EO-based Products in Support of Urban Heat Fluxes Estimation

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***Abstract*—Presently, there is a growing need for information suitable to effectively characterize the Urban Energy Budget (UEB) and, hence, to properly estimate the magnitude of the anthropogenic heat flux Q_F. Indeed, a precise knowledge of Q_F - whose implications for urban planners are still prone to large uncertainties - is fundamental for implementing effective strategies to improve thermal comfort and energy efficiency. To address this challenging issue, the Horizon 2020 URBANFLUXES project aims at developing a novel methodology for accurately estimating the different terms of the UEB based on the use of Earth Observation (EO) data and, hence, at reliably characterizing the Q_F spatiotemporal patterns and its implications on urban climate. In this paper, we aim at giving an overview of the EO-based products which have been identified as the most useful in the framework of the considered study. In particular, the suite which has been implemented so far in the first phase of the project includes biophysical parameters, morphology parameters as well as land-cover maps.**

Keywords—Earth observation; urban heat fluxes; anthropogenic heat flux

I. Introduction

Nowadays, in the climate change scenario a key challenge is to understand the relationship between urban form, energy use and carbon emissions. Indeed, a better understanding of the interactions between urban settlements and atmosphere is necessary for improving both planning-landscaping activities, and identifying effective mitigation strategies. In this context, how people live, work, move from one place to another and what they consume has impacts on the fabric, morphology and emissions in a city. Nevertheless, also the spatial organization itself of urban areas strongly affects the urban energy use.

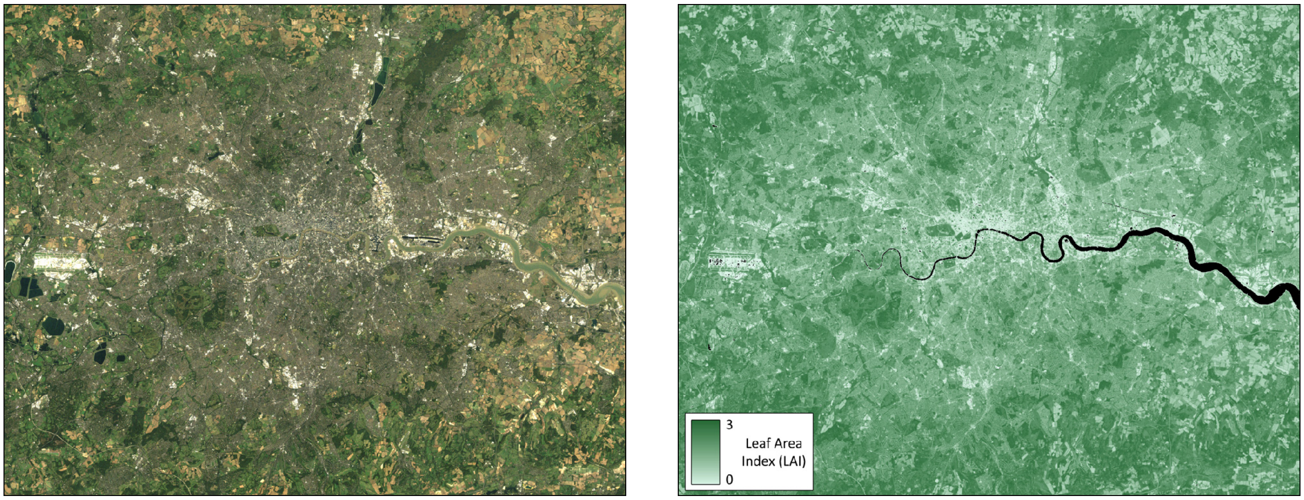
In urban areas the energy enters, passes through and leaves in different forms and physical states. Accordingly, the relationship among all the energy fluxes is modeled through the Urban Energy Budget (UEB) scheme, which, given the 3D nature of urban environments, is considered in the form of a volume. Here, three major types of fluxes are generally considered, namely radiative, turbulent and anthropogenic. Radiative fluxes are associated with shortwave radiation incoming from the sun and reflected by Earth's surface, as well as longwave radiation emitted by Earth's surface and radiated towards the surface by the atmosphere. Turbulent fluxes are driven by wind and are associated with the heating of Earth's surface and phase changes of water (e.g., evaporation). Instead, anthropogenic fluxes result from vehicular emissions, space heating and cooling of buildings, industrial processing and the metabolic heat release by people. In the UEB, the equivalent surface energy budget per unit surface area through the top of the volume is described as:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A + S \qquad (\mathrm{W\ m^{-2}})$$

Q^* represents the net all-wave radiative flux (i.e., the available energy at any location to heat the air or ground or evaporate water). Q_F denotes the anthropogenic heat flux. Q_H corresponds to the turbulent sensible heat flux, which is associated with convection and driven by difference in temperature between surface and atmosphere. Q_E is the turbulent latent heat flux, which is driven by the difference in vapor pressure between surface and atmosphere (e.g., evapotranspiration). ΔQ_S describes the net flow of heat stored in urban canopy and represents all the mechanisms of storage of energy within the volume (i.e., the air, on trees, in buildings, etc.). ΔQ_A is the net heat advection flux (i.e., the net horizontal flow of energy resulting from differences of surface characteristics). Finally, S represents all other sources and sinks.

At present, two are the main issues affecting a reliable characterization of the UEB. On the one hand, the spatial and temporal patterns of the anthropogenic heat flux Q_F, along with its impact on urban climate and related implications for urban planners are still prone to large uncertainties. Indeed, Q_F is difficult to determine both because it cannot be measured directly and exhibits a strongly varying pattern. Nevertheless, such information is of great importance for the development of effective strategies to improve thermal comfort and energy efficiency. On the other hand, so far different components of the UEB have been estimated by means of in-situ heat flux measurements, but these are solely representative of small areas (indeed urban surfaces are complex mixtures of different land covers and surface materials).

In such context, the Horizon 2020 URBANFLUXES (URBan ANthropogenic heat FLUX from Earth observation Satellites) project aims at overcoming these limitations by developing a novel methodology for accurately estimating the different terms of the UEB based on the use of Earth Observation (EO) data and, hence, at reliably characterizing the



(a) (b)

Fig. 1 – London: RGB true-color surface reflectance (a) and corresponding LAI (b) derived for the Landsat-5 scene acquired on 30th September 2011 using ATCOR-3.

Q_F spatiotemporal patterns and its implications on urban climate. Indeed, in contrast to in-situ measurements, EO provides the advantage of large-area spatial coverage at relatively high spatial resolution. Moreover, 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, which started in February 2015 and will last for 36 months, includes three study sites, namely: London (i.e., a highly urbanized mega city), Basel (i.e., a medium size city requiring a consistent amount of energy for heating), and Heraklion (i.e., a smaller city experiencing dynamic urbanization processes which requires a consistent amount of energy for cooling).

Main assumptions in URBANFLUXES are that: i) all energy consumed in buildings is released into the environment after use; ii) advection fluxes of latent and sensible heat are of similar size but opposite in sign (thus resulting in small ΔQ_A which is incorporated in the error of Q_F estimation); and iii) the term S is negligible. In this framework, Q^*, Q_H, Q_E and ΔQ_S are derived by exploiting EO-based products with the support of standard meteorological observations. The expected value of the residual term would then be an estimate of Q_F, since, from a measurement perspective, it is impossible to remove the anthropogenic contributions from the other terms in the UEB. In particular, Q_F is finally derived by regressing (Q_H + Q_E) versus (Q^* - ΔQ_S). In the light of the fine scale needed to properly characterize the fluxes in urban environments, a 100x100m cell size has been chosen to be employed.

In this paper, we aim at giving an overview of the EO-based products which have been so far generated for improving the current estimation of Q^*, Q_H, Q_E and ΔQ_S. In particular, URBANFLUXES brings together EO scientists on the one side and climate modellers on the other. Hence, several efforts have been spent in the first phase to agree a common language and clearly understand where the most benefits might come from the employment of EO-based products into different climate models used in the project either as direct input or constraint.

Three different types of EO-based products have been identified as the most useful in the framework of the considered study, namely biophysical parameters, morphology parameters and land-cover maps. In the following sections, details will be provided for each of them.

II. Biophysical Parameters

Biophysical parameters describe physical properties of Earth's surface and bear key information for properly characterizing geosphere-biosphere-atmosphere interactions. In this context, parameters derived by means of satellite imagery in URBANFLUXES include surface reflectance, the normalized difference vegetation index (NDVI), the leaf area index (LAI), the land surface temperature (LST), as well as the aerosol optical thickness (AOT) and the local solar zenith angle. However, it is worth noting that their estimation cannot solely refer to a single date since Q_F temporally exhibits strong variations and its largest impact results from changes in temperature conditions which severely influence the building energy use (e.g., in warmer days the demand for air conditioning increases, hence resulting in higher heat and, therefore, further demand for cooling). Accordingly, given their long-term record, the easy and free accessibility, the suitable spatial resolution (i.e., 30m), as well as the existence of established state-of-the art algorithm for deriving the chosen parameters, Landsat data have been employed in the first phase of the project. Specifically, for the three study sites all the available Landsat-5/7/8 images with cloud coverage lower than 60% acquired from 2010 onwards have been taken into consideration (summing up to 180 scenes for Basel, 162 for Heraklion and 128 for London). Then, the Atmospheric/ Topographic correction (ATCOR) software version 3 [1] specifically designed for satellite data has been employed for extracting the abovementioned parameters of interest. Pixels associated with clouds and cloud shadows have been masked by employing the C Function of Mask (CFMask) algorithm [2].

Surface reflectance represents the portion of incoming solar radiation reflected from Earth's surface and corresponds to what would be measured by a sensor held just above the Earth's surface without any artefacts due to the atmosphere or illumination and viewing geometry. For its estimation, the elevation, slope and aspect factor computed from the SRTM digital elevation model (DEM) at 1 arcsec (i.e., ~30m) spatial resolution have been used in ATCOR, while the empirical bidirectional reflectance distribution function (BRDF) correction was based on the local solar zenith angle (i.e., the angle between the surface normal of the DEM pixel and the solar zenith angle of the scene). While excluding the contribution of the atmosphere, ATCOR also estimates the AOT (at 550nm) which corresponds to the degree to which aerosols prevent the transmission of light by absorption or scattering of light. The corresponding NDVI is computed as the ratio of the difference between the estimated surface reflectance in the near infrared and red portion of the spectrum over their sum. The LAI is then obtained as $\log_{10}$(1-NDVI)/0.325 (such an approximation might be not completely correct in terms of absolute values; nonetheless, it allows to reliably capture seasonal trends). Finally, the LST is derived in ATCOR by fixing the surface emissivity to 0.98 and assuming mid-latitude atmosphere. Examples of the RGB true-color surface reflectance and the corresponding LAI derived for the Landsat-5 scene acquired on 30th September 2011 over London are reported in Fig. 1.a and 1.b, respectively.

III. Morphology Parameters

Morphology parameters describe the spatial structure of the urban environment and are estimated starting from digital surface models (DSM, where each pixel is associated with the elevation above the sea level of the corresponding ground or any feature on it) and digital terrain models (DTM, where each pixel is associated with the elevation above the sea level of the corresponding ground disregarding any feature on it) generated from LiDAR airborne imagery (i.e., as for Basel and London) or VHR satellite stereo imagery (i.e., as for Heraklion). In this context, the parameters identified as most informative for the purposes of URBANFLUXES are derived by means of the Urban Multi-scale Environmental Predictor (UMEP) software [3], which can be used in a variety of applications related to outdoor thermal comfort, urban energy consumption, climate change mitigation etc. Specifically, by simplifying the urban surface in three facets (i.e., roof, walls and ground facets) UMEP is employed to estimate for any given 100x100m cell: the plan area index (corresponding to the fraction of roof area), the frontal area index (defining the area of windward building walls relative to total plan area), the mean maximum and standard deviation of obstacle height, the roughness length (modelling the horizontal mean wind speed near the ground, which, in the log wind profile, is equivalent to the height at which the wind speed theoretically becomes zero), the zero displacement height (denoting the height in meters above the ground at which zero wind speed is achieved as a result of flow obstacles such as trees or buildings) and the total wall area. All of them are computed both isotropically and anisotropically (to consider all wind directions the grid is rotated based on a 5° interval). An example of the frontal area index derived at 100x100m spatial resolution for the area including the whole Greater London Authority (GLA) is reported in Fig. 2.b.

IV. Land-Cover Maps

A reliable categorization of 7 specific information classes for the investigated test sites proved to be a fundamental requirement from the urban climate modellers' side; indeed, fluxes exhibit a consistent variation over space depending on the underlying land-cover type. In particular, classes of interest include: buildings, impervious surfaces (i.e., roads, parking lots, squares, etc.), water, bare soil, low vegetation (intended as lower than 2m) and high vegetation (intended as greater or equal to 2m) split into evergreen and deciduous trees. To this purpose, in the first phase of the project very high resolution (VHR) SPOT and WorldView imagery has been employed in order to obtain fine scale and highly accurate land-cover maps. Specifically, the technique based on neural networks presented in [4] has been first used after manually defining training points by photointerpretation. High and low vegetation has been separated based on the normalized DSM (derived by subtracting the DTM from the DSM). For discriminating evergreen from deciduous trees a novel strategy has been applied. In particular, for each pixel the temporal standard deviation of the Landsat NDVI (derived using ATCOR as described in Section II) over a 2-year period has been computed. Based on the assumption that evergreen trees exhibit lower temporal variability with respect to deciduous, a threshold has been defined accordingly. The final land-cover map obtained for the London test site using SPOT imagery is reported in Fig. 2.a.

V. Use of EO-based Products in the UEB Estimation

The generated EO-based products are employed at multiple stages and different manners in URBANFLUXES.

The DART (Discrete Anisotropic Radiative Transfer) model [5] is employed to retrieve local scale Q*. Normally, starting from VHR EO imagery, DART simulates the radiative transfer in the Earth-Atmosphere using the discrete ordinate method, wherein radiation is restricted to propagate in a finite number of directions and any set of discrete directions can be used. In particular, it discretizes propagation directions for simulating accurately the radiative budget and satellite images for any view directions. In the project, the model has been adapted so that the EO-based surface reflectance is directly employed as input along with the corresponding AOT which is used for estimating direct and diffuse irradiance. Moreover, the LAI is used for constraining the amount of leaves simulated by DART for the trees assumed to be present in the investigated area of interest, whereas the EO-based LST and local solar zenith angle are compared to those internally derived by the model for identifying potential consistent discrepancies.

To estimate the turbulent heat fluxes, the roughness length for Q_H and Q_E, as well as the minimum stomatal resistance for

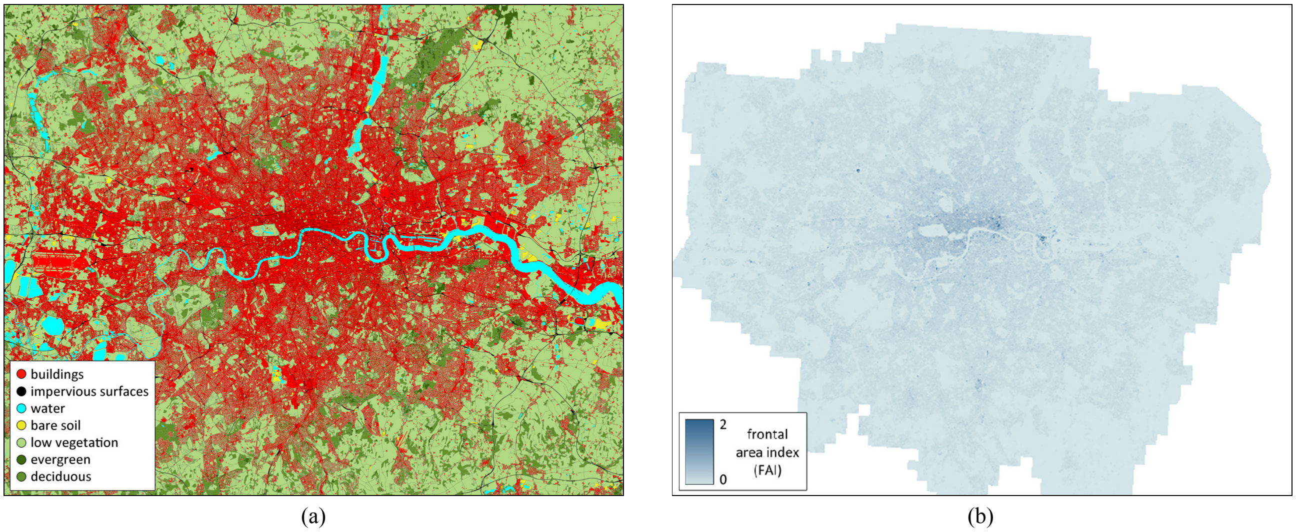


Fig. 2 – London: land-cover map generated from VHR SPOT imagery at 2.5 m resolution (a) and corresponding frontal area index derived at 100m spatial resolution for the area including the whole Greater London Authority (GLA).

latent heat flux are interpolated based on the derived EO-based urban morphology and biophysical parameters according with the methods presented in [6]-[8]. Indeed, Q_H and Q_E are strongly modified by the specific properties of the urban surface and the spatial variability of urban terrain. Moreover, the sensible heat flux Q_H is calculated exploiting the LST product, while Q_E is determined accounting for the local proportion of water and pervious surfaces derived from the EO-based land-cover maps, as well as the vegetation fraction estimated, for each available scene, on the basis of the computed NDVI.

Accurate estimation of ΔQ_S requires knowledge of the thermal conductivity of the surface material and the sub-surface vertical temperature profile for soil and inside walls, roofs and floors for buildings. Nevertheless, since such type of information is hard to retrieve, in URBANFLUXES ΔQ_S is estimated indirectly by using the Element Surface Temperature Method (ESTM) [9] where the three-dimensional urban surface is reduced to one-dimensional elements for building roofs, walls, as well as internal mass and road, representing the various components of the surface volume. In this framework, the EO-based LST and morphometric parameters are used as direct input together with land-cover fractions computed based on the classification maps described in Section IV (where each pixel denotes the fraction of the given class within the corresponding 100x100m surface). Moreover, the class "buildings" is further divided in sub-categories by taking into account the Urban Atlas 2012 layer.

VI. Conclusions

The URBANFLUXES project is expected to advance the current knowledge of the impacts of Q_F on urban climate, and, consequently, on energy consumption in cities. This will lead to the development of tools and strategies for effectively mitigating these effects, improving thermal comfort and energy efficiency. The dependence of the URBANFLUXES method on EO data is one of its key advantages, given the potential for transferability to any city. So far preliminary results obtained by integrating products derived from Landsat data, as well as VHR optical imagery in addition to DSM/DTM information proved particularly effective and promising. Nevertheless, in the remainder of the project Sentinel-1, Sentinel-2 and Sentinel-3 data are planned to be used and their potential for supporting the addressed research will be assessed into details.

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