A novel approach for anthropogenic heat flux estimation from space

Chrysoulakis N.[1], Esch T.[2], Gastellu-Etchegorry J.-P.[3], Grimmond C.S.B.[4], Parlow E.[5], Lindberg F.[6], Del Frate F.[7], Klostermann J.[8], Mitraka Z.[1], Heldens W.[2], Albitar A.[3], and Feigenwinter C.[5]

[1] *Foundation for Research and Technology Hellas (FORTH), Greece, zedd2@iacm.forth.gr*
[2] *German Aerospace Center (DLR), Germany, thomas.esch@dlr.de*
[3] *Centre d'Etude Spatiale de la Biosphère (CESBIO), France, jean-philippe.gastellu-etchegorry@cesbio.cnes.fr*
[4] *University of Reading, UK, c.s.grimmond@reading.ac.uk*
[5] *University of Basel, Switzerland, eberhard.parlow@unibas.ch*
[6] *University of Goeteborgs, Sweden, fredrikl@gvc.gu.se*
[7] *GEO-K s.r.l., Italy, delfrate@disp.uniroma2.it*
[8] *ALTERRA, Netherlands, judith.klostermann@wur.nl*

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1. Abstract

The recently launched H2020-Space project URBANFLUXES (URBan ANthrpogenic heat FLUX from Earth observation Satellites) investigates the potential of EO to retrieve anthropogenic heat flux, as a key component in the Urban Energy Budget (UEB). URBANFLUXES advances existing Earth Observation (EO) based methods for estimating spatial patterns of turbulent sensible and latent heat fluxes, as well as urban heat storage flux at city scale and local scale. Independent methods and models are engaged to evaluate the derived products and statistical analyses provide uncertainty measures. Optical, thermal and SAR data from existing satellite sensors are exploited to improve the accuracy of the UEB components spatial distribution calculation. Synergistic use of different types and of various resolution EO data allows estimates in local and city scale. The URBANFLUXES project prepares the ground for further innovative exploitation of EO data in scientific activities involving Earth system modelling and climate change studies in cities. The URBANFLUXES products will support system models to provide more robust climate simulations. Ultimate goal of the URBANFLUXES is to develop a highly automated method for estimating UEB components to use with Copernicus Sentinel data, enabling its integration into applications and operational services. The improved data quality, spatial coverage and revisit times of the Copernicus data will allow support of future emerging applications regarding sustainable urban planning, with the objective of improving the quality of life in cities.

2. Overview of the URBANFLUXES project

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. Both urban planning and Earth system science communities need spatially disaggregated Q_F data, at local (neighbourhood, or 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 potentially is a valuable tool for estimating the different Urban Energy Budget (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.

Several parameters describing the urban environment can be directly retrieved from EO data, such as the surface fractional cover, the surface albedo, emissivity and temperature. However, the main use of EO still remains the mapping of the urban land cover and morphology. All these parameters affect the UEB and relate to Q_F. Therefore, further investigation of the combination of satellite data with *in-situ* fluxes measurements and modelling, has the potential to reveal novel scientific insights on the role of Q_F within the UEB, although not specifically intended during the design of the current and expected in the near future satellite missions. With this goal, the synergistic use of remote sensing data acquired at different spatial resolutions and revisiting times seems very promising.

The concept of URBANFLUXES (URBan ANthrpogenic heat FLUX from Earth observation Satellites) introduces novel ideas on how anthropogenic heat emissions can be observed from space. URBANFLUXES will exploit the Copernicus Sentinels observations, which are expected to provide improved data quality, coverage and revisit times, increasing the value of EO data for scientific work and future emerging applications. These observations can reveal novel scientific insights on the detection and monitoring of anthropogenic heat emission, thereby generating new EO opportunities.

Since the rate of warming in cities is higher than the average global warming, both urban planning and Earth system science communities need spatially disaggregated anthropogenic heat emission data; such information is practically impossible to derive by point *in-situ* fluxes measurements, while satellite remote sensing is considered in URBANFLUXES as a valuable tool for estimating the UEB parameters. The basic idea behind URBANFLUXES is to break down UEB and to quantify the anthropogenic heat flux patterns of day and night, week and weekend, summer and winter times, by combining observations form different Copernicus Sentinels satellite missions. The anthropogenic heat flux is the heat flux resulting from vehicular emissions, space heating and cooling of buildings, industrial processing and the metabolic heat release by people. In URBANFLUXES, the UEB is considered in the context of a volume because of the three-dimensional nature of cities, as shown in Figure 1.

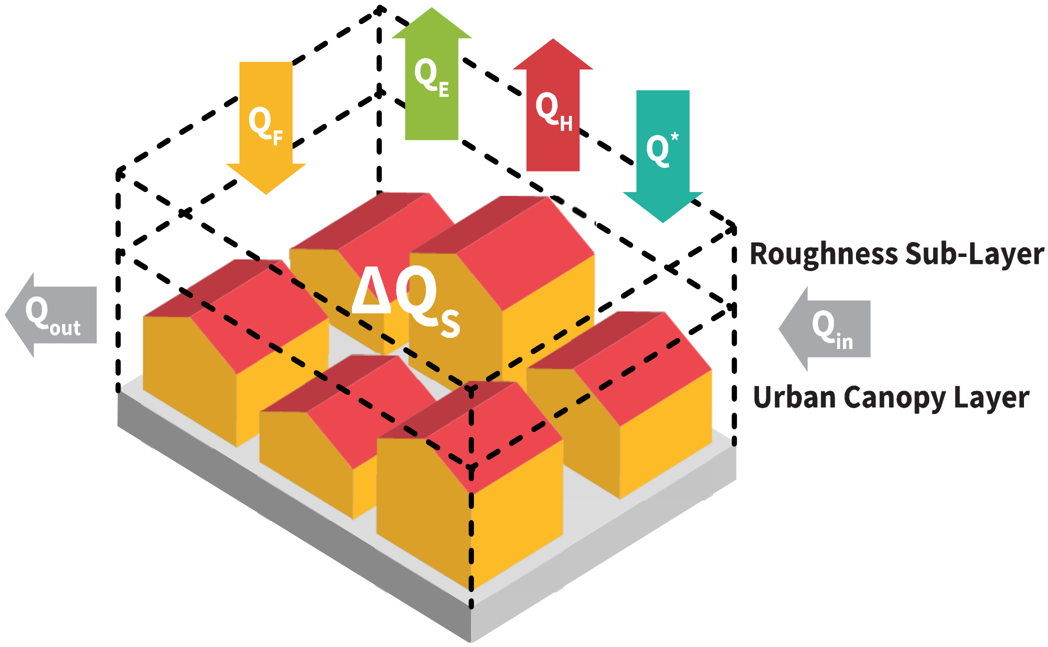

Fig. 1 The UEB is defined: $Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A + S$, where Q_F is the anthropogenic heat flux, Q^* is the net all-wave radiation flux, Q_H is the turbulent sensible heat flux and Q_E is the latent heat flux, ΔQ_S is the heat storage, $\Delta Q_A = Q_{in} – Q_{out}$ and S represents all other sources and sinks, within the control volume shown in this figure.

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 will answer 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. This method can be used operationally to derive spatiotemporal patterns of Q_F in the near future, when observations with adequate temporal resolution become available. URBANFLUXES therefore 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. To this end, the specific objectives of the project are:

- to improve the accuracy of the radiation balance spatial distribution calculation;
- to develop EO-based methods to estimate the flux of heat storage in the urban fabric;
- to improve EO-based methods to estimate turbulent sensible and latent heat fluxes and to evaluate them using flux measurement by *in-situ* Eddy Covariance instrumentation (or scintillometry) at selected case studies;
- to employ energy budget closure to estimate the anthropogenic heat flux spatial patterns at city scale and local scale (100 m x 100 m) at selected case studies;
- to specify and analyse the uncertainties associated with the derived products;
- to evaluate the products by comparisons with anthropogenic heat flux estimations by independent methods and models;
- to improve the understanding of the impact of the anthropogenic heat on energy budget, urban heat island (UHI) and urban climate; and to communicate this understanding to the urban planning community, which will in turn lead to a better understanding of what new knowledge is needed on the ground;

- to investigate the potential of exploitation of the Sentinels 2 and 3 synergistic observations to combine local scale and city scale observations, capable of retrieving Q_F and of the remaining UEB fluxes at the local scale, with the frequency of the Sentinel 3 series acquisitions.
- to develop a highly automated method for estimation of UEB components from Copernicus data, enabling its integration into applications and operational services;
- to standardise the resulting products, and by organizing an effective dissemination mechanism, to enhance their use by urban planners and decision makers in cities, as well as by EO scientists, Earth system modellers and urban climatologists;
- to support sustainable urban planning strategies relevant to climate change mitigation and adaptation in cities, by taking into account the contribution of Q_F.

The energy balance residual approach will be used in URBANFLUXES. Although a rather straightforward method when the rest UEB components are known, its primary drawback is the accumulation of estimation errors of each UEB in Q_F and the error of having neglected any unmeasured terms. Errors in the estimated flux terms include those stemming from normal observation inaccuracies plus the real spatial variability of the surface energy budget. The Q_F considered here captures only the effects of energy released within the system, which is not necessarily equivalent to energy consumption, as for example for the case of buildings, due to the heat transfer resistance between buildings and atmosphere and the thermal inertia of buildings. Q_F is estimated by regressing the sum of the turbulent heat fluxes versus the available energy, defined for every pixel. Given that UEB closure is achieved, the regression will result in Q_F, estimating also the respective uncertainty.

Three different urban areas are selected in URBANFLUXES as case studies: a highly urbanized mega city (London), where high values of Q_F are expected in all seasons; a typical central European medium size city, that requires a substantial amount of energy for heating (Basel metropolitan area); and a smaller, low latitude Mediterranean city with dynamic urbanization process that requires a substantial amount of energy for cooling (Heraklion). In both Basel and Heraklion lower Q_F values are expected; however the two latter cases are considered as representative test-beds to investigate possible limitations of the URBANFLUXES methodology. In all cities local scale and city scale Q_F estimations will be performed. Satellite observations will be analysed for typical days for all seasons taking also into account the synoptic meteorological conditions in the selection of these days. The effort will focus on both work days and holidays for each season. Especially for Heraklion, emphasis will be given on mapping of Q_F spatial patterns in summer, when the energy demand is high due to the air conditioning usage. To develop a method that will be welcomed by potential users, it is important to involve them in the project from the beginning. 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 CoP will make clear what aspects are important for the future users of the URBANFLUXES products. The scientists, in turn, explain what the possibilities and limitations of the methods and models are. The interactions are informal and open in order to lead to an increased understanding of the system under study for both the future users and the scientists. It also provides network contacts for collecting spatial and non-spatial datasets for each case study. This approach will also be used to create an “umbrella” CoP across the participating cities, as well as with the broader scientific community, to exchange ideas and experience of the URBANFLUXES products on a European level.

The overall URBANFLUXES approach is shown in Figure 2, showing the cross cutting process of the CoP, which facilitates the continuous interaction with the users (both planning and scientific communities). In the framework of the CoP the Q_F related user requirements will be captured and the demonstration of URBANFLUXES method and products will be performed. The increase in mutual understanding will be monitored and evaluated. URBANFLUXES is divided into two main phases: during the first phase an analysis method will be developed to estimate Q_F spatial patterns using currently available satellite data (Copernicus Contributing Missions for optical and SAR observations, as well as non-European missions for thermal infrared observations); during the second phase the developed method will be adapted to Sentinels synergy to derive Q_F spatiotemporal patterns. A network of simple meteorological stations will be used in all cities, whereas Eddy Covariance systems also will be used (in both London and Basel such systems are already operational; in Heraklion a new Eddy Covariance instrumentation will be installed specifically for this project). EO data initially will be analysed to map urban surface morphology and cover, whereas a new method will be developed to define Local Climate Zones (LCZ). Using the LCZ as a framework, new EO-based methods will be generated to estimate Q^*, ΔQ_s, Q_H and Q_E. The estimation of ΔQ_s will be supported by the auxiliary spatial datasets (collected in the frame of CoPs), whereas the estimation of Q_H and Q_E will be supported by standard meteorological measurements. Eddy Covariance measurements will be used to validate the Q_H and Q_E estimates, net radiation measurements will be used to validate Q^* estimates, whereas the ΔQ_s will be evaluated by comparisons with respective estimations by other methods (i.e. inventories) at specific locations in case studies. Based on these outcomes, the Q_F spatial patterns will be derived, evaluated by comparisons with Q_F estimated by other methods and demonstrated in the framework of an umbrella CoP event.

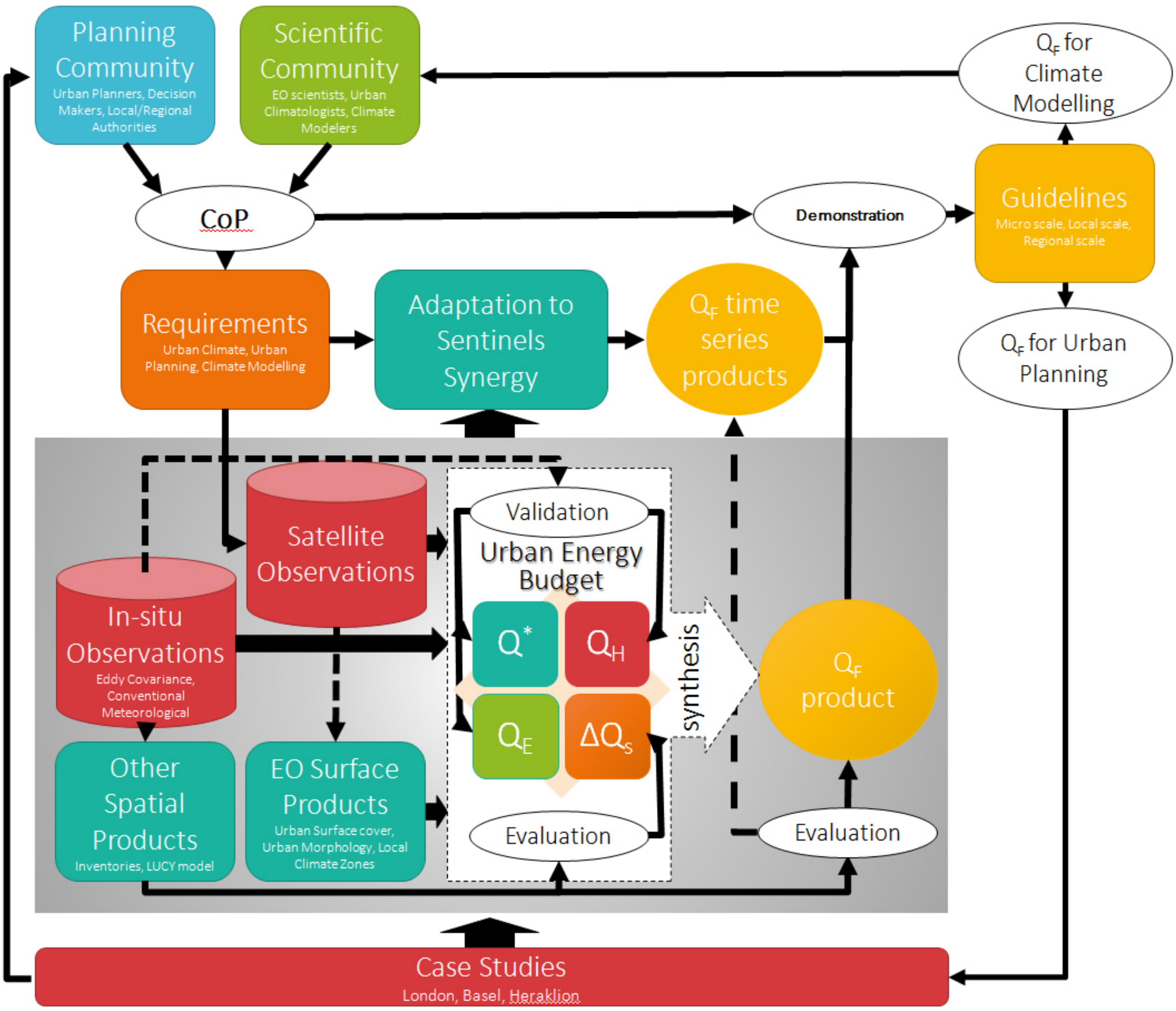

Fig. 2 Flowchart of the URBANFLUXES methodology.

URBANFLUXES is expected to generate a novel analysis method for estimation of UEB components from Copernicus data, enabling its integration into applications and operational services; for example to: develop rules of thumb for density and green space ratio, distinguish between insulated and non-insulated buildings/neighbourhoods and evaluate the implementation of climate change mitigation technologies such as solar-screening, green-belting and carbon-cooling. Despite its local importance, Q_F 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 Q_F to heat wave intensity and thus to allow insight into strategies for mitigation. Q_F 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 Q_F can be included in climate modelling. URBANFLUXES is therefore expected to advance the current knowledge of the impacts of Q_F on UHI 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.

The dependence of the URBANFLUXES method on EO data is one of its key advantages, given the potential for 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 QF 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.

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