Science of the Total Environment 542 (2016) 136–143

Contents lists available at ScienceDirect

Science of the Total Environment

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

Energy flux parametrization as an opportunity to get Urban Heat Island insights: The case of Athens, Greece (Thermopolis 2009 Campaign)

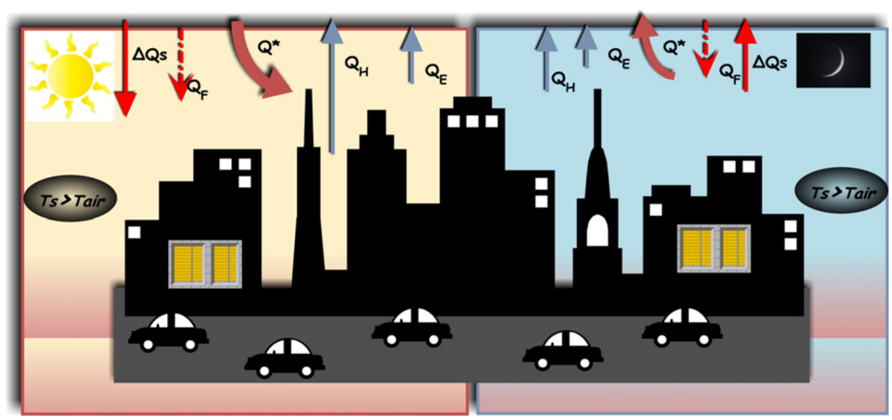
G. Loupa, S. Rapsomanikis *, A. Trepekli, K. Kourtidis

Laboratory of Atmospheric Pollution and of Control Engineering of Atmospheric Pollutants, Faculty of Engineering, Department of Environmental Engineering, Democritus University of Thrace, 67100 Xanthi, Greece

HIGHLIGHTS

- Simple urban canopy models applied to a densly built city centre during a heat wave.
- Model estimated energy fluxes tested against flux measurements to derive empirical parameters for urban planners.
- The relationship between anthropogenic releases, storage heat flux and surface and air temperatures.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 7 June 2015
Received in revised form 8 September 2015
Accepted 10 October 2015
Available online 3 November 2015

Editor: D. Barcelo

Keywords:
Objective hysteresis model
Storage heat flux density
kB^{-1}
Aerodynamic resistance for heat
Anthropogenic releases
Heat waves

ABSTRACT

Energy flux parameterization was effected for the city of Athens, Greece, by utilizing two approaches, the Local-Scale Urban Meteorological Parameterization Scheme (LUMPS) and the Bulk Approach (BA). In situ acquired data are used to validate the algorithms of these schemes and derive coefficients applicable to the study area. Model results from these corrected algorithms are compared with literature results for coefficients applicable to other cities and their varying construction materials. Asphalt and concrete surfaces, canyons and anthropogenic heat releases were found to be the key characteristics of the city center that sustain the elevated surface and air temperatures, under hot, sunny and dry weather, during the Mediterranean summer. A relationship between storage heat flux plus anthropogenic energy flux and temperatures (surface and lower atmosphere) is presented, that results in understanding of the interplay between temperatures, anthropogenic energy releases and the city characteristics under the Urban Heat Island conditions.

1. Introduction

Urban areas may conceal environmental challenges due to their high population density, town planning and diverse construction features.

* Corresponding author.
E-mail address: rapso@env.duth.gr (S. Rapsomanikis).

http://dx.doi.org/10.1016/j.scitotenv.2015.10.056

Urban canopy models (UCMs) provide a valuable tool to assist in urban planning and policy, related to air pollution and changes in energy budgets due to climate change (Baklanov et al., 2010; Järvi et al., 2011).

In Athens, Greece, a large Mediterranean metropolis, surface and canopy layer Urban Heat Island is well established and the city experiences frequent heat waves (Founda and Giannakopoulos, 2009; Kourtidis et al., 2015). Climate future projections revealed that heat waves will become more frequent and more intense over the Mediterranean region as well as the western and southern United States (Meehl and Tebaldi, 2004). During heat waves, human health and comfort, energy demands for cooling and water resources are stressed (Meehl and Tebaldi, 2004; Giannakopoulos and Psiloglou, 2006).

The Local-scale Urban Meteorological Parameterization Scheme (LUMPS) is one of the simplest available UCMs that can provide satisfactory results about urban energy budgets (Grimmond and Oke, 2002; Grimmond et al., 2010). LUMPS calculates storage, sensible and latent heat fluxes in the urban environment at local or neighborhood scale, based on the net radiation (Q^*), utilizing standard meteorological data and information on land cover fractions of the area (Grimmond and Oke, 2002). Recent examples of the LUMPS application is the study of Gober et al. (2009) which investigated the use of watered landscapes to manipulate Urban Heat Island (UHI) effects in Phoenix, USA or the work of House-Peters and Chang (2011) that have examined how the urban design could either increase or decrease heat and water related stresses at the neighborhood scale under different climate change scenarios. LUMPS results have shown successful comparisons of the predicted fluxes with observations from many cities, although it was not tested in the case of densely built areas with high-rise structures, under hot and dry conditions like in the present work (Hanna et al., 2011). Recent version of the LUMPS accounts also for the anthropogenic heat flux according to the approach presented by Pigeon et al. (2007) and Loridan et al. (2011). Here, a different approach was followed to determine anthropogenic heat flux, as presented by Järvi et al. (2011).

Bulk transfer approaches are also deployed to derive spatial and/or temporal variations of the components of the urban energy budget from remotely sensed data (either from satellites or aircraft flights) that provide information about land surface temperature, broadband emissivity, surface albedo, land cover combined with in situ micrometeorological parameters (Carlson et al., 1981; Voogt and Grimmond, 2000; Kato and Yamaguchi, 2007; Xu et al., 2008; Frey and Parlow, 2012).

Bulk transfer approaches (BA) offer the option to relate the physical parameters as surface and air temperature and local micrometeorological parameters, with the energetic basis of UHI. A prevailing and difficult to measure energy flux in the urban environment is the storage heat flux (ΔQs) and a large number of published work is devoted to parametrize this flux from remotely sensed data and routinely measured parameters such as air temperature (for example Kato and Yamaguchi, 2007; Anderson et al., 2008; Chang et al., 2010). Kotthaus and Grimmond (2014) commented that the storage heat flux combined with anthropogenic releases sustain an upward sensible heat flux even at night in densely built environments, hence the surface temperature is almost always higher than air temperature. In the present study, the relationship between ΔQs, surface temperature (Ts) and air temperature (T_{air}) was examined, as well as the effect of anthropogenic heat flux (Q_F).

The urban surface energy budget (SEB, Eq. (1)), is used as a starting point to examine which flux density/ies could be altered in a cost-effective way to improve the urban climate:

$$Q^* + Q_F = Q_H + Q_E + \Delta Qs + \Delta Q_A \ (\mathrm{W\ m^{-2}}) \tag{1}$$

where Q^* is the net all-wave radiation, Q_H and Q_E are the respective turbulent fluxes of sensible and latent heat, ΔQs is the storage heat flux and ΔQ_A is the net advective heat flux (Oke, 1988). Enhanced urban storage heat flux density compared with the rural surroundings and anthropogenic releases of heat and moisture are distinctive features of each megapolis in the world (Kato and Yamaguchi, 2007; Bohnenstengel et al., 2013). Man-made materials, such as asphalt and concrete, are accumulated in the urban canopy of the modern cities. These materials can store a large amount of the incoming net radiation, depending on their heat capacity, which increases their surface temperature (Asaeda and Ca, 1993; Anandakumar, 1999; Asaeda and Ca, 2000). Under hot and dry conditions, their surface temperature is higher than air temperature not only during daytime but even at night, leading in an upward sensible heat flux day and night. Anthropogenic activities, such as transportation, air-conditioning, other stationary sources and human metabolism, heat up the surface and the atmosphere of the city, also day and night (Aoyagi and Seino, 2011). Hence, the surface temperature of the urbanized areas is warmer compared to the rural surroundings day and night (surface heat island, SUHI) and the air temperature is also warmer, mainly at night (Urban Heat Island, UHI) (Kimura and Takahashi, 1991; Oke, 1982; Voogt and Oke, 2003).

In the present work, the UCMs that may be applied to the whole of the city, were utilized, with the aim to obtain closure for Eq. (1) (SEB). Parameters for input in the UCMs were obtained from in situ measurements during the Thermopolis Campaign. Having obtained Q^* and ΔT for the whole of the city and the rest of the parameters of the Eq. (1) from the MMet Tower footprint, (Rapsomanikis et al. 2014, Kourtidis et al., 2015), the UCMs mentioned above would be validated so that they could be applied for the whole of the city, albeit in heat wave conditions. The two UCMs applied in the present work, are the "LUMPS" (Grimmond and Oke, 2002) and the "BA" (vide infra). The validated LUMPS algorithms would result in calculated values of ΔQs, Q_H and Q_E of Eq. (1) for the city center. "LUMPS" uses the subroutine of "Objective Hysteresis Model" (OHM) to calculate the ΔQs. In the present work, two OHM literature methods will be used to calculate ΔQs. Also a new simplified approach will be attempted, so that by utilizing only the Ts and the T_{air} (above the surface) one can obtain the value of ΔQs for the city center. The BA will be used to calculate Q_H, from the in situ and remotely sensed values of ΔT (Ts − T_{air}). The delivered insights of UHI and the derived empirical parameters and coefficients should provide a closure for Eq. (1) and hence a basis for the application of effective mitigation strategies of UHI in Athens, Greece.

2. Methods

In the framework of the European Space Agency (ESA) project entitled "Urban Heat Islands and Urban Thermography", an extensive campaign was conducted in Athens, Greece during the summer of 2009, entitled "Thermopolis 2009" to characterize the UHI at different spatial scales. During the campaign (15 July to 2 August 2009) simultaneous airborne and ground measurements took place in the Athenian conurbation.

2.1. The site, meteorological conditions and available data

During the "Thermopolis 2009" campaign, a micrometeorological (MMet) tower was installed in the city center, on the rooftop of a building belonging to the Greek Ministry of Environment. Results and findings are described in detail in Rapsomanikis et al. (2014). However, a brief description of the site and results is described below. On the MMet tower 4 wind sentry cup anemometers (03102VM, R. M. Young Company US, 03002LM, R. M. Young Company, US) and a CSAT3 directional sonic anemometer (Campbell Scientific Ltd., UK) were positioned at the same heights as the thermometers (Thermo-sensor-Compact, Thies Clima- Die Adolf Thies GmbH & Co. KG, DE) and RH sensors (Hygroclip S3C03, Rotronic AG, CH; HMP45A, Vaisala Oyj, FL). The barometric pressure sensor (CS100, Setra Systems, Inc., US) was located at the same height as the CSAT3 which was directed towards the North. The data from all instruments were logged on two Campbell Scientific Ltd.CR10X data loggers and all were downloaded daily on a PC into one single spread sheet, designed by the software program DASYLAB.