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

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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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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 ($z = 0$).

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

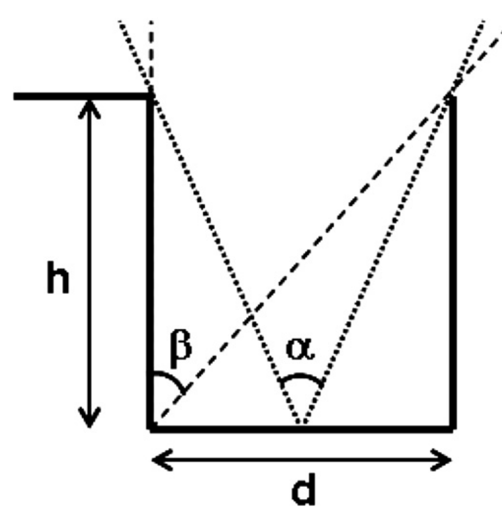

Fig. 1. Street canyon cross-section illustrating geometric shapes and definitions of the angles used for computing the sky view factors.