ARTICLE IN PRESS

Building and Environment xxx (2010) 1–9

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Modeling study of the aspect ratio influence on urban canopy energy fluxes with a modified wall-canyon energy budget scheme

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ARTICLE INFO

Article history:
Received 4 February 2010
Received in revised form
5 May 2010
Accepted 9 May 2010

Keywords:
Energy budget
Urban canopy
Modeling
Aspect ratio

ABSTRACT

The influence of the aspect ratio (building height/street canyon width) and the mean building height of cities on local energy fluxes and temperatures is studied by means of an Urban Canopy Model (UCM) coupled with a one-dimensional second-order turbulence closure model. The UCM presented is similar to the Town Energy Balance (TEB) model in most of its features but differs in a few important aspects. In particular, the street canyon walls are treated separately which leads to a different budget of radiation within the street canyon walls. The UCM has been calibrated using observations of incoming global and diffuse solar radiation, incoming long-wave radiation and air temperature at a site in São Paulo, Brazil. Sensitivity studies with various aspect ratios have been performed to assess their impact on urban temperatures and energy fluxes at the top of the canopy layer. In these simulations, it is assumed that the anthropogenic heat flux and latent heat fluxes are negligible. Results show that the simulated net radiation and sensible heat fluxes at the top of the canopy decrease and the stored heat increases as the aspect ratio increases. The simulated air temperature follows the behavior of the sensible heat flux.

1. Introduction

About 50% of the world's population lives in cities [17], and the fraction is growing. Thus the study of the urban boundary layer and urban climate is of great importance.

In built-up areas, where most of the urban population is usually found, the urban structures affect the radiative and thermal surface properties. For instance, as the building height increases, the shadowed area becomes obviously larger. Reviews and details concerning the urban boundary layer or the urban canopy layer are discussed in many references (e.g., [2,25]). A review of the urban energy fluxes is given by Oke [20]. The methods used for investigating the urban canopy layer do not differ much from those employed to study crop or forest canopies. There are a number of three-dimensional urban canopy models available. For example, five models based on Computational Fluid Dynamics (CFD) are compared in Hanna et al. [5]. However, CFD models are not usually employed in combination with operational mesoscale meteorological models because of the computational cost. On the other hand, non-dimensional UCMs such as the Town Energy Balance (TEB) method [13] are often coupled with mesoscale meteorological models (see also Refs. [9,12]). The simulations presented here were obtained by using a UCM coupled with a one-dimensional (vertical) turbulent transport model [10,11]. The UCM code employed in this study is mostly based on Masson's [13] TEB but independently implemented by Marciotto [10]. The general goal of such an implementation is to have available a versatile tool for a better understanding of processes in both the urban canopy and the urban boundary layer above the canopy. In this paper the analysis focuses on near-surface quantities, at approximately the elevation of the urban canopy. The main goal of this paper is to investigate the influence of building height and aspect ratio on urban energy fluxes in order to improve upon the TEB model. Ali-Toudert and Mayer [1] have reported on the influence of the aspect ratio on the urban air temperature and on the thermal comfort in urban canopies. They stress that a planned combination of suitable aspect ratios and canyon orientation can improve thermal comfort at pedestrian level. The impact of aspect ratio on air and surface temperature has also been recently reported by Memon et al. [16] who found a positive correlation for uniform surface heating (assumed to represent a nighttime period) but a slightly negative correlation for direct surface heating (assumed to represent a daytime period). Thus, it becomes apparent that the aspect ratio can influence the surface and air temperatures and, consequently, the energy fluxes in urban canyons.

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doi:10.1016/j.buildenv.2010.05.012

List of symbols

Latin

A	ratio of urban area to the total area (urban plus rural) (dimensionless)
b	building width (m)
c_p	dry air specific heat capacity at constant pressure (J K $^{-1}$ kg^{-1})
C_D	momentum transfer coefficient (drag coefficient) (dimensionless)
C_H	heat transfer coefficient (dimensionless)
d	distance between buildings (m)
d_0	zero-plane displacement height (m)
h	building height (m)
h/d	aspect ratio (dimensionless)
Q_H	sensible heat flux (W m^{-2})
Q_S	stored energy flux in the canopy (road, walls, roof and air inside the building (W m^{-2}))
Q^*	net radiation flux at a particular solid surface (W m^{-2})
S_0	global (direct plus diffuse) solar radiation flux at the canopy top (W m^{-2})
S^{dir}	direct solar radiation flux incident at a particular surface (W m^{-2})
S^{dif}	diffuse solar radiation flux (W m^{-2})
U_{air}	wind speed at the first level of the turbulence model (used to feed the urban canopy model) (m s^{-1})
U_{can}	wind speed at street canyon center (calculated from U_{top} using a exponential profile) (m s^{-1})
U_{top}	wind speed at the street canyon top (calculated from U_{air} using a logarithm profile) (m s^{-1})
z_0	roughness length (m)

Greek

α	angle which defines the sky view factor for the road; albedo of a particular solid surface (rad)
β	angle which defines the sky view factor for the walls (rad)
λ	zenith angle (rad)
λ_0	zenith angle which determines the complete road shading ($\equiv\beta$, above) (rad)
ρ	air density (kg m^{-3})
χ	ratio of direct to global solar radiation flux (dimensionless)
Ψ	sky view factor (dimensionless)

Subscripts

f	roof
r	road/street
w	wall (west or east)
ww	west wall
we	east wall
(i)	inner wall layer

2. Model

Masson's [13] TEB model is used as a basis for the modifications discussed below. The urban canopy is represented in a one-dimensional model such as TEB by an array of infinite street canyons whose aspect ratio (ratio of building height to distance between buildings, h/d) is allowed to be varied. The simulated heat and momentum fluxes are used as inputs to an atmospheric turbulence closure model implemented by Oliveira [23] based on Mellor and Yamada [14,15] and using parameterizations of results of large eddy simulations presented by Nakanishi [18]. The turbulence closure model is one-dimensional (there are no horizontal gradients). Air warming or cooling due to radiation flux divergence and due to the phase change of water vapor are not included. The UCM computes the energy fluxes in a similar manner as the TEB model described by Masson [13]. However, the UCM described in this paper differs from TEB in some important aspects such as

(a) the number of layers of solid surfaces;
(b) the construction of the sky view factors;
(c) the method of accounting for the energy fluxes on walls;
(d) the computation of transfer coefficients for turbulent fluxes;
(e) the way that the fluxes are combined to form the average fluxes.

The UCM version presented here uses two layers to describe the heat conduction into roads, walls and roofs. Its outputs have been found to be similar to those from an earlier implementation with three layers, provided the thicknesses of the two layers are carefully chosen.

The diffuse components of solar short-wave and downward atmospheric long-wave radiation that reach the surfaces of the canyon are computed using the sky view factor for a given point on the road, Ψ_r, and on the wall, Ψ_w. The sky view factor is defined as the fraction of the sky that is visible from a given point on the solid surfaces. In this UCM, it is based on the solid angle through which diffuse radiation can strike the solid surfaces, being computed as the ratio of the solid angle of visible sky to the solid angle of a flat open field. Since it is assumed that the canyon is infinitely long, the sky view factor is estimated in terms of plane angles instead of solid angles. As shown in Fig. 1, Ψ_r is the arc defined by the angle α divided by 180°, and Ψ_w is the arc defined by the angle β divided by 180°. Note that Ψ_r is calculated at the middle of the street ($y = d/2$) and Ψ_w is calculated at the bottom of the wall ($z = 0$).

$$\Psi_r(y = d/2) = \begin{Bmatrix} 1+\frac{1}{\pi}\arctan\left(\frac{h/d}{(h/d)^2-1/4}\right) \text{ for } h/d \le 1/2 \\ 1+\frac{1}{\pi}\arctan\left(\frac{h/d}{(h/d)^2-1/4}\right) \text{ for } h/d > 1/2 \end{Bmatrix}, \quad (1a)$$

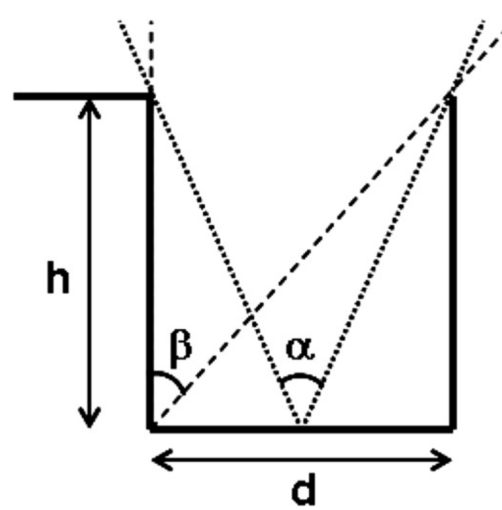

Fig. 1. Street canyon cross-section illustrating geometric shapes and definitions of the angles used for computing the sky view factors.

$$\Psi_{\mathrm{w}}(z=0)=\frac{1}{\pi}\arctan\left(\frac{1}{h/d}\right). \tag{1b}$$

In fact, the sky view factor varies from one point to another on the road or on the wall, such that a more precise formula might be given through the integration of point-values across the road and the wall. However, these variations are very slight (less than 10%) and do not significantly change the values [7]. The sky view factors for the road and walls are calculated using the above equations as a function of the aspect ratio are shown in Fig. 2, where they are compared with those proposed by Oke [19] and Masson [13].

To derive the equations describing the incoming direct solar radiation on each solid surface, road, west wall, east wall and roof, it is assumed that the zenith angle varies from the East ($-\pi/2$) to the West ($\pi/2$) so that we obtain:

$$S_{\mathrm{r}}^{\mathrm{dir}}=\begin{cases}\chi S_0\left(1-\frac{\tan\lambda}{\tan\lambda_0}\right) & \text{for } |\lambda|\leq\lambda_0\\ 0 & \text{for } |\lambda|>\lambda_0\end{cases}, \tag{2a}$$

$$S_{\mathrm{ww}}^{\mathrm{dir}}=\begin{cases}\chi S_0\tan\lambda_0 & \text{for } -\frac{\pi}{2}\leq\lambda<-\lambda_0\\ \chi S_0\tan\lambda & \text{for } -\lambda_0\leq\lambda<0\\ 0 & \text{for } 0\leq\lambda\leq\frac{\pi}{2}\end{cases}, \tag{2b}$$

$$S_{\mathrm{we}}^{\mathrm{dir}}=\begin{cases}0 & \text{for } -\frac{\pi}{2}\leq\lambda<0\\ \chi S_0\tan\lambda & \text{for } 0\leq\lambda<\lambda_0\\ \chi S_0\tan\lambda_0 & \text{for } \lambda_0\leq\lambda\leq\frac{\pi}{2}\end{cases}, \tag{2c}$$

$$S_{\mathrm{f}}^{\mathrm{dir}}=\chi S_0, \tag{2d}$$

where S_0 is the global downward short-wave radiation at the canyon top, λ is the zenith angle, $\lambda_0=\arctan[1/(h/d)]$ is the angle that implies complete road shading, and χ is the ratio of the direct solar radiation to the global solar radiation. These equations assume that the canyon array is oriented in the North–South direction. If the canyon orientation is other than N–S, all terms in which the zenith angle appears have to be multiplied by a factor $\sin\theta$, where θ is the direction relative to N–S. The diffuse radiation is assumed to be isotropic and its incoming value for each surface is distinguished from others just by the sky view factor Ψ:

$$S_{\mathrm{r,w,f}}^{\mathrm{dif}}=(1-\chi)\Psi_{\mathrm{r,w,f}}S_0. \tag{3}$$

The net radiation, i.e. short- plus long-wave, on each surface is computed in the same manner as in Masson [13] but applying corrections because the walls are treated separately. It follows that the incoming radiation over the road and walls decreases as the aspect ratio increase.

All transfer coefficients (proportional to u^{*2}/U^2, where u^* is the friction velocity and U is the wind) are represented by the standard formula suggested by Enriquez and Friehe [3] and Garratt [4]:

$$\frac{\kappa^2}{\ln\left(\frac{z-d_0}{z_0}\right)^2}. \tag{4}$$

The roughness lengths, z_0, for momentum and heat are assumed to be the same. Atmospheric stability is assumed to have minimal effect in a built-up urban environment [2]. The atmospheric stability within the urban roughness layer area is close to neutral or adiabatic because of the intense mechanical mixing due to the buildings, and due to the anthropogenic heat fluxes that are present day and night. The sensible heat flux contribution of each solid surface, and the street canyon itself are then given by a bulk formulation:

$$Q_{\mathrm{H\ r,ww,we}}=\rho c_{\mathrm{p}}C_{\mathrm{H1}}U_{\mathrm{can}}\left(T_{\mathrm{r,ww,we}}-T_{\mathrm{can}}\right), \tag{5}$$

$$Q_{\mathrm{H\ f}}=\rho c_{\mathrm{p}}C_{\mathrm{H2}}U_{\mathrm{top}}\left(T_{\mathrm{f}}-T_{\mathrm{air}}\right). \tag{6}$$

$$Q_{\mathrm{H\ can}}=\rho c_{\mathrm{p}}C_{\mathrm{H2}}U_{\mathrm{air}}(T_{\mathrm{can}}-T_{\mathrm{air}}), \tag{7}$$

where the subscripts r, ww, we and f refer, respectively, to road (street), west wall, east wall and roof, ρ is the air density, c_{p} is the specific heat at constant pressure, and T_{can} and T_{air} are, respectively, the air temperature in the center of the canyon ($d/2$, $h/2$) and the air temperature above the canopy. The difference between C_{H1} and C_{H2} depends on the values of z_0 and d_0. For the street and walls U_{can} is the wind speed assumed to be in the center of the canyon ($d/2$, $h/2$) and U_{top} is the wind speed above the canopy. The radiative and sensible heat fluxes from the canyon walls are computed by taking into account the two side walls of the canyons separately. This assumption is slightly different from that of Masson [13] who accounted for the canyon walls together. Hence, in UCM, the west and east walls interact with radiation and sensible heat flux independently. The short- and long-wave diffuse radiations are also affected by the two-wall representation. The components of the sensible heat flux within the canyon, for example, are written as

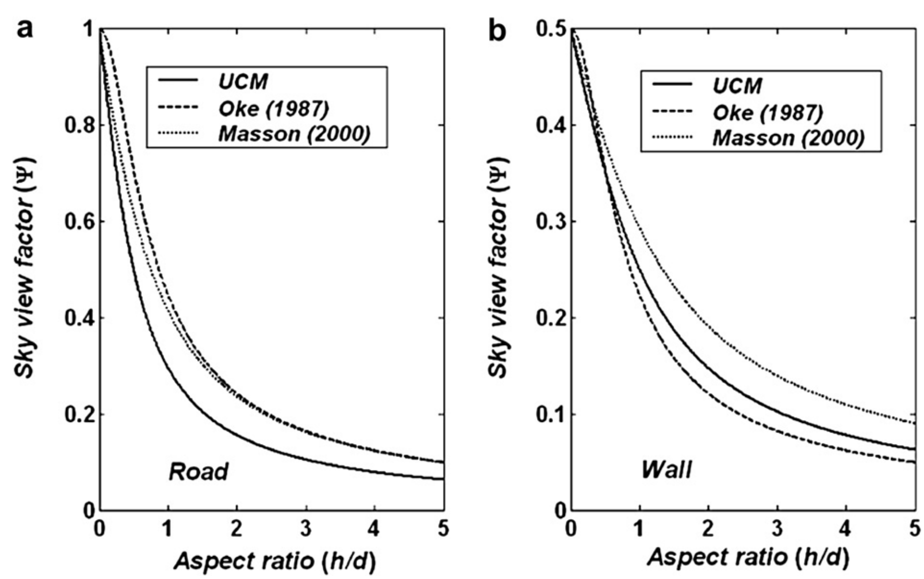

Fig. 2. Comparison of road (i.e., street) and building wall sky view factors as a function of aspect ratio for three models: UCM, Oke (1987) and Masson (2000).

$$Q_{\mathrm{H\ can}} = Q_{\mathrm{H\ r}} + \frac{h}{d}(Q_{\mathrm{H\ ww}} + Q_{\mathrm{H\ we}}) \quad \text{(wall contribution computed separately)}, \tag{8}$$

instead of

$$Q_{\mathrm{H\ can}} = Q_{\mathrm{H\ r}} + \frac{2h}{d}Q_{\mathrm{H\ w}} \quad \text{(wall contribution computed together)}, \tag{9}$$

in which H_{can} is the total canopy sensible heat flux leaving the top of the canopy, and H_{r}, H_{ww} and H_{we} are, respectively, the street, west wall and east wall contributions to the total canyon sensible heat flux. Also, H_{w} is the combined sensible heat flux of the west and east walls. For short-wave radiation the treatment is analogous, and the factor $2h/d$ is replaced by h/d. As it will be seen in the Section 4, the TEB and UCM treatments lead to slightly different energy fluxes.

The coupling of the second-order turbulence closure model with the UCM is carried out via characteristic scales and via the temperature, wind and humidity near the ground or street surface level. The turbulence model provides wind speed, temperature and humidity at a reference height, z_{R}, about 10 m above the ground level (Fig. 3), which are assumed to apply in the UCM at a level of $2h$. This accounts for a situation in which the wind streamline is shifted up as it approaches a built-up area. Hanna et al. [6] analyzed data from JU2003 (Oklahoma City), Urban 2000 (Salt Lake City) and MSG05 (New York City), and found that the mean scalar wind speed and direction on the tops of downtown building, from 100 m up to 300 m tall, are approximately equal to winds observed at a height of 10 m at a nearby airport. Hence, the use of an upwind speed from a lower level to feed the urban canopy model is quite reasonable.

The output characteristic scales (u_* and T_* and q_*) are computed from fluxes which apply to the entire canopy layer. The canopy may have a height greater than the first turbulence level, even though the output characteristic scales feed the turbulence model at the level of about 10 m. Since the parameterizations do not take into account the effects of channeling or re-circulations inside the canyon, only the magnitude of the wind velocity (i.e., the wind speed) is important as an input to UCM. The wind speeds at the top of the canyon and inside the canyon are determined following the methodology suggested by Masson [13]. U_{top} is calculated from U_{air} (the input wind speed at the first level of the turbulence model) by means of a logarithmic profile, and U_{can} is calculated from U_{top} using an exponential profile. A smooth blending of the logarithmic profile at $z > h$ and the exponential profile at $z < h$ is then imposed. The UCM can also account for the fractional area of vegetation cover, $(1 - A)$, where A is the fractional area of urban surfaces ($0 \le A \le 1$). Therefore the total flux is $AF_{\mathrm{urban}} + (1 - A)F_{\mathrm{rural}}$. However, in the current paper, only urban surfaces are studied and hence $A = 1$. The mean canopy sensible flux is then given by the weighted area average

$$Q_{\mathrm{H}} = \frac{bQ_{\mathrm{H\ f}} + dQ_{\mathrm{H\ r}} + h(Q_{\mathrm{H\ ww}} + Q_{\mathrm{H\ we}})}{b + d}, \tag{10}$$

and the canyon temperature is obtained from Eqs. (5), (7) and (8) by assuming that the fluxes are in equilibrium in each time step:

$$T_{\mathrm{can}} = \frac{T_{\mathrm{r}} + \dfrac{h}{d}(T_{\mathrm{ww}} + T_{\mathrm{we}}) + \dfrac{C_{\mathrm{H2}}U_{\mathrm{air}}}{C_{\mathrm{H1}}U_{\mathrm{can}}}T_{\mathrm{air}}}{1 + \dfrac{2h}{d} + \dfrac{C_{\mathrm{H2}}U_{\mathrm{air}}}{C_{\mathrm{H1}}U_{\mathrm{can}}}}. \tag{11}$$

The canopy effective radiation flux Q^* and storage 'flux' Q_{S} are computed from their respective solid surface fluxes in the same way as the sensible heat flux. Note that the so-called 'canopy' variables actually apply at a level of approximately h (i.e., mean building height).

UCM allows the inner building temperature, T_{in}, to vary as the heat flux divergence inside the building varies:

$$\rho c_{\mathrm{p}}\frac{\partial T_{\mathrm{in}}}{\partial t} = -\nabla\cdot\left(0, H_{\mathrm{(i)ww}} + H_{\mathrm{(i)we}}, H_{\mathrm{(i)f}}\right). \tag{12}$$

The fluxes from the inner walls and the inner ceiling into the air inside the building are computed as

$$\left(H_{\mathrm{(i)ww}} + H_{\mathrm{(i)we}}, H_{\mathrm{(i)f}}\right) = -k\left(\frac{T_{\mathrm{(i)ww}} - T_{\mathrm{in}}}{b/2} + \frac{T_{\mathrm{(i)we}} - T_{\mathrm{in}}}{b/2}, \frac{T_{\mathrm{(i)f}} - T_{\mathrm{in}}}{h/2}\right), \tag{13}$$

and the gradient operator is scaled as $(0,1/(b/2),1/(h/2))$, where b is the building width. Note that those fluxes are defined to be positive

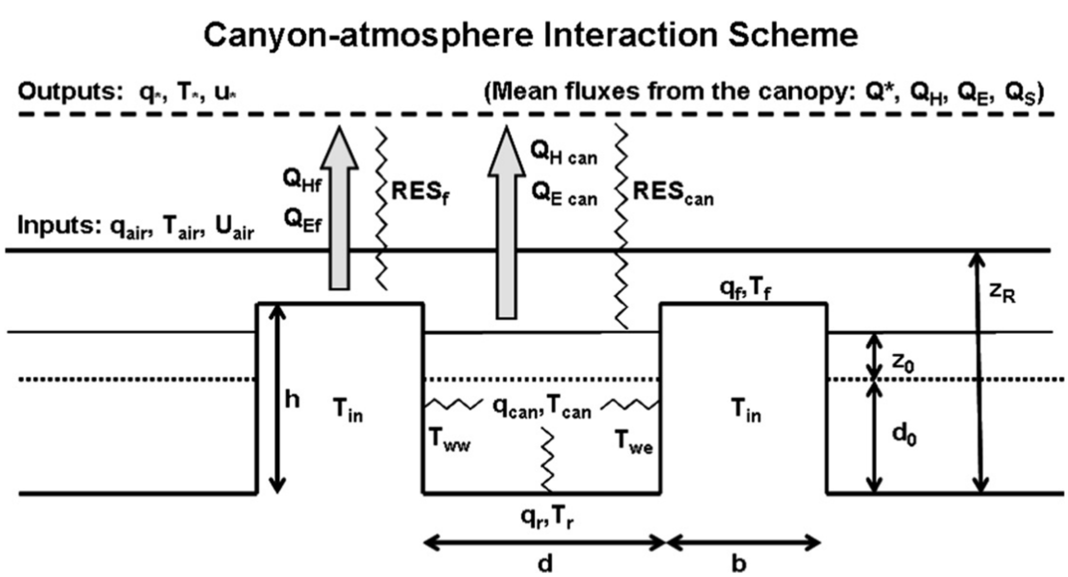

Fig. 3. Sketch of the canopy–atmosphere model interaction. The second-order turbulence closure model is fed by the characteristic scales of velocity u^*, temperature T^*, and humidity q^* at the first level where the second-order statistical moments (variances and covariances) are computed. The turbulence closure model, in turn, feeds the UCM with U_{R}, T_{R} and q_{R}, at the reference height $z_{\mathrm{R}} \approx 10$ m, which is the first level for mean quantities. From the point of view of the vertical mesh grid the canopy is always treated as it were flat.

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when they are outward in order to be consistent with Eq. (12). The heat flux between the inner floor and the air inside the building are neglected. The model does not account for multiple floors. Again, an equilibrium state is assumed for each time step, so that the time derivative can be neglected, from which the following equation is obtained

$$T_{\mathrm{in}} = \frac{(h/b)^2\left(T_{(\mathrm{i})\mathrm{ww}} + T_{(\mathrm{i})\mathrm{we}}\right) + T_{(\mathrm{i})\mathrm{f}}}{2(h/b)^2+1}. \tag{14}$$

Note that, under such assumptions, there is no need to know k. For tall buildings, the walls control the inner building temperature, as would be expected. The motivation for this formulation is twofold: first, we do not need to assume an *ad hoc* energy source due to a heating/cooling system by setting the building inner temperature constant. Second, this formulation will simplify the inclusion of a heating/cooling system whose power and total heat production will vary *dynamically* as a function of the inner temperature.

3. Calibration and sensitivity studies

The UCM calibration was carried out using observed global and diffuse short-wave radiation fluxes, long-wave radiation fluxes and air temperature from time series collected at a micrometeorological station at the University of São Paulo in Brazil. The micrometeorological station is on a building 20 m tall on the university campus, with other buildings within 20–40 m and with lawns and trees in between. The campus is in the metropolitan area, with buildings and obstacles extending for several kilometers in all directions. Since 1994, on the University of São Paulo main campus (23.4°S, 46.7°W, 742 m asl), global and diffuse short-wave radiation have been routinely measured using, respectively, the Eppley Lab. Inc. pyranometer model 8-48 (SN28455), and model 2 (SN28513F3) [21,22]. Long-wave radiation has been measured at the site by the Eppley Lab. Inc. precision infrared radiometer model PIR. The sampling rate is 0.2 Hz and the raw observations are block-averaged over 5 min periods. Observations have been averaged over 1 h and one month periods over the available 10 years of records in order to attempt to filter out seasonal and non-local effects. The calibration was carried out first by adjusting the atmosphere transmittance in order to fit the observed global radiation amplitude and then adjusting the ratio between global to diffuse radiation. The incoming radiation observation is not used as input to the model but is needed to set some internal model parameters. The 1-D atmospheric turbulence model, with which the UCM is coupled, parameterizes the incoming short- and long-wave radiation based on the sun position for a given day of the year and a given time, and based on a bulk atmospheric transmittance. Thus, radiation observations are needed to calibrate the bulk transmittance coefficients and the ratio of direct to global radiation. These observations are taken at the micrometeorological station previously described.

To study the model performance and determine which value of aspect ratio best matches the observations, two typical days of the year (DOY) were simulated, 69 and 211. These days are assumed to

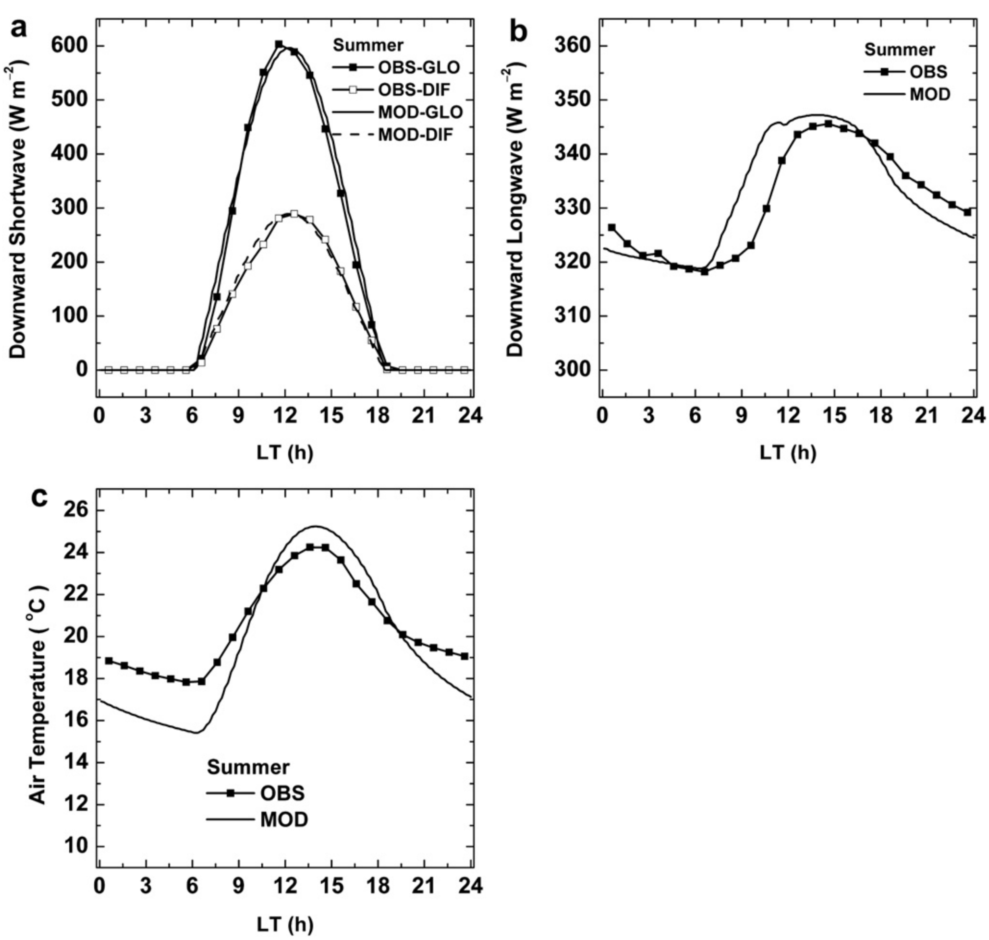

Fig. 4. Results of calibration of UCM inputs with observations from a summer day (DOY 69) in São Paulo. Lines with symbols are averaged observations and lines without symbols are model outputs, for the assumed aspect ratio $h/d = 2$. (a) Global and diffuse solar radiation, (b) downward long-wave radiation and (c) air temperature. The relatively large value of the diffuse solar radiation is due to presence of clouds in the averaged data.

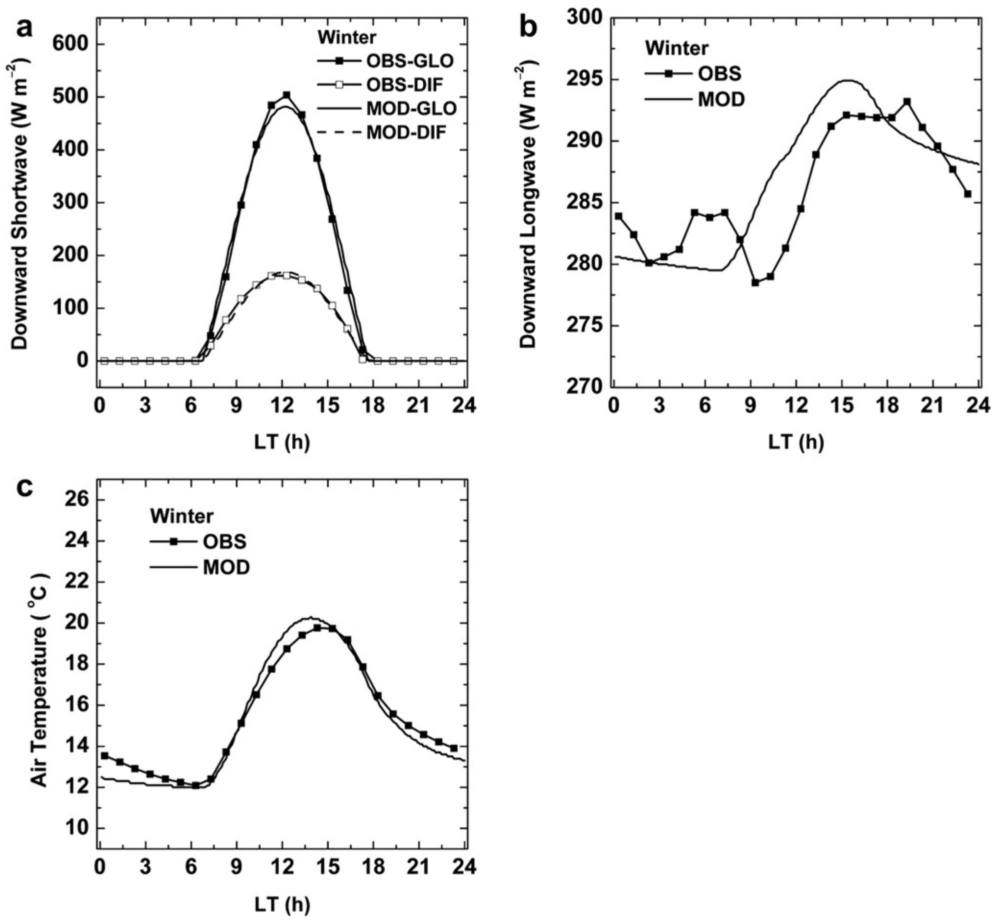

Fig. 5. As Fig. 4 but for a winter day (DOY 211).

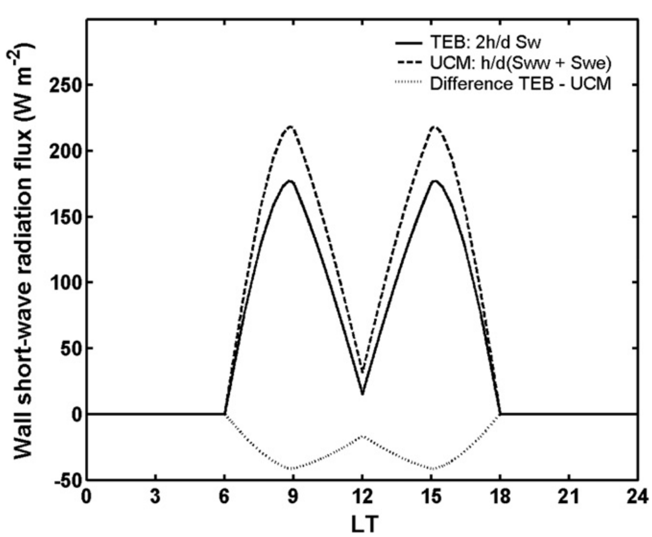

Fig. 6. Direct plus diffuse solar radiation fluxes estimated by UCM taking into account the two walls together (solid line) and taking into account the walls separately (dashed line). The difference in the flux estimates is shown by the dotted line. The greatest differences occur at the times of largest solar exposure, 09 and 15 LT. These values correspond to $h/d = 1$ and are averaged over all canyon orientations, from 0 to 90°. At noon the net radiation on the walls is not zero because of the diffuse component which is variable but always non-zero during the daytime. In these simulations 1000 W m^{-2} is assumed as incoming global radiation and only the radiation budget scheme is considered.

be representative of the southern hemisphere summer and winter, respectively. Because the real characteristics of the canopy where the observations were taken are not included explicitly in the model, some of the canopy parameters in the model have to be

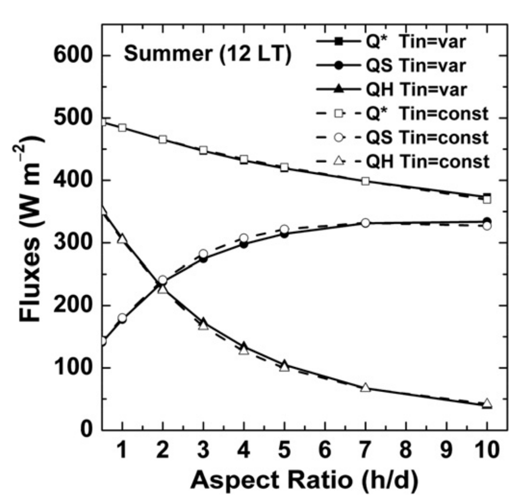

Fig. 7. UCM-simulated fluxes at 12 LT as a function of aspect ratio. Continuous lines refer to the simulation in which the temperature inside the building was allowed to vary and dashed lines refer to the simulation for which the temperature inside the building is constant. Fluxes are computed as the contributions of all surfaces, including streets, walls, and roofs. The sensible heat flux is given by Eq. (10). The net radiation flux and the stored energy flux are calculated in the same way.

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adjusted to best fit the model outputs with the observations on these two days. The aspect ratio h/d is found to be the parameter that has the largest effect on the energy fluxes. A value of h/d of 2 provides the best fit to the observations. The actual aspect ratio of the site is difficult to estimate, because the area is very irregular and vegetation is present. Intuitively we would expect that the actual aspect ratio would be somewhat smaller. Fig. 4a–c show the comparisons of the model simulations with observations for summer, where global and diffuse solar radiation can be simulated with an accuracy of 10% most of the time, for the assumed aspect ratio of 2. Downward long-wave radiation is simulated within about 10% although there is a phase shift of about 3 h, with the modeled value occurring earlier than the observed. The modeled temperature has the diurnal amplitude greater than observed (about 10 °C versus 7 °C). During the daytime the difference in temperature is smaller (~0.5 °C) than during the nighttime (2 °C). During winter (Fig. 5a–c) there is agreement within 25 W m^{-2} or 5% in solar (short-wave) radiation. It is seen that, during the winter the simulated long-wave radiation is shifted by about 3 h relative to the observations. The winter diurnal temperature curve is better reproduced than in the summer, with the difference less than 1 °C.

4. Results and discussion

Two sets of sensitivity studies are described in this section. First, to assess the differences in model outputs by TEB and UCM due to different parameterizations of the walls on the net short-wave radiation, simulations were carried out for nine different canyon orientations. The outputs of the models were averaged over the nine orientations. The aspect ratio is assumed to equal one for this particular analysis. Second, sensitivity runs were made where the diurnal variations of fluxes and temperature were studied for aspect ratios of 0.5, 1, 2, 3, 4, 5, 7 and 10. The canyon orientation was assumed to be North–South for these runs.

4.1. Effect of computing radiation fluxes on the two street canyon walls separately

To better understand the diurnal variations of the effects of canyon orientation on solar fluxes within the street canyon, the direction of the canyon relative to the North–South direction was varied by 11.25° increments from 0° to 90°. The averaged solar radiation flux over all directions was also calculated. Fig. 6 shows the results of simulations taking into account only the two types of radiation schemes (TEB and UCM), where an *ad hoc* global incoming radiation of 1000 W m^{-2} is assumed. The maximum difference in the two models (TEB – UCM) ranges from −16 W m^{-2}, for an array of street canyons perpendicular to the North–South direction, to −60 W m^{-2}, for street canyons parallel to the North–South direction. The averaged value of the maximum difference for all street canyon directions is approximately −40 W m^{-2}. Note that the expressions for the short-wave radiation flux, using the forms Eqs. (8) and (9), are

$$S^*_{can} = S^*_r + \frac{h}{d}\left(S^*_{ww} + S^*_{we}\right) \quad \text{(wall contribution computed separately)}, \tag{15}$$

$$S^*_{can} = S^*_r + \frac{2h}{d}S^*_w \quad \text{(wall contribution computed together)}. \tag{16}$$

The differences found between Eqs. (12) and (13) can generate a bias as large as 40 W m^{-2} in the estimation of other heat fluxes.

4.2. Variation of the components of energy fluxes with aspect ratio

A set of eight sensitivity simulations was carried out with different values of aspect ratio (h/d), in which the width of the street canyon, d, was kept constant. Thus in the following discussion the expressions *aspect ratio* and *building height* are not independent. The aspect ratios were varied to represent urban canopies ranging from low buildings and/or wide streets to tall buildings and/or narrow streets. The values assumed for the aspect ratio are: 0.5, 1, 2, 3, 4, 5, 7 and 10. Note that the largest few values occur very infrequently and mainly in the centers of large cities. The horizontal dimensions of the buildings in the canopy, the building width and the distance between building are $b = d = 10$ m. The reference level, the surface roughness length z_0 and the displacement length d_0 are assumed to be, respectively, $2h$, $h/20$, and $2h/3$. These parameters are considered as typical for homogeneous canopies and are based on values mentioned by Roth [25] and Britter and Hanna [2].

Fig. 7 show the midday (12 LT) model-simulated behavior of the net radiation flux Q^*, sensible heat flux Q_H, and canopy stored heat flux Q_S as a function of the aspect ratio, h/d. These fluxes are representative of the whole canopy. As aspect ratio increases (from 0.5 to 10), net radiation flux decreases by about 120 W m^{-2} (from 490 W m^{-2} to 370 W m^{-2}) whereas sensible heat flux Q_H decreases by about 300 W m^{-2} (from 360 W m^{-2} to 60 W m^{-2}). Thus sensible heat flux has a much larger relative decrease than net radiation

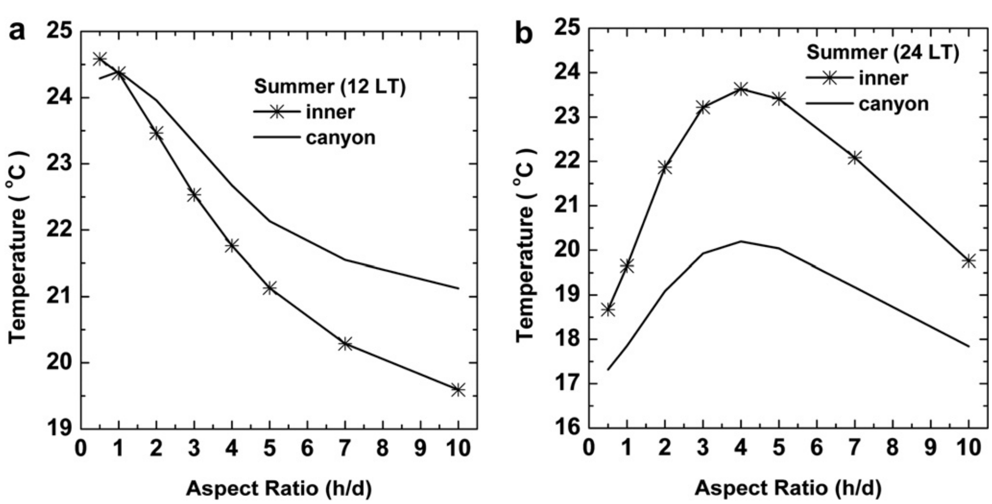

Fig. 8. Building inner temperature and canyon air temperature variation with aspect ratio as simulated by UCM: (a) 12 LT and (b) 24 LT.

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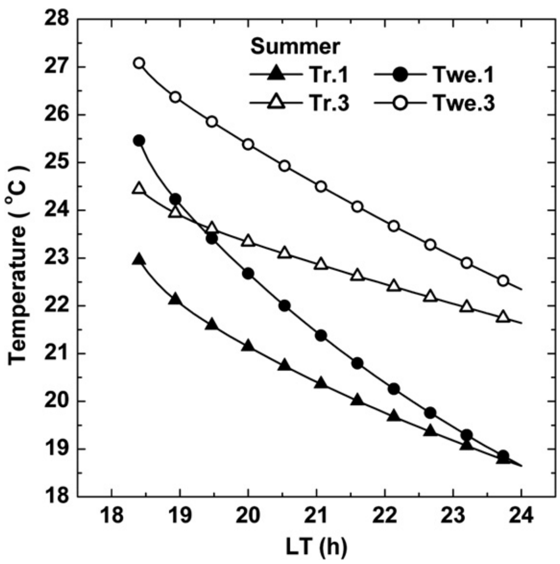

Fig. 9. Model-simulated street/road (r) and east wall (we) temperature after sunset. Solutions are shown for aspect ratios $h/d = 1$ and $h/d = 3$.

(about 84% versus about 25%). On the other hand, the canopy stored energy flux Q_S increases by about $+180\ \mathrm{W\,m^{-2}}$ (from about $140\ \mathrm{W\,m^{-2}}$ to $340\ \mathrm{W\,m^{-2}}$) as aspect ratio increases. The dashed lines represent model simulations where the building inner temperature is kept constant at 20 °C.

In Fig. 8a the simulated temperature inside the building and within the canyon at 12 LT are plotted versus aspect ratio. Simulated temperatures are seen to monotonically decrease as aspect ratio increases, primarily due to the sun shading effect. The canyon temperature decreases less with h/d than does the inside building temperature (3 °C versus 5 °C). The smaller inner temperature for a given h/d can be explained by the thermal inertia of the building, since the plotted temperatures represent midday values. Within the canyon, turbulent mixing is taking place, causing the canyon temperature trends to follow the temperature of the outside building walls. Recall that the fluxes and other variables discussed above apply near the top of the canopy, at a height of about h. Similar decreases in air temperature as a function of aspect ratio are reported by Ali-Touterd and Mayer [1], who found a variation in air temperature at pedestrian level of about 2 °C at 12 LT for h/d ranging from 0.5 to 4.

Fig. 8b shows that during the night (24 LT) the general temperature variation with h/d indicates a warming effect for $h/d < 4$ as h/d increases, due to trapping of outgoing long-wave radiation by the tall buildings. However, for $h/d > 4$, there is a cooling as h/d increases further. It is well known that, due to long-wave trapping, a smaller cooling rate is expected for street canyons with larger aspect ratios.

In Fig. 9 the modeled street and east wall temperature after sunset (18–24 LT) are plotted. Results for two aspect ratios are shown, $h/d = 1$ and $h/d = 3$. The average cooling rates for the street and for the east wall when $h/d = 1$ are respectively -0.77 °C/h and -1.22 °C/h. When $h/d = 3$, they are -0.50 °C/h and -0.85 °C/h, respectively. An increase in the aspect ratio from 1 to 3 leads to a decrease of the cooling rate: $+0.27$ °C/h for the street and $+0.37$ °C/h for the east wall.

It was shown above how the model-simulated energy flux components and temperature are affected by the aspect ratio, for the conditions assumed in this study. Since the width of the street and the width of the building have been assumed constant, the calculated variations of energy fluxes and temperatures with aspect ratio can also be thought of as variations with building height. Because no anthropogenic heat flux was considered here, and also latent heat flux has been assumed negligible, it can be concluded that the results in this paper depend solely on the *geometric* features of the urban canopy. Regarding this point, it is useful to distinguish the different effects that the mean building height h has on the energy budget. The main factors which increase with h are shadowed area, canopy mass, and long-wave trapping. Shadowing contributes to the reduction of the net radiation flux during the day, which results in smaller temperatures at midday. Shadowing also contributes to smaller long-wave emissions from the canopy surfaces at night. An increase in canopy mass contributes to the input energy being distributed over a larger mass of material, resulting a smaller air temperature. An increase in long-wave trapping contributes to an increase in canopy air temperature at night.

Heat fluxes due to anthropogenic releases can also increase with aspect ratio as discussed in Ref. [11], but this feature is not taking into account in this paper. Hence, according to the results presented here, long-wave trapping should play an import role only during nighttime.

In a small-scale field experiment closely related to our assumptions (no anthropogenic and no latent heat fluxes), Pearlmutter et al. [24] found that daytime air temperatures decreased as aspect ratio increased. The experiment by Pearlmutter et al. employed an array of concrete blocks in the desert. They also concluded that cities with compact building placement in areas of hot and dry climate, like the case presented here, tend to have lower temperatures when compared with cities with buildings spread farther apart.

5. Conclusions and further comments

The UCM described in this paper is intended to improve upon the TEB model by Masson [13] by accounting for differences in energy fluxes on the two walls of a street canyon and by a few other minor revisions. The UCM simulations verify that the aspect ratio has a significant effect on the energy fluxes and temperatures in homogeneous urban areas. The UCM estimates of net radiation flux are sometimes significantly different (by about $50\ \mathrm{W\,m^{-2}}$) from the TEB model estimates. When the aspect ratio (equivalently the building height) is increased, and provided that other settings are kept unchanged, the UCM simulations show that the stored energy flux increases while the sensible heat flux decreases at the top of the canopy layer. These specific processes are difficult to observe in field experiments because the dependence on the aspect ratio can be obscured by other variables (e.g., the anthropogenic heat flux, the reduced availability of water in the underlying surface, and the large amount of spatial heterogeneities in all factors). Additional small-scale field experiments, such as described by Pearlmutter et al. [24] or Kanda et al. [8], for instance, would be ideal to verify the impact of aspect ratio on energy fluxes and other meteorological variables described in this paper.

Acknowledgements

This paper is part of the main author's Ph.D. thesis, which was supported by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CNPq), Brazil. The authors are thankful to the National Science Foundation (NSF), USA, under grant number 0750878 to the Harvard School of Public Health for the current support. The authors also thank Rex E. Britter and Leslie K. Norford of the Massachusetts Institute of Technology for making helpful comments over the course of this study.

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