% of the 658,953 motorcycles registered up to 2007.

The only information available concerning the number of people visiting São Paulo daily is based on the demographic data of the 2000 census analysis carried out by Aranha (2005) and Ântico (2005). According to these authors, the city of São Paulo is the main destination of the surrounding 38 cities, receiving between 590,000 and 612,000 people daily from outside areas. Therefore, it will be assumed here that an average of 601,000 people visited the city daily in 2000. To assess the daily population movement for 2004, 2005, 2006 and 2007, it was considered that the daily population displacement from the surrounding areas increased according to the expected population growth, which was 2.24% between 2000 and 2004, 2.8% between 2000 and 2005, 3.36% between 2000 and 2006 and 4% between 2000 and 2007. Thus, the diurnal evolution of ρ_{pop} in 2007 is 0.0127 person m^{-2} at night (before 05:00 LT and after 19:00 LT) and 0.0135 person m^{-2} during the day (between 07:00 LT and 17:00 LT). The population densities during the night-to-day and day-to-night transition periods are set to 0.0131 person m^{-2}. These values were obtained by considering *NWRP* equals 10,886,518 (IBGE, 2008), *WP* equals 625,000 people and the urbanized area *A* equals 854 km^2 in expression (4).

The hourly values of *f* was estimated using the diurnal evolution of the monthly average values of electricity consumption in the State of São Paulo (ONSE, 2008). A similar method was used by Sailor and Lu (2004) to estimate the hourly fraction of energy consumed daily in several cities in the USA. The diurnal evolution of *f* in the city of São Paulo is indicated in Fig. 4 for the summer and winter of 2007. For comparison, the hourly fraction of electricity consumption for the USA cities proposed by Sailor and Lu (2004). Curiously, the pattern of consumption of electricity in the State of São Paulo is similar the pattern of consumption in the USA.

The hourly values of g were not available for 2007. Therefore, in the expression (9) the hourly fraction is obtained by assuming that the daily consumption is evenly distributed over the entire 24-hour period of 24. Thus, g is set to 0.0417 for the city of São Paulo.

4.1 Diurnal evolution of Q_F

Considering expressions (1)-(4), the diurnal evolution of the anthropogenic energy flux released by vehicular sources is evaluated for 2007. In this case, neither the diurnal evolution of the population density nor *pcDVD* change during the months within a year. This value varies only from one year to another, which is why the diurnal evolution of Q_{FV} is based on the hourly annual values of these variables.

The diurnal evolution of Q_{FV} in São Paulo shows three peaks (Fig. 3). Two of these peaks correspond to the hours when the traffic is most intense (early morning and evening). The local maximum between 10:00 LT and 12:00 LT corresponds to the release period for restricted vehicles based on license plate number. During the driving restriction hours (07:00-10:00 LT and 17:00-20:00 LT), 20% of the vehicles are not allowed in the central portions of São Paulo. The local maximum between 10:00 LT and 12:00 LT is a peculiarity of São Paulo that is due to this traffic restriction.

The diurnal variation of Q_{FS} for the summer (February) and winter (August) of 2007 is indicated Fig. 5. In the summer of 2007, Q_{FS} varied from 4.51 Wm^{-2} at 04:00 LT to 6.01 Wm^{-2} at 16:00 LT (Fig. 5a). In the winter, Q_{FS} varied from 4.77 Wm^{-2} at 03:00 LT to 6.81 Wm^{-2} at 19:00 LT (Fig. 5b). Comparatively, the amplitude of the diurnal cycle in summer (1.50 Wm^{-2}) is slightly smaller than that observed in the winter (2.04 Wm^{-2}, Fig. 5b).

In the case of Q_{FM} the diurnal evolution was estimated using, in expression (11), the population density estimates for 2007 and an energy release from metabolic activity of 75 W for the period of less activity (from 23:00 LT to 05:00 LT) and 115 W for the period of greater activity (from 07:00 to 21:00 LT), as proposed by Oke (1988). In the transition periods (05:00 LT to 07:00 LT and 21:00 LT to 23:00 LT), the rate of metabolic energy released was estimated by a linear interpolation between the values of lesser and great activity and vice versa. The energy released by animal metabolism was not considered because there is no information about the number and type of animals in the city of São Paulo.

The diurnal cicle of Q_{FV}, Q_{FS} , Q_{FM} and Q_F for August are indicated in Fig. 6. Comparatively to the diurnal evolution for February Q_F for August is not significantly different. The relative difference is equal to 2% and it is due to the variation in the Q_{FS}. The small seasonal variation observed in the diurnal evolution of Q_F (Fig. 6), with the winter (August) values systematically larger than the summer (February) values, corroborates the belief that even for a subtropical city like São Paulo, one should expect larger values of Q_F in winter than in summer. However, as discussed above, this comparison is somehow misleading because the results shown in Fig. 6 reflect only the seasonal variation of Q_{FS}. To avoid this problem, the analysis of the seasonal variation of Q_F and its components will be carried out in the next sections using monthly values exclusively. The analysis in this section will focus only on the contributions of vehicular, stationary and human metabolic sources in the diurnal evolution of Q_F.

The Q_F shows a diurnal evolution with three relative maxima, with the largest occurring early in the morning (~19.9 Wm^{-2}) and in the late afternoon (~20.3 Wm^{-2}). The relative maximum, which occurs around noontime (~19.6 Wm^{-2}), reflects the diurnal pattern of vehicle traffic that seems to be specific to São Paulo (Fig. 6).

Considering the entire daytime period, the integral of diurnal evolution of the energy flux released by vehicular sources contributes approximately 50% of the total anthropogenic energy flux. The stationary sources and human metabolism represent about 41% and 9% of the anthropogenic energy flux, respectively.

5 Seasonal variation of Q_F in the city of São Paulo

The seasonal evolution of Q_F was characterized using monthly values of the anthropogenic energy flux released by vehicular, stationary and metabolic sources in São Paulo City, as indicated in Fig. 7 (for 2007 only) and Fig. 8 (2004 to 2007).

In 2007, the mean monthly values of Q_{FV}, Q_{FS}, Q_{FM} and Q_F were, respectively, 16.8 ± 0.25 MJ m^{-2} $month^{-1}$, 14.3 ± 0.16 MJ m^{-2} $month^{-1}$, 3.5 ± 0.03 MJ m^{-2} $month^{-1}$ and 34.6 ± 0.41 MJ m^{-2} $month^{-1}$.

The vehicular source is the dominant factor during summer and winter (Fig. 7a). Approximately 51% of Q_F was due to the energy released by 3.2 million vehicles traveling daily in São Paulo (Lents et al. 2004; Roson 2008).

The energy released by the stationary sources is responsible for approximately 41% of the Q_F (Fig. 7a). This figure remains relatively constant throughout the year, which may indicate that these sources do not use electricity or fuel for heating during winter or for cooling during summer. Indeed, São Paulo is located in a region of subtropical climate where most of the residences and buildings do not require heating during winter.

The energy released by metabolic activities in São Paulo contributes 8% of Q_F (Fig. 7a). In most cases described in the literature, the energy released by metabolic activities represents 2-3% of Q_F (Oke 1988; Grimmond 1992; Sailor and Lu 2004). An exception is Tokyo, where the contribution from metabolic sources is 5-10% (Ichinose et al. 1999). In cities located in countries that have lower per capita energy consumption, the Q_{FM} contribution to Q_F can be greater than 5% (Sailor and Lu 2004). São Paulo occupies an upper range of Q_{FM} contribution to Q_F because of its large number of inhabitants (more than

11 million) and the low per capita energy consumption of its population (Sailor and Lu 2004).

The apparent lack of correlation between the time variation of Q_F and the seasonal evolution of São Paulo's climate is better visualized by the relative deviation from the annual mean of the vehicular (white column), stationary (gray column) and metabolic (light gray column) sources and Q_F (continuous line) displayed in Fig. 7b for 2007. In general, Q_F and its major components, Q_{FV} and Q_{FS}, show a variation smaller than ±10%. During the vacation periods, which occur at the beginning (January and February) and middle of the year (July), the relative deviations of Q_F and Q_{FV} are negative. The largest negative deviation, approximately -10%, is observed during the summer vacation period. After the summer vacation in January and before the winter vacation in July, the relative deviations of Q_{FV} and Q_{FS} oscillate around zero, while Q_F goes through a minimum negative in May and increases progressively, becoming positive due to the augmentation in Q_{FV}. During the second semester, the relative deviation of Q_F becomes positive. These patterns are basically associated with the increase in economic activity that begins after the summer vacation, showing a maximum in November. Therefore, the time evolution of Q_F in São Paulo is not related to the seasonal evolution of the local climate but, rather, closely follows the city's economic activity.

The patterns found for 2007 are also observed in the period from 2004 to 2007 (Fig. 8). In general Q_F, Q_{FV} and Q_{FS} increase after the summer vacation period at the beginning of the year and decrease slightly during the winter vacation period (Fig. 8).

One important result observed in Fig. 8 is the progressive annual increase in the amplitude of the monthly values of Q_F, Q_{FV} and Q_{FS} between 2004 and 2007. This effect will be explored further in the following sections.

5.1 Seasonal variation of Q_F in terms of net radiation

Figure 9 shows a comparison between the seasonal evolution of net radiation and Q_F observed in São Paulo. The net radiation was observed at the IAG site (Fig. 1) from 2004 to 2007 using a net radiometer from Kipp-Zonen (Ferreira et al. 2007).

The total input of energy in the urban canopy (Q^* + Q_F) is 365.8 MJ m^{-2} $month^{-1}$ in February (summer) and 249.3 MJ m^{-2} $month^{-1}$ in August (winter), and Q_F contributes about 29.4 MJ m^{-2} $month^{-1}$ in February and 33.0 MJ m^{-2} $month^{-1}$ in August. The average monthly values of Q_F correspond to approximately 9% of the monthly values of the net radiation at the surface during summer and 15% during winter. Annually, the anthropogenic energy flux represents nearly 11% of the net radiation observed in São Paulo.

5.2. Seasonal variation of Q_F in terms of latitude

The intensity of the seasonal variation of Q_F is strongly correlated with climate. In general, cities in the middle and high latitudes use more energy during winter for heating and lighting, while in cities located in the low latitudes, like São Paulo, the energy used for heating and lighting is small or even negligible. Table 2 shows the anthropogenic energy flux (daily maximum) during the summer and winter months in São Paulo compared to several cities located in the middle and high latitudes (Grimmond 1992; Kłysik 1996; Sailor and Hart 2006; Pigeon et al. 2007).

In São Paulo the Q_F shows no significant seasonal variations. The relative deviation, estimated as the ratio of winter-summer difference for São Paulo is 1.0 % (Table 2). In high latitude cities the relative deviation varies from 53% (Vancouver) to 350% (Lodz).

The dependence of Q_F on climate can be better visualized in Fig. 10. There, the points in the scatter plot with small scattering indicate the relationship between the seasonal variations of Q_F and the latitude. These points correspond to cities in Table 2 and in the

Table 1 of Sailor and Hart (2006). The interpolated curve was obtained with a coefficient of determination (R^2) equal to 0.89, using 62 points (indicated by solid circle in Fig. 10. The 4 cities displayed by solid star correspond to Budapest, Portland, Seattle and Vancouver was not included in the interpolation. Based on the available information there is no apparent reason for the discrepant behavior of these 4 cities. However, if 62 out of 66 cities follow the interpolate curve with $R^2 = 0.89$, it can be concluded that the seasonal variation of Q_F increases exponentially with latitude, as indicated in Fig. 10.

6 Inter-annual variations of Q_F in São Paulo

The time variation of the annual values of Q_{FV}, Q_{FS} and Q_F considering the annual consumption of fuel and electricity by vehicular and stationary sources, as described in Tables 3 and 4, are indicated in Fig. 11 for 2004-2007.

The annual values of Q_{FV} (Fig. 11a) indicate that the energy released by vehicular sources associated with the combustion of gasoline, diesel oil, hydrous alcohol and anhydrous alcohol increases at an annual rate of 1.5 MJ m^{-2} $year^{-1}$, 1.0 MJ m^{-2} $year^{-1}$, 5.2 MJ m^{-2} $year^{-1}$ and 1.3 MJ m^{-2} $year^{-1}$, respectively. The total energy released from the combustion of fuel increases at an annual rate of 8.1 MJ m^{-2} $year^{-1}$. Because the number of cars during this period remains relatively constant, the only significant variation that affects the annual evolution of Q_{FV} components individually is the increase in the fraction of vehicles fueled by hydrous alcohol, which varied from 15.4% in 2004 to 21.5% in 2007 (Table 3). Given the fact that diesel oil vehicles remain constant and the increase in alcohol vehicles is followed by a decrease in the fraction of vehicles fueled by gasoline, the annual rate of increase in Q_{FV} seems to be due to changes in the number of cars fueled by alcohol. It should be emphasized that the numbers of vehicles in Table 3 correspond to the vehicles registered in the city of São Paulo up to December 31 in each year.

Comparatively, the energy released annually from the consumption of electricity and fuel (natural gas, LPG and fuel oil) by the stationary sources is indicated in Fig. 11b. This figure shows that the annual evolution of energy released from the consumption of electricity, natural gas, LPG and fuel oil by stationary sources has grown annually at a rate of 4.3 MJ m^{-2} $year^{-1}$ and 2.8 MJ m^{-2} $year^{-1}$, respectively. The energy released from the consumption of LPG has slightly increased during this period, whereas the energy released from the combustion of oil decreased annually by about 0.5 MJ m^{-2} $year^{-1}$.

Table 4 shows the annual consumption of electricity in São Paulo from 2004 to 2007 and the fraction of electricity usage per consumer type (residence, commerce, industry and others). As can be seen in Table 4, almost 40% of the electricity consumption in São Paulo is used in residences, about 30% is used in commerce and less than 20% is consumed by the industrial sector. The progressive increase in the consumption of electricity from 2004 to 2007 reflects the growth of the industrial sector and other economic sectors in Brazil (Silva and Guerra 2009). Moreover, the annual values in Table 4 indicate that the industrial sector is responsible for the major consumption of natural gas (about 80% of total consumption). The residential and commercial sector accounted for only 2.5% of total consumption in 2007 (Table 4).

The time variation of Q_F (Fig. 9c) indicates an increase at an annual rate of 19.6 MJ m^{-2} $year^{-1}$ from 2004 to 2006 and 30.5 MJ m^{-2} $year^{-1}$ in 2007. The city of São Paulo released 355.2 MJ m^{-2} $year^{-1}$ in 2004 and 415.5 MJ m^{-2} $year^{-1}$ in 2007. These variations reflect the annual increases observed in Q_{FV} (Fig. 11a) and Q_{FS} (Fig. 11b). Annually, the contributions of Q_{FV}, Q_{FS} and Q_{FM} to the anthropogenic energy flux were 47.5%, 42.0% and 10.5%, respectively. These fractions of annual values of Q_F are consistent with those based on diurnal and seasonal evolution in the previous sections.

7 Conclusions

The main objective of this work was to describe the anthropogenic energy flux of São Paulo using the energy inventory method.

Based on the results described in the previous sections, one can conclude the following:

- The diurnal evolution of Q_F shows three relative maxima, with the largest occurring early in the morning (~19.9 Wm^{-2}) and in the late afternoon (~20.3 Wm^{-2}). The smallest relative maximum occurs around noontime (~19.6 Wm^{-2}) for 2007.
- The energy released by vehicular sources is dominant term, contributing 50% (49.0% monthly and 47.5% annually) of the total anthropogenic energy flux.
- The stationary sources and human metabolism contribute approximately 41% (41% monthly and 42% annually) and 9% of the anthropogenic energy flux, respectively (10% monthly and 10.5% annually).
- There is no significant seasonal variation for the stationary sources of anthropogenic energy flux, indicating the city of São Paulo does not require a significant amount of energy for heating or lighting in the winter as do cities in higher latitudes or higher altitudes (Sailor and Lu, 2004).
- The anthropogenic energy flux corresponds to 9% of the net radiation in the summer and about 15% in the winter. The annual average values of the anthropogenic energy flux are near 11% of the net radiation from 2004 to 2007.

In most of the work available in the literature, the fraction of vehicular sources contributing to the total anthropogenic energy flux varies between 47% and 62%. In São Paulo, the vehicular fraction is 52%. This large contribution reflects:

a) the large number of vehicles circulating daily, at around 3.2 million or half of the total existing fleet; and
b) the high average distance traveled by these vehicles, at 46.6 km per day.

The number of cars traveling daily in the city of São Paulo is greater than most cities where the anthropogenic energy flux has been evaluated (Table 2). The large fleet in São Paulo is the direct consequence of an incipient public transportation system that is present in most third world cities.

One important result from this work is that the diurnal evolution of both vehicle traffic (traffic fraction) and electricity consumption were estimated objectively for the city of São Paulo, and they happened to similar to the diurnal evolution found in cities in the USA. Another important conclusion is that the seasonal variation of the anthropogenic energy flux varies exponentially with latitude. An empirical expression represented by an exponential growth was fitted with a coefficient of determination of 0.89, considering 62 of 66 cities.

Another important point brought up by this work is that Q_F, according to the estimates carried out here, is increasing at an annual rate of 19.6 MJ m^{-2} year^{-1} (~5%). This indicates that Q_F may increase by about 50% in 10 years. This increase may intensify the effects associated with the anthropogenic release of energy on the urban climate of São Paulo, especially in the urban heat island.

This study is based on the hypothesis that all of the energy released by vehicular, stationary and metabolic sources is evenly distributed over the urbanized area of São Paulo (854 km^2). In comparison to other large cities (Table 2), the relatively small values of the anthropogenic energy flux in São Paulo (~20 W m^{-2}) may be a consequence of this hypothesis. One would expect larger Q_F values if small and highly urbanized areas were considered isolated (Kłysik 1996; Ichinose et al. 1999). In this case, a larger Q_F would be confined to small portions of São Paulo and would be a major source of energy for the spatial variations in its urban heat island (UHI). It is known that in some areas of São Paulo, the UHI may reach as much as 12^{o}C (Monteiro 1976). The next step will be to investigate the spatial variability of Q_F in São Paulo.

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Table Captions

Table 1 Parameters ($a_{Fuel,}$, NHC_{Fuel} , ρ_{Fuel} , FE and EV_{Fuel}) used to estimate the total energy released from vehicular sources in the city of São Paulo during 2007

Table 2 Summary of the seasonal variation of the anthropogenic energy flux and related features for some cities

Table 3 Number and fraction (a_{Fuel}) of vehicles registered by fuel type and annual consumption of fuels by vehicles (C_{Fuel}) used to estimate the energy flux released from fuel combustion by vehicular sources from 2004 to 2007

Table 4 Annual consumption of electricity, natural gas, LPG and fuel oil in the city of São Paulo from 2004 to 2007. Fraction of consumption and by consumer type is available only for electricity and natural gas

Figure Captions

Fig. 1 The geographical position of São Paulo is indicated by the white line contour in the central portion of the LANDSAT image. The urban area is indicated by *A*, and it corresponds to the light gray portion inside the city of São Paulo. The net radiation data were measured at IAG (23º33'35"S, 46º43'55"W)

Fig. 2 Diurnal evolution of the traffic fraction of vehicles in motion within the urban region of São Paulo observed in 2004 (solid line) and during rush hours in 2007 (black triangle). As a reference, the traffic fraction based on observations performed in 99 cities over 19 states in the USA by Hallenbeck et al. (1997) is also indicated (dashed line)

Fig. 3 Diurnal evolution of the anthropogenic energy flux associated with vehicular sources (Q_{FV}) during 2007

Fig. 4 Diurnal evolution of the hourly fraction of daily electricity consumption f for (a) summer (February) and (b) winter (August) for the State of São Paulo (solid line) in 2007. Daily electricity consumption in USA (dashed line) is indicated for reference

Fig. 5 Diurnal evolution of anthropogenic heat associated with stationary sources (Q_{FS}) during (a) summer (February) and (b) winter (August) in São Paulo during 2007

Fig. 6 Diurnal evolution of the anthropogenic energy flux (Q_F) associated with vehicular sources (dashed dotted line), stationary sources (dashed line), human metabolism (dotted line) and total (solid line) for winter (August) in 2007

Fig. 7 Seasonal evolution of the anthropogenic energy flux associated with: (a) vehicular sources (white column), stationary sources (gray column) and metabolic sources (light gray column); (b) relative deviation from the annual mean of the daily values of Q_{FV} (white column), Q_{FS} (gray column) and Q_F (continuous line)

Fig. 8 Seasonal evolution of monthly values of the anthropogenic energy flux due to (a) vehicular sources, (b) stationary sources and (c) vehicular, stationary and metabolic sources in São Paulo during 2007 (gray column). The time evolution for 2004 (dotted line), 2005 (dashed line) and 2006 (solid line) are also indicated in (a), (b) and (c)

Fig. 9 Seasonal variation of the net radiation (gray column), Q_F (light gray column) and Q^*+Q_F (solid line) in the city of São Paulo. Average monthly values based on observations carried out from 2004 to 2007. The vertical lines indicate standard error

Fig. 10 Dispersion diagram between relative deviations of the anthropogenic energy flux normalized by summer values of Q_F^{MAX} for the cities indicated in Table 2 and in Table 1 of Sailor and Hart (2006). The relative deviation corresponds to Q_F^{MAX} in the winter minus Q_F^{MAX} in the summer. The fitted expression for relative deviation for latitude in degrees is: $\left(\dfrac{Q_F^{MAX}Winter - Q_F^{MAX}Summer}{Q_F^{MAX}Summer}\right)100\% = 0.21\exp(Lat/6.95) - 13.05$. The cities indicated by letters are described in Table 2. They correspond to São Paulo (SP), Budapest (BU), Montreal (MO), Vancouver (VA), Lodz (LO) and Toulouse (TO), Seattle (SE) and Portland (PO). They are also described in Table 1 of Sailor and Hart (2006)

Fig. 11 Time evolution of annual values of energy released in the city of São Paulo by (a) vehicular sources associated with the consumption of gasoline, diesel oil, hydrous alcohol and anhydrous alcohol; (b) stationary sources associated with the consumption of electricity, natural gas, LPG and fuel oil; and (c) Q_F

Table 1 Parameters (a_{Fuel}, NHC_{Fuel} , ρ_{Fuel} , FE and EV_{Fuel}) used to estimate the total energy released from vehicular sources in the city of São Paulo during 2007

Fuel	a_{Fuel} $ (%)	NHC_{Fuel} & (MJ kg^{-1})	ρ_{Fuel} # (kg m^{-3})	FE $ (m l^{-1})	EV_{Fuel} + (J m^{-1})
Gasoline#	61.0	44.1	738	12,000	2,712
Gasoline# (motorcycle)	12.1	44.1	738	25,000	1,302
Hydrous Alcohol	21.5	24.9	809	8,000	2,518
Diesel oil	5.4	42.6	851	2,000	18,126

$ CETESB (2008); &, @ (SSE, 2008); # Gasoline sold in Brazil contains 25% anhydrous alcohol (SSE, 2008); + DETRAN(2008).

Table 2 Summary of the seasonal variations of anthropogenic energy flux and related features for some cities

City (Lat; Long; Alt)	Density (person km^{-2})	Q_F^{MAX} (Wm^{-2})		Relative deviation[4] (%)
		Summer	Winter	
São Paulo (SP) [$] (23º33'S; 46º43'W; 792 m)	12.748	20.1	20.3	1.0
Budapest[1] (B) (47° 28′ N, 19° 3′ E; 102m)	11.500	32	52	62.50
Montreal[1] (M) (45° 30′ N, 73° 33′ W; 57m)	14.102	57	153	168.42
Vancouver[3] (V) (49º13'N; 123º06'W; 70 m)	5.085	23	14	53.0
Łódz[1] (L) (51º47'N; 19º28'E; 200 m)	2.608	12	54	350.0
Toulose[2] (T) (43º36'N; 1º26'E; 166m)	1.221	30	70	133.33

[1]Kłysik (1996); [2]Pigeon et al. (2007); [3]Grimmond (1992). [$]Summer values correspond to February and winter values to August 2007; [4]Relative deviation $= \left(\frac{Q_F^{MAX} \text{W int er} - Q_F^{MAX} \text{Summer}}{Q_F^{MAX} \text{Summer}} \right) 100\,\%$

Table 3 Number and fraction (a_{Fuel}) of vehicles registered by fuel type and annual consumption of fuels by vehicles (C_{Fuel}) used to estimate the energy flux released from fuel combustion by vehicular sources in the city of São Paulo from 2004 to 2007

Year	**Number of Vehicles**[+]	**Type of fuel**	a_{Fuel}[$] (%)	C_{Fuel}[@] (m^3 $year^{-1}$)
2004	5,801,194	Gasoline[#]	78.8	2,812,765
		Hydrous Alcohol	15.4	534,128
		Diesel oil	5.8	1,385,507
2005	5,335,900	Gasoline[#]	78.0	2,912,801
		Hydrous Alcohol	16.4	579,308
		Diesel oil	5.6	1,384,287
2006	5,621,049	Gasoline[#]	76.0	2,935,273
		Hydrous Alcohol	18.4	918,095
		Diesel oil	5.6	1,282,273
2007	5,989,234	Gasoline[#]	73.1	3,027,360
		Hydrous Alcohol	21.5	1,420,192
		Diesel oil	5.4	1,482,514

[#]Gasoline sold in Brazil contains 25% anhydrous alcohol (SSE, 2008); [+] Registered vehicles (DETRAN, 2008); [$] CETESB (2005, 2006, 2007, 2008); [@] SSE (2007, 2008).

Table 4 Annual consumption of electricity, natural gas, LPG and fuel oil in the city of São Paulo from 2004 to 2007. Fraction of consumption and by consumer type are available only for electricity and natural gas

Year	Consumer type	Electricity		Natural gas		LPG	Fuel oil
		Fraction of consumption [consumer] (%)	Consumption (GWh) [consumer number]	Fraction of consumption [consumer] (%)	Consumption (m^3) [consumer number]	Consumption (m^3)	Consumption (m^3)
2004	Residence	39 [92.7]	21,120 [3.658.529]	2.6 [97.8]	701,569,281 [459.514]	735,962	81,651
	Commerce	33 [6.7]		2.3 [1.9]			
	Industry	17 [0.4]		81.0 [0.2]			
	Others	11 [0.2]		14.1 [0.1]			
2005	Residence	39 [92.4]	22,410 [3.746.891]	2.3 [97.9]	815,269,926 [502.476]	717,391	63,937
	Commerce	33 [6.9]		2.1 [1.8]			
	Industry	17 [0.4]		78.0 [0.2]			
	Others	11 [0.3]		17.6 [0.1]			
2006	Residence	38 [92.1]	24,190 [3.861.753]	2.2 [98.0]	933,503,227 [540.679]	703,254	36,599
	Commerce	33 [7.1]		1.9 [1.7]			
	Industry	17 [0.5]		80.0 [0.2]			
	Others	12 [0.3]		15.9 [0.1]			
2007	Residence	39 [91.5]	25,240 [3.982.922]	2.2 [98.1]	955,174,285 [598.520]	742,347	42,798
	Commerce	33 [7.6]		1.8 [1.6]			
	Industry	17 [0.6]		80.0 [0.2]			
	Others	11 [0.3]		16.0 [0.1]			

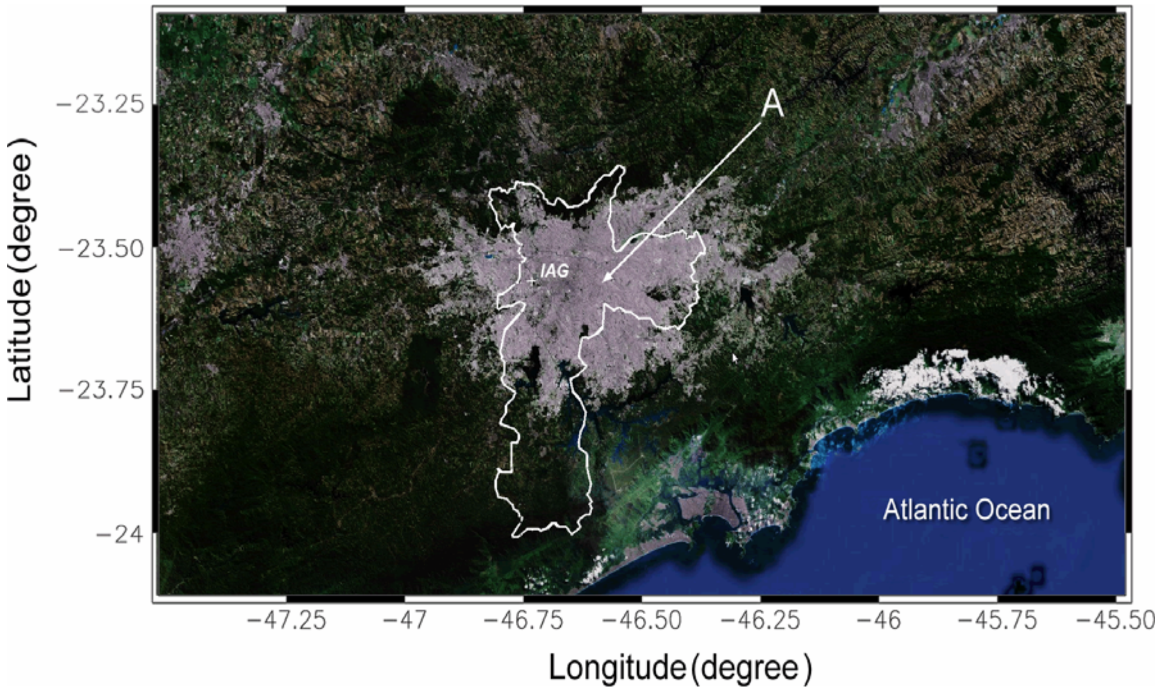


Fig. 1 The geographic position of the city of São Paulo is indicated by the white line contour in the central portion of the LANDSAT image. The most urbanized area is indicated by the light gray color. The investigated region corresponds to the intersection between São Paulo City and the light gray portion within its domain. The net radiation data was measured at IAG (23º33’35”S. 46º43’55”W)

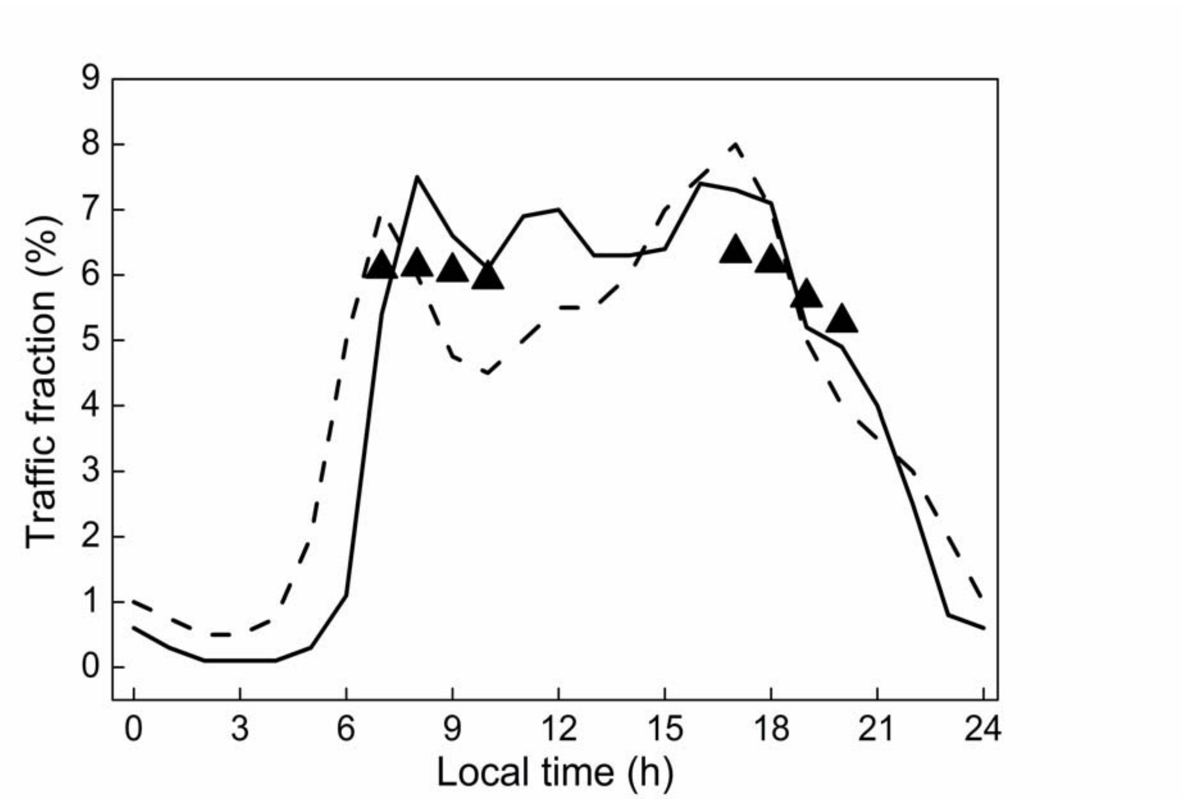


Fig. 2 Diurnal evolution of the traffic fraction of vehicles in movement within the urban region of São Paulo observed in 2004 (solid line) and during rush hours in 2007 (black triangle). As a reference, the traffic fraction in the USA, based on observations performed in 99 cities over 19 states by Hallenbeck et al. (1997), is also indicated (dashed line)

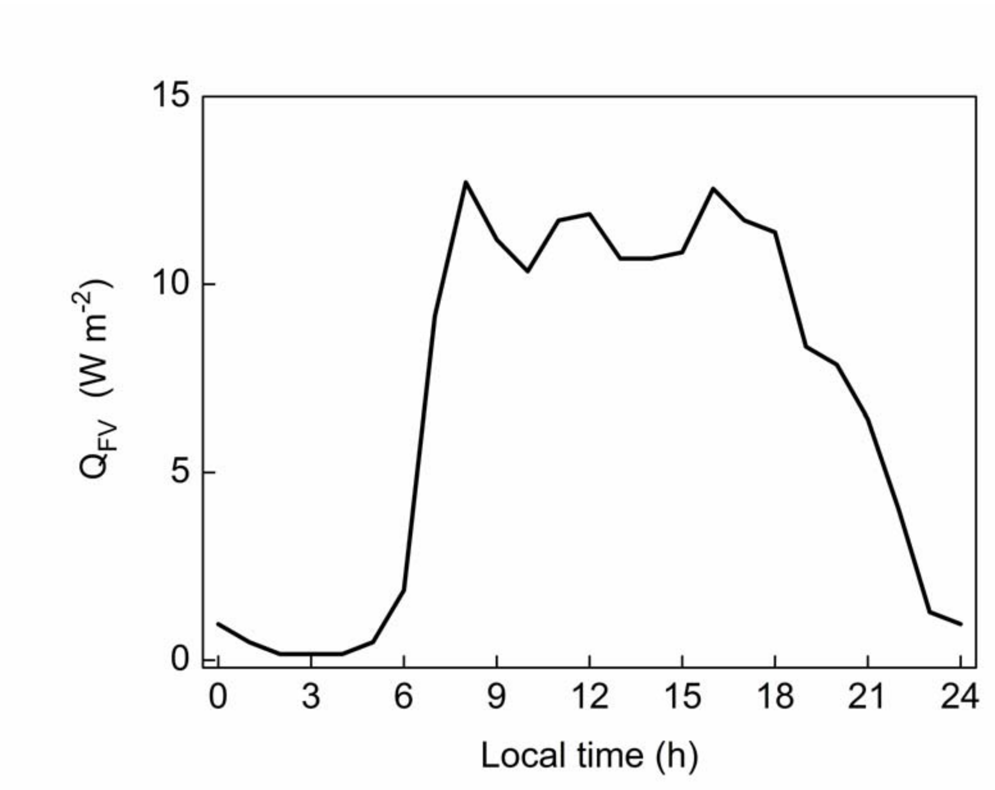


Fig. 3 Diurnal evolution of the anthropogenic energy flux associated with vehicular sources (Q_{FV}) during 2007

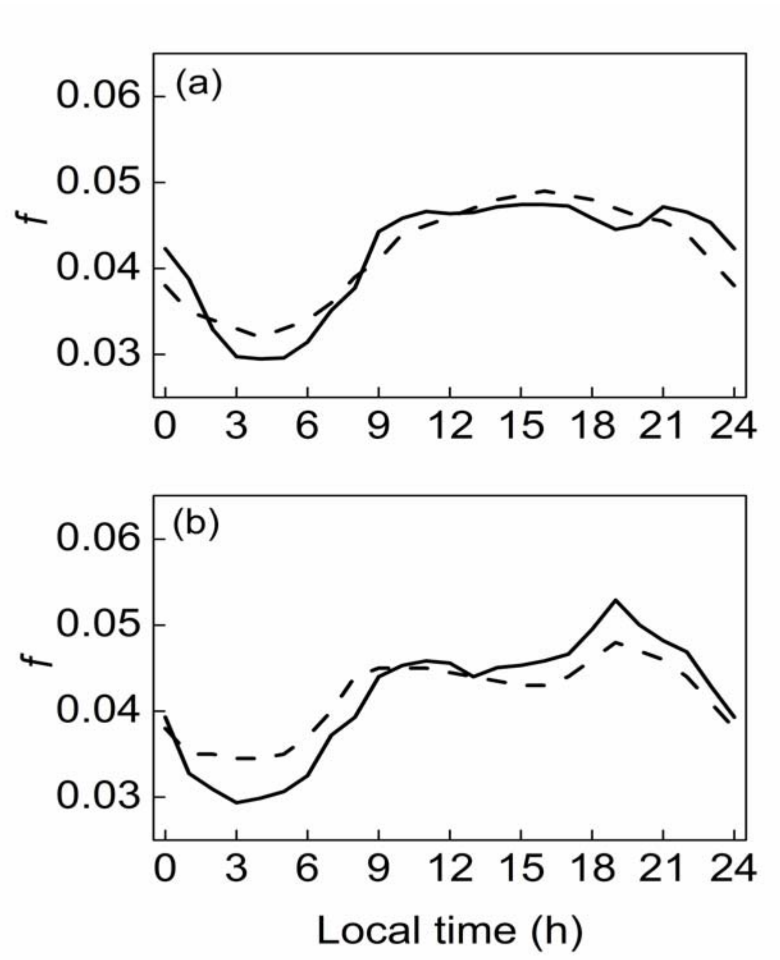


Fig. 4 Diurnal evolution of hourly fraction of daily electricity consumption *f* for (a) summer (February) and (b) winter (August) for the State of São Paulo (solid line) in 2007. Daily electricity consumption in USA (dashed line) is indicated as a reference

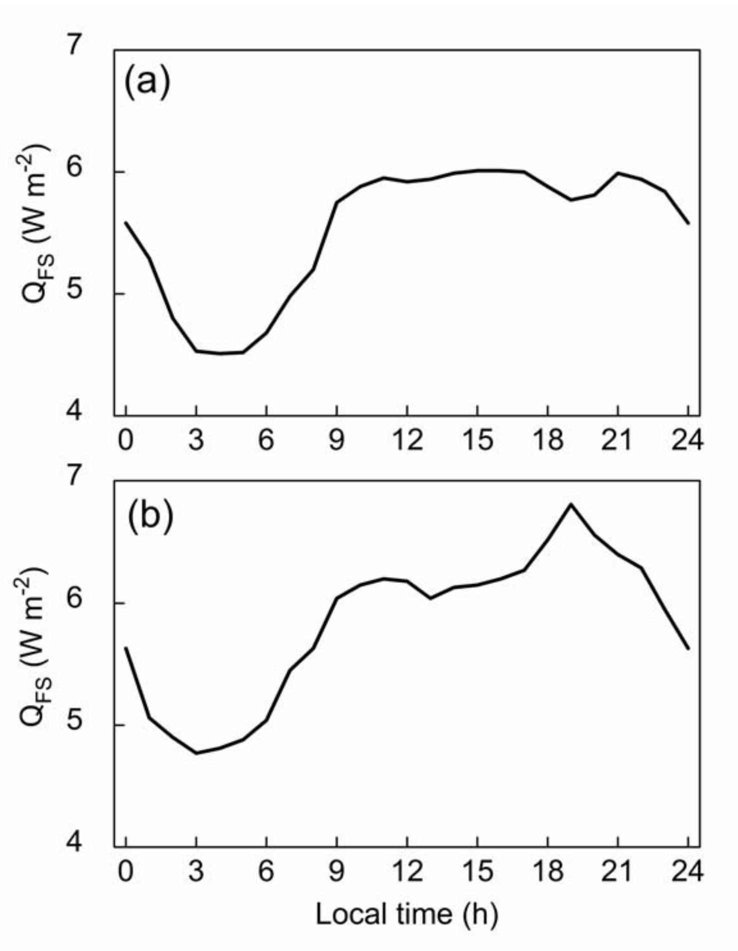


Fig. 5 Diurnal evolution of anthropogenic heat associated with stationary sources (Q_{FS}) during (a) summer (February) and (b) winter (August) in São Paulo during 2007

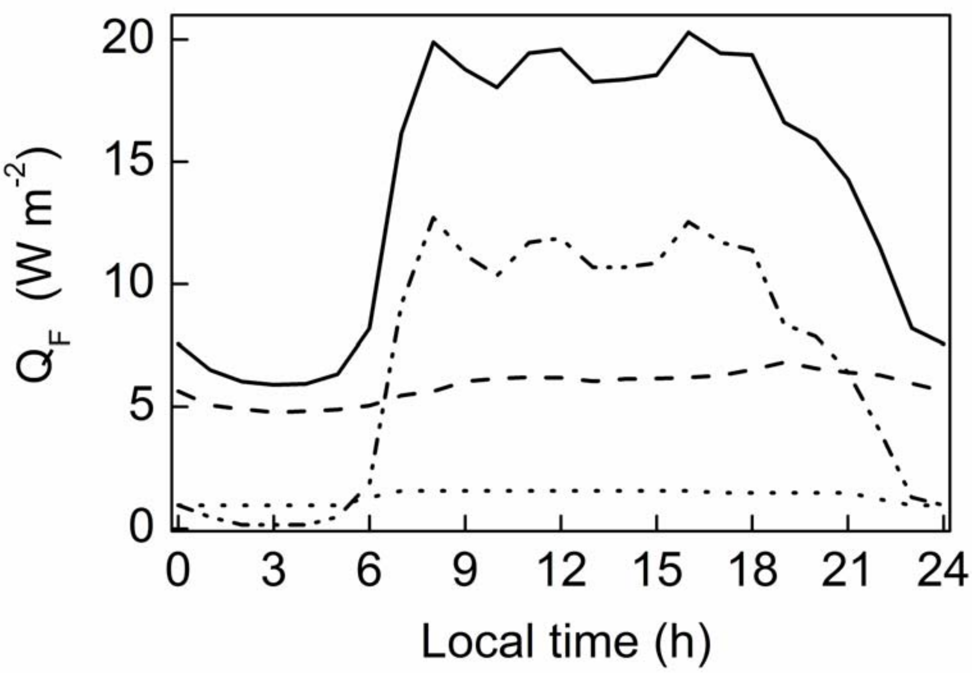


Fig. 6 Diurnal evolution of the anthropogenic energy flux (Q_F) associated with vehicular sources (dashed dotted line), stationary sources (dashed line), human metabolism (dotted line) and total (solid line) for winter (August) in the city of São Paulo in 2007

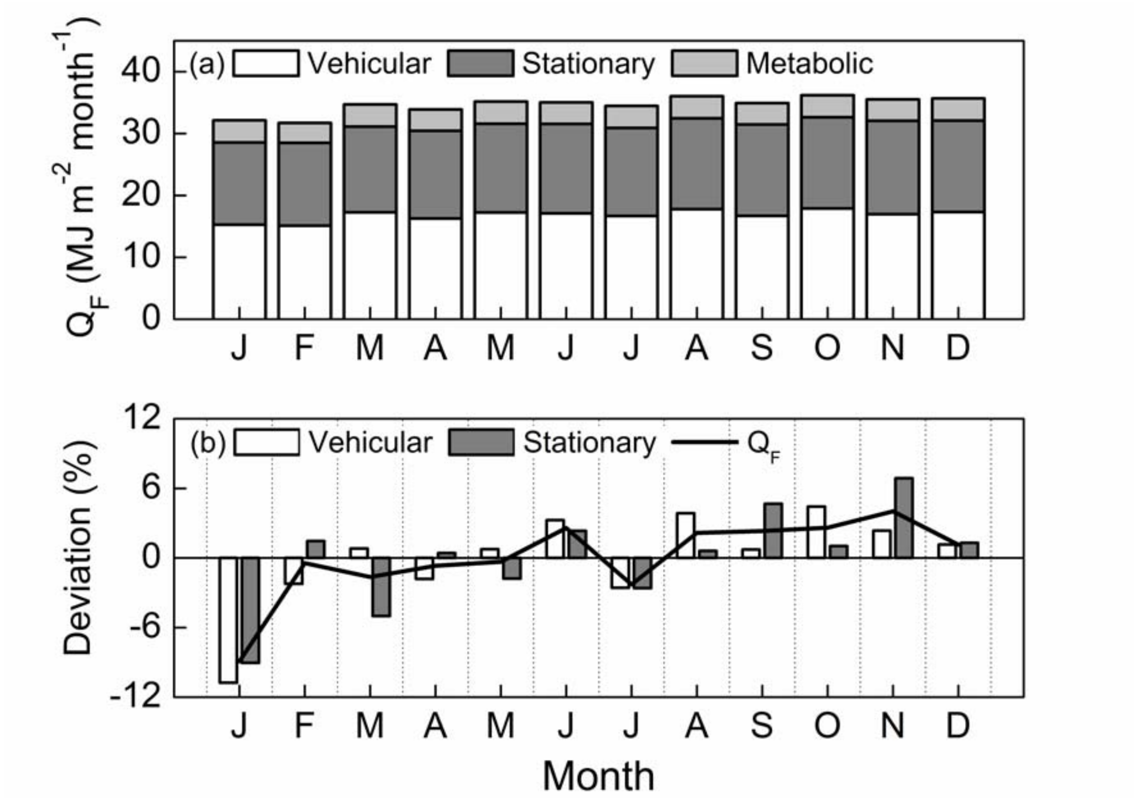
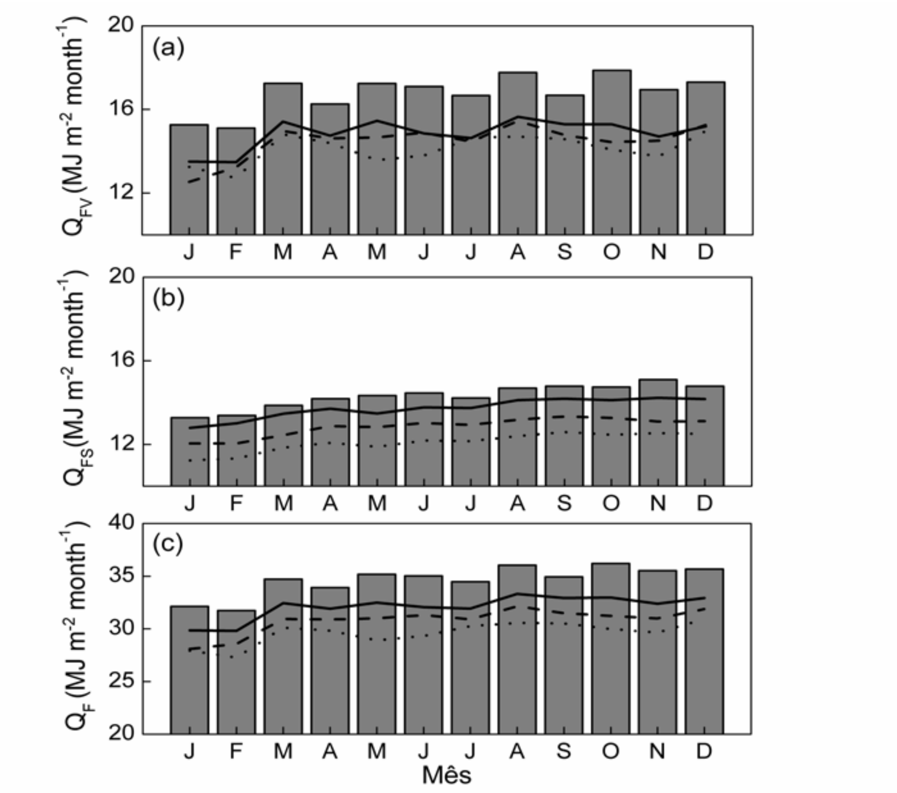


Fig. 7 Seasonal evolution of the anthropogenic energy flux associated with: (a) vehicular sources (white column), stationary sources (gray column) and metabolic sources (light gray column); and (b) relative deviation from the annual mean of the monthly values of Q_{FV} (white column), Q_{FS} (gray column) and Q_F (continuous line)



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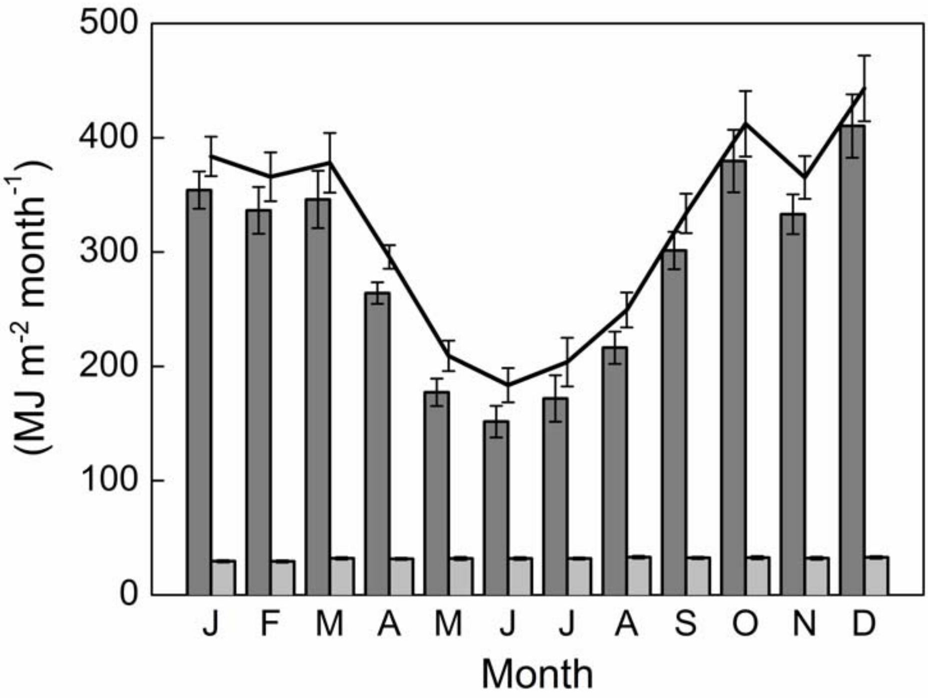

Fig. 9 Seasonal variation of the net radiation (gray column), Q_F (light gray column) and Q^*+Q_F (solid line) in the city of São Paulo. Average monthly values based on observations carried out from 2004 to 2007. The vertical lines indicate standard error

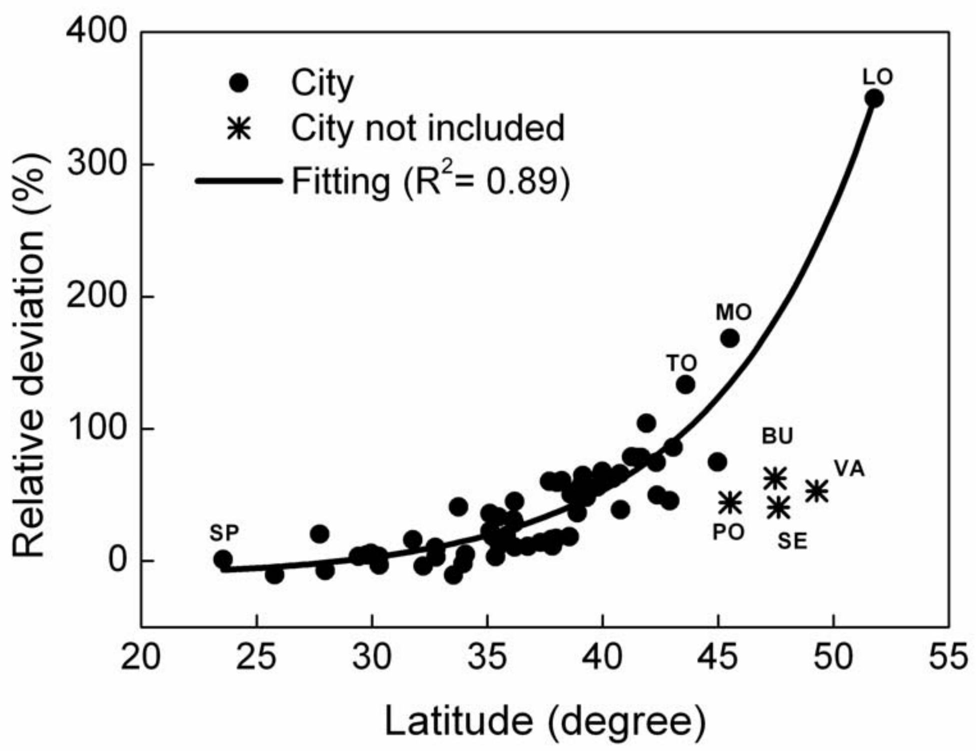

Fig. 10 Dispersion diagram between relative deviations of the anthropogenic energy flux normalized by summer values of Q_F^{MAX} for the cities indicated in Table 2 and in Table 1 of Sailor and Hart (2006). The relative deviation corresponds to Q_F^{MAX} in the winter minus Q_F^{MAX} in the summer. The fitted expression for relative deviation for latitude in degrees is: $\left(\frac{Q_F^{MAX} Winter - Q_F^{MAX} Summer}{Q_F^{MAX} Summer}\right)100\% = 0.21\exp(Lat/6.95) - 13.05$. The cities indicated by letters are described in Table 2. They correspond to São Paulo (SP), Budapest (BU), Montreal (MO), Vancouver (VA), Lodz (LO) and Toulouse (TO), Seattle (SE) and Portland (PO). They are also described in Table 1 of Sailor and Hart (2006)

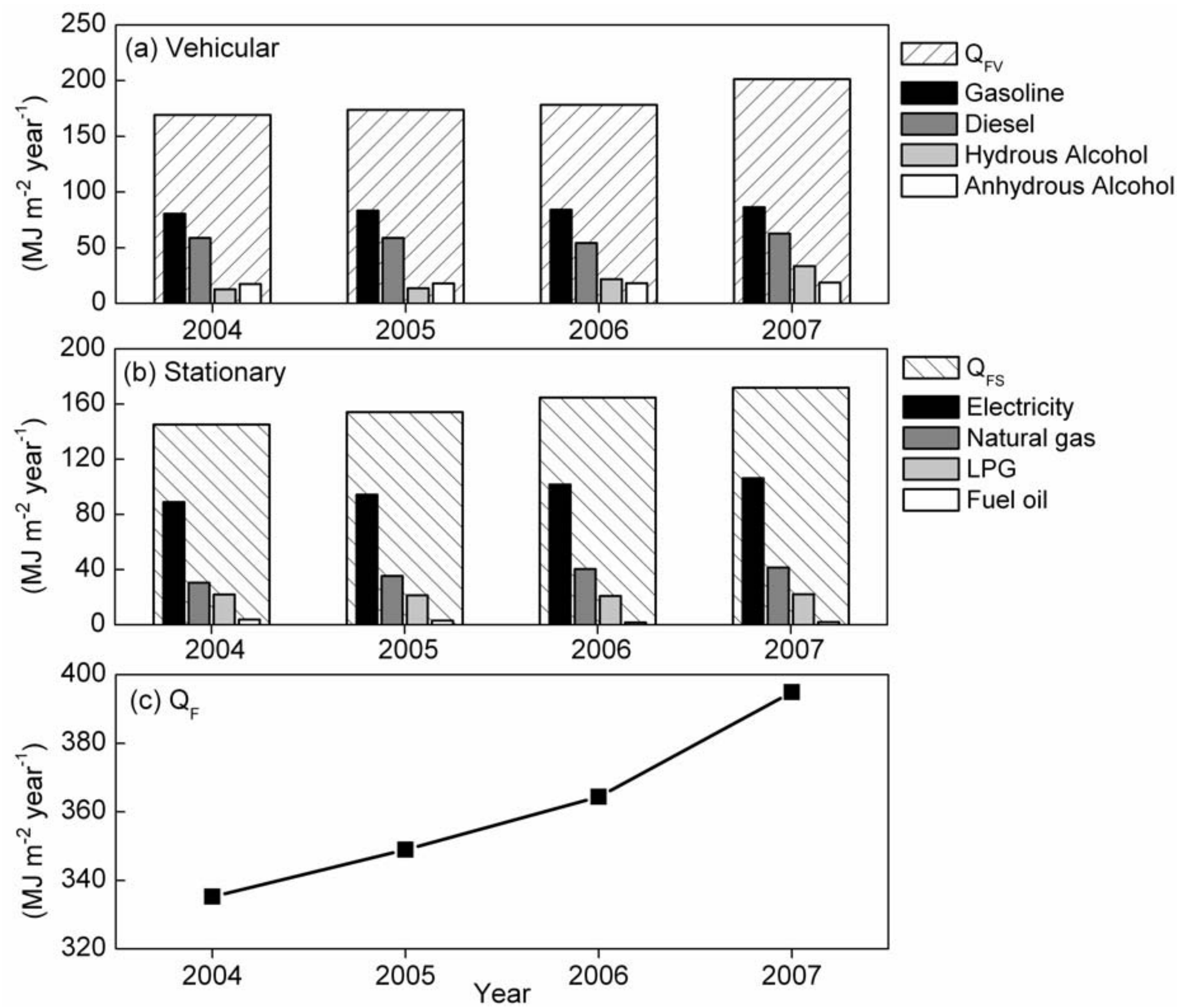

Fig. 11 Time evolution of annual values of energy released in the city of São Paulo by (a) vehicular sources associated with the consumption of gasoline, diesel oil, hydrous alcohol and anhydrous alcohol; (b) stationary sources associated with the consumption of electricity, natural gas, LPG and fuel oil; and (c) Q_F