Anthropogenic Heat Flux Estimation from Space:

Results of the second phase of the URBANFLUXES Project

Nektarios Chrysoulakis
Foundation for Research and Technology Hellas (FORTH),
Heraklion, Greece
zedd2@iacm.forth.gr

Mattia Marconcini
German Aerospace Center (DLR)
Wessling, Germany

Jean-Philippe Gastellu-Etchegorry
Centre d'Etude Spatiale de la Biosphère (CESBIO),
Toulouse, France

C.S.B Grimmong
University of Reading
Reading, United Kingdom

Christian Feigenwinter
University of Basel
Basel, Switzerland

Fredrik Lindberg
University of Goeteborgs
Goteborg, Sweden

Fabio Del Frate
GEO-K s.r.l.,
Rome, Italy

Judith Klostermann
ALTERRA,
Wageningen, The Netherlands

Zina Mitraka
Foundation for Research and Technology Hellas (FORTH),
Heraklion, Greece

Thomas Esch
German Aerospace Center (DLR)
Wessling, Germany

Lucas Landier
Centre d'Etude Spatiale de la Biosphère (CESBIO),
Toulouse, France

Andy Gabey
University of Reading
Reading, United Kingdom

Eberhard Parlow
University of Basel
Basel, Switzerland

Frans Olofson
University of Goeteborgs
Goteborg, Sweden

***Abstract*—The H2020-Space project URBANFLUXES (URBan ANthrpogenic heat FLUX from Earth observation Satellites) investigates the potential of Copernicus Sentinels to retrieve anthropogenic heat flux, as a key component of the Urban Energy Budget (UEB). URBANFLUXES advances the current knowledge of the impacts of UEB fluxes on urban heat island and consequently on energy consumption in cities. This will lead to the development of tools and strategies to mitigate these effects, improving thermal comfort and energy efficiency. In URBANFLUXES, the anthropogenic heat flux is estimated as a residual of UEB. Therefore, the rest UEB components, namely, the net all-wave radiation (Q*), the net change in heat storage (ΔQs) and the turbulent sensible (Q_H) and latent (Q_E) heat fluxes are independently estimated from Earth Observation (EO), whereas the advection term is included in the error of the anthropogenic heat flux estimation from the UEB closure. The project exploits Sentinels observations, which provide improved data quality, coverage and revisit times and increase the value of EO data for scientific work and future emerging applications. These observations can reveal novel scientific insights for the detection and monitoring of the spatial distribution of the urban energy budget fluxes in cities, thereby generating new EO opportunities. URBANFLUXES thus exploits the European capacity for space-borne observations to enable the development of operational services in the field of urban environmental monitoring and energy efficiency in cities.**

Keywords—Copernicus Sentinels; Earth Observation; Urban Climate; Urban Energy Budget.

I. INTRODUCTION

The anthropogenic heat flux (Q_F) is the heat flux resulting from vehicular emissions, space heating and cooling of buildings, industrial processing and the metabolic heat release by people. During the last years, significant advances have been made in the correct simulation of the physics of urban climate

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processes associated with higher computational capacity, improved spatial and spectral resolution of Earth Observation (EO) sensors and an increased ability to couple the schemes with atmospheric models. Q_F is difficult to determine because of its strongly varying pattern and because it cannot be measured directly. It is therefore not surprising that many different approaches to estimate this term of the Urban Energy Budget (UEB) can be found in literature. Three general approaches have been recognized to estimate Q_F [1]: the use of statistics on energy consumption; the closure of the energy budget and for the building sector, the building energy modelling approach.

In non-urban settings, remotely sensed radiometric surface temperatures derived from thermal infrared imagery have been used extensively to model sensible heat flux (Q_H), most typically over large homogenous areas and sometimes in conjunction with direct in-situ measurements. Over urban areas, thermal infrared imagery has been widely used to estimate surface UHI intensity, and to less extent to parameterize urban energy fluxes. Voogt and Grimmond in [2] successfully obtained urban sensible heat flux using a combination of airborne imagery, ground-based temperature measures and in-situ meteorological station data, whilst Offerle [3] used four different aerodynamic methods and two flux models to derive urban sensible heat fluxes measures from ASTER and Landsat observations. Both these studies concluded that the flux modelling approach provided an acceptable means of estimating urban sensible heat fluxes, though some uncertainty remains on the accuracies that can be achieved. Chrysoulakis [4] used ASTER multispectral imagery to estimate the net all-wave radiation balance (Q^*), whereas Xu et al. [5] explored the use of a new airborne hyperspectral remote sensing system, the Chinese Operative Modular Imaging Spectometer, to investigate the spatial distribution of sensible heat flux at various spatial scales in Shanghai. They concluded that if a high spatial resolution land cover map is not available for a particular study area where energy budget calculations need to be made, relatively consistent results may be gained using significantly lower spatial resolution data.

There is a need to develop uniform data for large samples of urban areas both within region and across regions. However, data for urban areas required in the analysis of energy fluxes are rarely collected and not in a consistent manner. One advantage of EO is the ability to capture consistent measurements across the universe of cities in order to understand something that might be relevant outside the jurisdiction of one particular urban area. Both urban planning and Earth system science communities need spatially disaggregated Q_F data, at local (neighbourhood, or areas larger than the order of 100 m x 100 m) and city scales. Such information is practically impossible to derive by point in-situ fluxes measurements, while satellite remote sensing is a valuable tool for estimating UEB parameters exploiting Earth Observation EO data. While the estimation of Q_F spatial patterns by current EO systems is a scientific challenge, the major challenge lies on the innovative exploitation of the Copernicus Sentinels synergistic observations to estimate the spatiotemporal patterns of Q_F and all other UEB fluxes. URBANFLUXES (URBan ANthropogenic heat FLUX from Earth observation Satellites) was launched in 2015 to meet this challenge [6].

URBANFLUXES is a joint effort of eight European Organizations aiming at introducing novel ideas on anthropogenic heat flux observation from space, and thus generating new EO opportunities to benefit climate change mitigation/adaptation and civil protection. Knowing the anthropogenic heat flux patterns in time and space can be an incentive for cooler urban design and support climate change mitigation and adaptation planning at local scale. Introducing spatio-temporal information on anthropogenic heat in urban planning can lead to a reduced winter and/or summer peak of heat emissions, a reduction in CO_2 emissions, improved energy efficiency and better human comfort in the urban areas. The dependence of the URBANFLUXES method on EO data is one of its key advantages, giving the method the considerable leverage in transferability to any city. An easy and low-cost implementation to any city is expected. The research therefore will have the potential to support sustainable urban planning strategies, by taking into account the spatiotemporal distribution of Q_F in cities. The long term operation of the Sentinels series guarantees the future supply of satellite observations, providing the means for the development and realization of the URBANFLUXES methodology. URBANFLUXES is a three year project, started in 2015. An overview of the second phase of URBANFLUXES is presented in this study, focusing on its approach and presenting the results that came out during the second year of the project.

II. Approach

The main goal of URBANFLUXES is to investigate the potential of EO to retrieve Q_F, supported by simple meteorological measurements. The main research question addresses whether EO is able to provide reliable estimates of Q_F for the time of the satellite acquisition. URBANFLUXES answers this question by investigating the potential of EO to retrieve Q_F spatial patterns, by developing a method capable of deriving Q_F from current and future EO systems. URBANFLUXES aims to develop an EO-based methodology easily transferable to any urban area and capable of providing Q_F benchmark data for different applications. URBANFLUXES is expected to increase the value of EO data for scientific analyses and future emerging applications (such as urban planning and local/regional level climate change mitigation/adaptation), by exploiting the improved data quality, coverage and revisit times of the Copernicus Sentinels data.

The project uses a Community of Practice (CoP) approach, which means that in the case studies, local stakeholders and scientists of the URBANFLUXES project will meet on a regular basis in order to learn from each other. The cross cutting process of the CoP, which facilitates the continuous interaction with the users is clear. In the framework of the CoP the Q_F related user requirements were captured and the demonstration of URBANFLUXES method and products will be performed.

The general formula of the UEB is:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A + S \quad (1)$$

where, Q_E is the turbulent latent heat flux, ΔQ_S is the net change in heat storage, ΔQ_A is the net advected flux and S represents all the other sources and sinks. Assuming that all energy consumed in buildings is released into the environment after use and the S term is negligible, then Q_F can be estimated as a residual from Eq. (1), incorporating ΔQ_A in the error of the energy balance closure.

A network of simple meteorological stations has been deployed in all cities, whereas Eddy Covariance (EC) systems and scintillometrs are also be used. Satellite data are analyzed to map urban surface morphology and cover, whereas a new method is being developed to define UEB meaningful local zones. The Discrete Anisotropic Radiative Transfer (DART) model [7] is employed to improve the estimation of the net all-wave radiation balance, whereas the Element Surface Temperature Method (ESTM), as per [8], adjusted to satellite observations is used to improve the estimation the estimation of the net change in heat storage. Furthermore the estimation of the turbulent sensible and latent heat fluxes is based on the Aerodynamic Resistance Method (ARM) as per [9]. Based on these outcomes, Q_F is estimated from Eq. (1) by regressing the sum of the turbulent heat fluxes versus the available energy. Finally, the whole approach will be adapted to Sentinels synergy to derive Q_F spatiotemporal patterns. The main variables used to calculate the different fluxes and how they were derived (e.g. EO data, in situ) are shown in Table I. From this table is also clear how the meteorological station data are integrated in the URBANFLUXES EO system.

TABLE I. VARIABLES USED TO CALCULATE THE DIFFERENT FLUXES

Flux	***Variable***	***Source***
Q*	Surface albedo	EO, Model
	Surface emissivity	EO, GIS
	Sourface temperature	EO
ΔQ_S	Rate of temperature change for each surface element	EO, *In-situ*
	Surface element thickness	EO, GIS
	Surface element fraction	EO
Q_H	Sourface roughness	EO
	Sourface temperature	EO
	Air temperatre	*In-situ*
Q_E	Sourface roughness	EO
	Stomatal resistance	EO
	Saturation water vapour pressure	*In-situ*
	Atmospheric water vapour pressure	*In-situ*

III. RESULTS AND DISCUSSION

The estimation of Q* needs the surface temperature and albedo. The surface temperature can be derived from satellite thermal infrared observations, however for the estimation of albedo, radiative transfer modelling is required to account for the urban surface anisotropy. In the framework of URBANFLUXES an original and operational methodology for deriving maps of urban albedo from satellite images was devised, without the need of in-situ measurements or information, although this type information could improve results. The DART model was calibrated with satellite observations to simulate the urban surface albedo at the time of satellite image acquisition and at the spatial resolution of the respective satellite image. DART can compute the albedo for any hour and date, using actual atmosphere data derived from in-situ or satellite acquisitions (e.g. ECMWF, Aeronet network, Sentinel-3). The adjustment of DART to URBANFLUXES does not rely simply on a function of urban anisotropic reflectance. A major point of the two developed methodologies is take advantage of the urban databases (morphology and cover) that were developed in the framework of the project.

A sensitivity test was performed to prepare the implementation of the ESTM in URBANFLUXES case studies. From the initial sensitivity tests, the following results were drawn: there was low sensitivity to the internal air temperatures; the method of averaging component surface temperatures had a large influence; the results are sensitive to building dimensions used in the calculations; and the thermal responses of building material had a large effect. In this study, to consider the spatial variations of the storage heat flux a 5 km x 5 km area of central Basel was used. The spatial variation of ΔQ_S was calculated using a 100 m x 100 m grid. Figure 1 [10] shows the estimated ΔQ_S for a Landsat scene (30 August, 2015 at 11:16 CET). In this example, the spatial pattern is affected by urban morphology and surface temperatures. Materials, indoor and outdoor air temperature were the same for the whole model domain. The highest ΔQ_S was found in the central parts of the city (the densest part of Basel, with the warmest surface temperatures at this time). Cooler areas, with lower building density, such as parks and open water, showed, as expected, lower ΔQ_S. More detailed information on materials would probably accentuate the spatial differences of ΔQ_S, given that dense urban areas tends to include materials, such as stone and concrete which have the ability to store more energy and hence increase ΔQ_S.

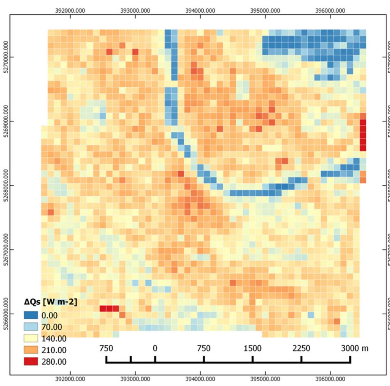

Fig. 1. Storage heat flux calculations for central Basel on 30 August, 2015 (11:16 CET), at 100 m x 100 m spatial resolution (adapted from [10]).

The turbulent sensible (Q_H) and latent (Q_E) heat fluxes are strongly modified by the properties of the urban surface, i.e. 3D geometry, high roughness, impervious surfaces, complex source/sink distribution and injections of heat and water into the urban atmosphere by human activities (traffic, heating, waste management, etc.). In URBANFLUXES, the ARM was employed to estimate the turbulent heat fluxes by combining satellite and Wireless Sensors Network (WSN) observations. To determine the input parameters for the aerodynamic resistance, the approach of [5] was modified to the satellite data. Both, roughness length (for heat and momentum) and displacement height were needed in this calculation. Roughness parameters were calculated using the real urban surfaces parameterization of [9]. Stomatal resistance was calculated after [11], using the simplified equation from [12]. The roughness length for Q_H and Q_E, as well as the minimum stomatal resistance for latent heat flux, interpolated based on the urban morphology and the urban surface characteristics, as they were derived from EO. WSN observations were used to support the turbulent fluxes estimation from EO data. Figure 2 [13] shows the estimated Q_H for a Landsat scene (30 August, 2015 at 11:16 CET). The highest values were found in the most densely built-up and industrial areas with high surface temperatures and missing vegetation.

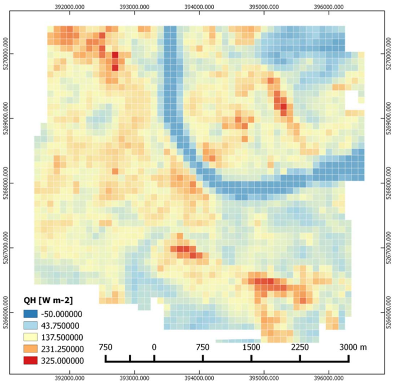

Fig. 2. Sensible heat flux calculations for central Basel on 30 August, 2015 (11:16 CET), at 100 m x 100 m spatial resolution (adapted from [13]).

IV. Conclusions

Despite its local importance, the anthropogenic heat flux is omitted from climate models simulations. Observations of global temperature evolution indicate a pronounced warming over the last 150 years, with an increase in the occurrence of heat waves. The added value and benefit expected to emerge from URBANFLUXES is therefore related to quality of life, because it is expected to improve our understanding of the contribution of UEB to heat wave intensity and thus to allow insight into strategies for mitigation. UEB estimates are needed for all cities to be able to document the magnitude of the fluxes effects on urban climate so that the impact of the anthropogenic heat flux can be included in climate modelling. URBANFLUXES is therefore expected to advance the current knowledge of the impacts of UEB on urban heat island and hence on urban climate, and consequently on energy consumption in cities. This will lead to the development of tools and strategies to mitigate these effects, improving thermal comfort (social benefit) and energy efficiency (economic benefit). The long term operation of the Sentinels series guarantees the future supply of satellite observations, providing the means for the development and realization of the URBANFLUXES methodology.

URBANFLUXES is expected to support sustainable planning strategies relevant to climate change mitigation and adaptation in cities, because knowledge of UEB spatio-temporal patterns is important for urban planning (e.g. to reduce or prevent anthropogenic heat hot spots), health (e.g. to estimate the impact on thermal comfort) and future proofing (e.g. to plan and implement interventions towards anthropogenic heat reduction). Planning tools, such as Urban Climatic Maps and Climatope Maps, should be enriched with information on UEB patterns. Mapping provides visualization of assessments of these phenomena to help planners, developers and policy makers make better decisions on mitigation and adaptation.

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