Building and Environment 83 (2015) 50–64

Contents lists available at ScienceDirect

Building and Environment

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

Breakdown of the night time urban heat island energy budget

P.J.C. Schrijvers [a, c, *], H.J.J. Jonker [a, c], S. Kenjereš [b, c], S.R. de Roode [a, c]

[a] Atmospheric Physics Section, Department of Geoscience & Remote Sensing, Faculty of Civil Engineering and Geotechnology, Delft University of Technology, Stevinweg 1, 2628CN Delft, The Netherlands
[b] Transport Phenomena Section, Department of Chemical Engineering, Faculty of Applied Sciences, Delft University of Technology, Julianalaan 136, 2628BL, The Netherlands
[c] J.M. Burgers Centre for Fluid Dynamics, Julianalaan 136, 2628BL, The Netherlands

ARTICLE INFO

Article history:
Received 6 June 2014
Received in revised form
31 July 2014
Accepted 8 August 2014
Available online 21 August 2014

Keywords:
Urban heat island
Model development
Radiative transfer
Surface energy balance
Computational Fluid Dynamics

ABSTRACT

This conceptual study aims at identifying the dominant factors involved in the night time urban heat island energy budget at building level for an idealized 2D urban geometry. For this purpose a simulation model has been developed which combines radiative transfer, conductive heat transfer and convective heat transport by Computational Fluid Dynamics (CFD) modelling at 1 m spatial resolution. A wide range of building height (H) to street width (W) ratios are considered. Starting from radiative equilibrium, complexity is added with each next test case, adding the long wave trapping effect, heat transfer by conduction and finally by convective transport of sensible heat. It is found that the long wave trapping effect is the main mechanism controlling the surface temperature for lower H/W ratios. With increasing H/W ratio the long wave trapping effect equals the absorbed long wave radiation by the sky, while the conductive heat flux is increasing relative to the absorbed radiation. The sensible heat flux process shows different behaviour for different H/W ratios. For $H/W \leq 1.0$, one single vortex is formed spanning the whole street canyon. For deeper canyons, this vortex only spans the upper part of the canyon and a stably stratified flow is formed in the lower parts of the canyon, reaching very low air temperatures in these regions. This shows that there is a subtle and complex interplay between all processes and reveals the necessity to represent all physical processes as accurately as possible.

1. Introduction

The Urban Heat Island (UHI) is a well documented effect of anthropogenic changes to the environment [1]. Several studies have shown a reduced decrease of night time air temperature of the urban environment in the range of 1–10 K [2–6], and several causes for the temperature difference between the urban and rural environment have been proposed.

In principle, the urban heat island effect could be due to [2,7–10] 1) low ventilation, 2) reduced evaporation, 3) enhanced release of stored heat in the urban material, 4) trapping of long wave radiation, 5) anthropogenic heat emissions, 6) enhanced absorption of short wave radiation, 7) increased long wave radiation from the sky, and any combination of these factors. A priori, it is unclear which effect is dominant.

Several studies have been performed to find the effects of the urban environment on air temperature. Nunez and Oke [9] performed measurements in a specially instrumented street canyon with a building height (H) to street width (W) ratio (H/W) of 0.7 in Vancouver, Canada. They found that during the night, the radiative deficit is almost entirely compensated by the release of subsurface heat storage showing the importance of canyon material.

Oke [10] suggested seven above mentioned causes of the urban heat island, and eliminates five of them based on observations. The two remaining causes are: decreased long-wave radiation loss (long wave trapping) and an increased release of heat stored in the urban material. The relevant parameters governing the differences in air temperature were found to be the radiative geometry and the surface thermal properties. Anthropogenic heat was discarded in Ref. [10] as a source of the UHI, since the UHI is strongest in summer, whereas the peak anthropogenic heat is emitted during winter.

The conclusion about anthropogenic heat was opposed by Ryu and Baik [11], who performed a systematic study of different physical processes with the meso-scale WRF (Weather and

* Corresponding author. Atmospheric Physics Section, Department of Geoscience & Remote Sensing, Faculty of Civil Engineering and Geotechnology, Delft University of Technology, Stevinweg 1, 2628CN Delft, The Netherlands.
E-mail address: p.j.c.schrijvers@tudelft.nl (P.J.C. Schrijvers).

http://dx.doi.org/10.1016/j.buildenv.2014.08.012

Research Forecasting) model, which works on a larger scale and the urban environment is parametrized. Three main causative factors were identified: anthropogenic heat, impervious surfaces and 3D urban geometry. Their study indicated that during night time, the anthropogenic heat contributes most to the urban heat island, followed by the impervious surface factor (reduction in surface moisture availability and increased thermal inertia) and the 3D urban geometry (additional heat stored in vertical walls, radiation trapping and reduction of ventilation).

In this study, performed within the Climate Proof Cities consortium [12], the line of Ryu and Baik [11] is continued, but on a smaller scale: the scale of the urban street canyon. For this purpose a new simulation model has been developed in the line of Krayenhoff and Voogt [13] and Krayenhoff [14], which combines radiative transfer, heat conduction into the ground and obstacles and Computational Fluid Dynamics (CFD) calculations for turbulent transport of sensible heat. This model and its validation is discussed in section 2. This section also includes the case set-up. Instead of looking at all the different processes acting together, this study chose to start from the simplest case with only radiative transfer, and add physical processes step by step. In this way insight is gained in the different mechanisms that play a role in the urban heat island without losing the physical interpretation of the cases. The results of the simulations can be found in section 3. Model assumptions and limitations of the model are discussed in section 4, after which conclusions are drawn. Our goal is to quantify the contribution of the factors controlling the urban heat island. Therefore this study does not only add complexity in the processes that we consider, but we also consider a range of H/W ratios (0.0, 0.5, 1.0, 2.0 and 4.0) in order to study the importance of building geometry.

2. Methods and case set-up

To perform this study, a new transient 2D model has been developed which couples three different energy transport phenomena: radiative transfer, conduction and ventilation. Radiative transfer is computed with a Monte-Carlo model, whereas ventilation is modelled using a CFD model. The surface energy balance is computed, which involves a 1D heat conduction equation for the conductive heat flux in the urban material. A transient simulation is conducted where the diurnal cycle is taken into account. This is necessary for the computation of the conductive heat flux, which is dependent on the day time conditions. All sub models will be discussed and validated separately in this section.

2.1. Radiative transfer

A Monte-Carlo model is developed to compute the radiative transfer in a complex urban geometry. The Monte-Carlo model computes photon paths for direct and diffuse short wave radiation and long wave radiation emitted by the sky and by walls. Direct and diffuse splitting of short wave radiation is based on Skartveit et al. [15].

Used variables in Ref. [15] are (see Table 2) I the solar constant, d_n the Julian date, latitude and longitude, T_L the Linke turbidity factor [16] and γ the solar zenith angle, which is computed based on Iqbal [17]. Only clear skies are considered, which results in a maximum incoming direct short wave radiative flux at the top of the domain of 833.1 W m^{-2} and a maximum incoming downward diffuse short wave radiative flux of 84.2 W m^{-2} at mid-day.

For long wave radiation, the Stefan–Boltzmann law ($E = \varepsilon\sigma T_s^4$) is assumed, where Kirchoff's law is applied, i.e. the same value of ϵ is used for the absorption and emission of long wave radiation ($\alpha = \epsilon$). If a surface is hit, reflected photon packets require a new direction based on the Lambertian cosine law. The same assumption is made for diffuse emitted photon packets emitted at the top of the domain, such that the angle distribution is cosine weighted. The amount of long wave radiation emitted by the sky is taken as $LW_{\text{sky}} = \varepsilon_{\text{sky}}\sigma T_a^4$, where the emissivity of the sky is computed according to Prata [18] as.

$$\varepsilon_{\text{sky}} = 1 - \left(1 + c\frac{e_a}{T_a}\right) \times \exp\left[-\sqrt{1.2 + 3.0 \times c\frac{e_a}{T_a}}\right] \tag{1}$$

where e_a is the water vapour pressure (in hPa), T_a the free stream air temperature (in K) and $c = 46.5$ K/hPa is constant based on typical values for the water vapour scale height and temperature lapse rate [18].

Photon path tracking is done by taking step sizes from one grid cell face to another. If a surface is hit, a fraction of the energy ζ is absorbed (based on material albedo or emissivity), while the remainder travels in a random direction based on the Lambertian cosine law with a fraction $(1 - \zeta)$ energy left. Horizontal periodic boundary conditions are applied, such that a photon packet can only leave the domain through the top boundary. To reduce computation time, photon packets with less than 0.5% of the initial energy are discarded in an unbiased manner.

All diffuse radiative components (diffuse short wave radiation, long wave radiation emitted by the sky and long wave radiation emitted by surfaces) are computed once, after which the photon distribution is stored. Long wave radiation emitted by the sky and the diffuse short wave component are only dependent on the amount of radiation entering the domain and the building geometry, and not on time of the day. For the long wave radiation emitted by the surface, the surface temperature determines the amount of emitted long wave radiation. Therefore the spatial photon distribution is stored per grid cell. Not only the amount of emitted energy is stored, but also the emitted radiation that is absorbed at another surface (long wave trapping). Direct short wave radiation is computed each time step, since the solar zenith angle changes with time.

The number of photon packets shot is dependent on the covered area and the size of the obstacles. $N = 10^5$ photons per m^2 are taken

Table 1
Model constants for the standard $k-\epsilon$ turbulence model.

C_μ	σ_k	σ_ϵ	$C_{\epsilon 1}$	$C_{\epsilon 2}$	$C_{\epsilon 3}$
0.09	1.0	1.3	1.44	1.92	1.44

Table 2
Input constants for radiative transfer, heat conduction and the CFD model.

Radiation	
Emissivity	0.95
Albedo	0.40
Latitude	52° 22′ N
Longitude	4° 53′ E
Start date	2012-06-10 00:00
End date	2012-06-20 23:59
Heat conduction	
λ	0.72 W m^{-1} K^{-1}
ρ	1920 kg m^{-3}
C_v	835 J kg^{-1} K^{-1}
CFD	
T_a	293.15 K
U	4.0 m/s
Cell width	1.0 m
Cell expansion	5%
Max cell size	25 m