IMPACT OF CITY VERTICALIZATION ON URBAN SURFACE ENERGY BUDGET: A MODELING STUDY
Edson Marciotto* **

*Harvard School of Public Health, Boston, USA; **Former: University of São Paulo, São Paulo, Brazil

Abstract

The impact of verticalization of cities on local climate is studied with an urban canopy model (UCM) coupled to an atmospheric turbulence model. Simulations with various aspect ratios were performed in order to assess the impact of aspect ratio on urban temperature and energy budget. Results show that net radiation suffers a decreasing as the aspect ratio increase. It is also observed the geometry of canyon affects in a substantial manner the energy partition of sensible and stored heat, decreasing the first and increasing the last. Air temperature follows the behavior of sensible heat flux. An interesting point in these results is that simple physical mechanisms can be recognized and are enough to explain all these features. The implications of these results on the causes of urban heat island are discussed.

Key words: surface energy budget, urban canopy modeling, urban heat island.

1. INTRODUCTION

Most part of the population of Brazil (80%) and also of the world (50%) lives in cities, becoming the study of the urban boundary layer (UBL) of great importance. In general, the production of pollutants derived of burning of fossil fuels like gasoline and diesel takes place in a rate superior than the UBL can disperse them, giving rise to recurrent pollution episodes. The urbanization process also affects the radiative and thermal surface properties. A third effect of the urban centers on UBL is due to anthropogenic heat. In this way, the geometry of the urban surface and the human activity directly affect the momentum, heat and humidity fluxes near the ground within the so-called urban canopy layer (UCL). The concept of UBL and UCL are discussed, for example, in Roth (2000) and Britter & Hanna (2003). A common characteristic of UCMs is the adimensionality, that is, canopy processes are described in a single grid-point. Although there exist three-dimensional models, based on computational fluid dynamics, their use for meteorological and climate purposes, e.g. coupled with a meso- or large-scale model, is not viable because of computational cost. The advantage of adimensional models is their high computational performance when coupled with atmospheric models. The results presented here was obtained with an UCM implemented by Marciotto (2008) and coupled to an 1-dimensional turbulence model by Oliveira (2003). The main goals of such an implementation is to have available a versatile tool for studying of processes in both urban canopy and urban boundary layer. In this paper the results presented will be restricted to near surface quantities. A discussion on vertical profiles and UBL time evolution is under preparation.

2. MODEL AND SIMULATIONS

The UCM is represented by an array of infinity canyons, whose aspect ratio (ratio of building height to road width, h/d) can be changed. The output heat and momentum fluxes are used to force the atmospheric turbulence model, which is a second order closure model (Mellor & Yamada, 1982). The turbulence model is one-dimensional (there is no advection scheme) and air warming/cooling due to radiation processes as well as warming/cooling due to the phase change of water vapor are not included. It is possible to take into account man made heat with aid of some hypotheses, but it is not done with the objective of studying just the role of canyon geometry on the energy budget. The UCM computes the energy budget in a similar fashion of TEB, but differs from it in some aspects such as: form of representing the turbulence exchange coefficients, form of representing the turbulent fluxes, number of layers (two instead of three) of solid surfaces, and construction of the sky view factors. UCM does not use the aerodynamic resistances suggested by Masson (2000). All turbulence exchange coefficients are represented by the classical formula (Garratt, 1992). The UCM sky view factors are based on the solid angle by which sky is "seen" by road or wall. Unlike Masson (2000), the treatment of radiative flux and heat is computed taking into account the walls of canyons separately, instead of together. In this way, west or east wall interacts with radiation and heat flux independently, being the factor $2h/d \ F_w$ substituted by $h/d \ (F_{w\w} + F_{w\e})$. As it will be seen these two treatment forms lead to different radiative budgets. The calibration of UCM was performed by fitting the global and diffusive irradiance and the air temperature at reference height (10 m). Since the model goals is concerned about local effects on urban boundary layer, data was hourly and monthly averaged over about 10 years time series in order to filter season and non-local forcings. In effect, the remaining time series of irradiance and temperature have a mean diurnal cycle which represents the atmosphere in an unperturbed state. It was chosen to simulate two typical year-days, 069 and 211, representing respectively southern summer and southern winter. To fit model outputs on the data it is expected that some canopy parameters have to be adjusted. The canopy parameter that seemed most important was the aspect ratio, whose a value of 3 allowed the best fit for

1 Email: emarciotto@yahoo.com
winter season. Once the model is calibrated, a set of eight simulations was performed. In each one aspect ratio (h/d) was the only parameter changed for a given season. In fact, distance between west and east buildings was kept unchanged and just the building height was varied. The aspect ratios were used to represent urban canopies ranging from low buildings and/or wide roads to tall buildings and/or narrow roads and the values are: 0.1, 0.2, 0.5, 1.0, 2.0, 3.0 4.0 and 10.0.

3. RESULTS AND DISCUSSION

In the computation of radiative flux the direction of the canyon relative to NS direction was ranged from 0° to 90°. The averaged value take over all directions was also considered. The maximum difference TEB–UCM ranges from –16 W/m², for an array of canyons perpendicular to the NS direction, up to –60 W/m², for canyon parallel to the NS direction. The averaged value of maximum difference for all directions is approximately –40 W/m² (Fig. 1). Such a difference can generate large bias in the estimate of heat fluxes in general and particularly in anthropogenic heat, whose modeling is strongly-dependent of urban/social structure of each city in particular and linked in a weaker way to natural phenomena.

![Figure 1](image.png)

**Figure 1.** Direct plus diffusive solar radiation budget obtained taking into account the two walls together (continuum line) and taking into account the walls separately (dashed line). The difference in the budget on canyon walls is shown by the dotted line. The greatest differences occur at time of most insulation, 0900 and 1500 LT. Values for h/d = 1.

The lack of suitable observational constraints in urban studies is still a shortcoming, especially in developing countries. As an example, some estimates of anthropogenic heat flux for the metropolitan area of São Paulo – Brazil (MASP) show that this component of energy budget is not greater than 60 W/m² (Ferreira, 2007). Hence, a model that underestimates the net short-wave in up to 40 W/m² will lead the anthropogenic heat estimates to 100 W/m² for MASP. The sensible heat flux estimated by Ferreira (2007) is smaller than canopy energy stored flux. There are several studies in the literature which show that the G/H ratio may be either greater or less than 1. The main difference of these works is the site which is studied. Even though characteristic aspects (building height, vegetation cover, etc) of such localities were not analyzed yet, it seems that the G/H ratio is a local feature. Mean thermal properties and the water availability of each site also affect the ratio between the energy budget components. Nonetheless, the simulations with the UCM lead to conclude that the aspect ratio plays the most important role.

The impact of aspect ratio on the energy budget components is shown in Fig. 2. The canopy stored energy flux increase with h/d, whereas the sensible heat flux presents an opposite behavior. As can be seen, net radiation decreases almost linearly as h/d increases. Latent heat flux presents a strange behavior which will be studied in the future. However, this aspect does not prejudice the analysis since the variations of LE is very small compared to the other fluxes. The net radiation behavior is a straight consequence of the increasing shadow areas within the canopy. In the range of h/d simulated, net radiation varies of approximately 104 W/m² in summer and 36 W/m² in winter. Fig. 3 shows how air temperature changes as a function of h/d. In all cases the temperature decreases as the aspect ratio increases; an asymptotic behavior for daylight period can be observed. By comparing the air temperature behavior for each hour of diurnal cycle, as a function of h/d, it is found that during night-time the air temperature suffers a decrease greater than during daytime. Summer values are −3.7 °C at 1200 LT and −6.4 °C at 2400 LT, whereas in winter it has obtained −4.7 °C and −5.5 °C. Tab. 1 summarizes the total variation of air temperature and fluxes with respect to a variation of the aspect ratio of 10 – 0.1.

An equivalent statement is that air temperature over the urban canopy decrease as a function of building height; therefore, it is not possible conclude that is the geometric feature of cities verticalization a prior cause of the UHI. Nonetheless, the classical study by Oke (1982) shows that UHI intensity is an increasing function of h (which is equivalent to say that UHI intensity decreases with the sky view factor, Ψ, as shown in Oke’s plot). In this point, it is needed to separate the various contributions that the verticalization brings to the energy budget.
The main factors which increases with verticalization (and their contribution) are: long-wave trapping (positive), shadowed area (negative), anthropogenic heat (positive) and canopy mass (negative). Results show an increased long-wave trapping for higher aspect ratios, but the behavior, even though similar, is not the same as that encountered in Oke (1982). Shadowed areas contribute for a reduction in the amount of stored energy during the day, which implies less long-wave emission by canopy surfaces at night. Therefore, the trapping of long-wave radiation at night do not seem to be the principal cause of an UHI intensity of up to 12 °C as mentioned in Oke (1982). On the other hand, a strong correlation between population city and UHI intensity is found. Then one can suppose that UHI should be mainly associated to the density of human activity per unit area, which in turn is roughly proportional to the aspect ratio. Another important factor that influences directly the UHI intensity is related to the difference between rural and urban energy budget due to the amount of available surface water to evaporate. The latent heat of vaporization of water is very high (2.5 MJ/kg) so that a little variation in the amount of surface water could alter substantially the energy partition between the turbulent fluxes. Simulations performed with the UCM (not presented here), representing a dry urban canopy, reveals that for a given aspect ratio UHI is intensified when the fraction of urban area is larger. Thus, in the absence of anthropogenic heat production and for a dry urban canopy, one can conclude that the UHI is better associated to the horizontal scale of cities. The higher is the aspect ratio the larger is the urban canopy mass, consequently the input energy in the urban area is...
distributed over a larger amount of material, resulting a lower surface and air temperature. A model by Tso et al. (1990), which takes into account the mass of urban canopy per unit area, suggests that the explanation of the proposed cooling mechanism of the canopy due to the increase of the aspect ratio is correct. The decay of maximum temperature presented by Tso et al. (1990) is linear within the range of building mass considered, instead of roughly exponential as shown in Fig. 3. Since the mass canopy increase directly proportional to the height building, one could think that Fig. 3 is not consistent a priori with Tso et al. results. But a fundamental difference between them is the presence of shadowed regions in UCM, which contributes further to the temperature reduction as the height (therefore, mass) of buildings gets higher. The model by Tso et al. has no vertical structure, consisting of the ground surface only. UCM temperature results present a more complex behavior due to the shadow effect that is not present in Tso et al. model.

The effect of the verticalization on decrease of the air temperature was also observed in the experiments in reduced scale of Pearlmutter et al. (2006). They concluded that cities with compact arrangement in areas of hot and dry climate, like the case presented here, tend to have smaller temperatures when compared with more sparse arrangements. It is important to highlight that the experiment of Pearlmutter et al. use an array of concrete canyons, becoming this reduced model much closer than that is represented by UCM. Another way of the aspect ratio to influence the rate of air cooling would be due to the sensible heat flux, once the roughness length is calculated from building height and affects directly the sensible heat flux, which is calculated by means of bulk formulas. However, UCM simulations show that sensible heat flux divided mean velocity ($H/U$) keeps a similar behavior as shown in Fig. 2. Therefore, decreasing mean velocity over the urban canopy is not responsible for sensible heat behavior encountered in the simulations.

4. CONCLUSION

The simulations using the UCM implemented by Marciotto (2008) suggests that the geometric aspect of verticalization alone acts in the opposite direction of the UHI. When the aspect ratio (equivalently the building height) is increased and provided that other settings keep the same, the energy stored flux becomes larger whereas the sensible heat flux becomes smaller. The impact of verticalization on energy budget suggests the human activity per unit area must be at least partially associated to the UHI intensity. The described process above, perhaps, have not been noted yet because in most of the existent observational works in the literature such a dependence of the aspect ratio was masqueraded by other variables (anthropogenic heat, the low availability of water, high heterogeneity, etc.) which are considered together explicit or implicitly in the measurement process. Of course, like all models the UCM has some shortcomings, but the underlying physics implied by the analyses of results is very simple, indeed, no further than energy conservation. In the model, canopy homogeneity is fundamental to observe clearly the impact of verticalization. In real scale field experiments the required homogeneity is not matched. Thus, more experiments like that of Pearlmutter et al. (2006) or an adaptation of COSMO experiment (Kanda et al., 2005) would be ideal to verify the impact of geometry on meteorological quantities presented here.

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