Spatial Distribution of Sensible and Latent Heat Flux in the City of Basel (Switzerland)

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Abstract—Urban surfaces are a complex mixture of different land covers and surface materials; the relative magnitudes of the surface energy balance components therefore vary widely across a city. Eddy covariance (EC) measurements provide the best estimates of turbulent heat fluxes but are restricted to the source area. Land surface modeling with earth observation (EO) data is beneficial for extrapolation of a larger area since citywide information is possible. Turbulent sensible and latent heat fluxes are calculated by a combination of micrometeorological approaches (the aerodynamic resistance method, ARM), EO data, and GIS techniques. Input data such as land cover fractions and surface temperatures are derived from Landsat 8 OLI and TIRS, urban morphology was calculated from high-resolution digital building models and GIS data layers, and meteorological data were provided by flux tower measurements. Twenty-two Landsat scenes covering all seasons and different meteorological conditions were analyzed. Sensible heat fluxes were highest for industrial areas, railway stations, and areas with high building density, mainly corresponding to the pixels with highest surface-to-air temperature differences. The spatial distribution of latent heat flux is strongly related to the saturation deficit of vapor and the (minimum) stomatal resistance of vegetation types. Seasonal variations are highly dependent on meteorological conditions, i.e., air temperature, water vapor saturation deficit, and wind speed. Comparison of measured fluxes with modeled fluxes in the weighted source area of the flux towers is moderately accurate due to known drawbacks in the modeling approach and uncertainties inherent to EC measurements, particularly in urban areas.

Index Terms—Aerodynamic resistance method, earth observation (EO), eddy covariance (EC), GIS, urban energy budget, URBANFLUXES.

NOMENCLATURE

\( \rho \) \hspace{1em} Air density (kg m\(^{-3}\)).

\( \varepsilon \) \hspace{1em} Emissivity dimensionless.

\( \Delta Q_A \) \hspace{1em} Net advective heat flux (W m\(^{-2}\)).

\( \Delta Q_S \) \hspace{1em} Net storage heat flux (W m\(^{-2}\)).

\( u_s, U \) \hspace{1em} Friction velocity and wind velocity (m s\(^{-1}\)).

\( e_s*, e_a \) \hspace{1em} Saturation and atmospheric vapor pressure (hPa).

\( L \) \hspace{1em} Monin–Obukhov length (m).

\( L \uparrow \downarrow \) \hspace{1em} Upwelling/downwelling longwave radiation (W m\(^{-2}\)).

\( \text{PAR} \) \hspace{1em} Photosynthetically active radiation (W m\(^{-2}\)).

\( Q_{E,F,H} \) \hspace{1em} Latent/anthropogenic/sensible heat flux (W m\(^{-2}\)).

\( r_a \) \hspace{1em} Atmospheric resistance (s m\(^{-1}\)).

\( \text{Re} \) \hspace{1em} Reynolds number (dimensionless).

\( R_n \) \hspace{1em} Net radiation (W m\(^{-2}\)).

\( r_s \text{MIN}, r_s \) \hspace{1em} (Minimum) stomatal resistance (s m\(^{-1}\)).

\( T_s, T_a, T_{rad} \) \hspace{1em} Surface/air/radiation temperature (K).

\( z_{0m}, z_{0h} \) \hspace{1em} Roughness lengths for momentum and heat (m).

\( z_{ref}, z_d \) \hspace{1em} Reference height and zero-plane displacement height (m).

I. INTRODUCTION

The URBANFLUXES Horizon 2020 project (http://urbanfluxes.eu) aims to derive the Urban Energy Budget and the anthropogenic heat flux from earth observation (EO) data. Each component of the urban energy balance after [1]

\[ R_n + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \]  

with the net radiation \( R_n \), the sensible \( Q_H \) and latent \( Q_E \) heat flux, the storage heat flux \( \Delta Q_S \), and the anthropogenic heat flux \( Q_F \) being evaluated in a separate work package [2] and the net advection \( \Delta Q_A \) is assumed to be zero. This study concentrates on the fluxes of sensible and latent heat, which are strongly modified by the properties of the urban surface, i.e., three-dimensional (3-D) 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.). The spatial variability of urban terrain complicates their estimation. The existence of various surface types and different exposures to solar radiation in a complex surface geometry leads to significant variations in heat fluxes over short distances. This problem is well known,

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II. METHODS

A. Flux Calculation

In URBANFLUXES, the Aerodynamic Resistance Method (ARM) to estimate $Q_H$ uses the simple relation (e.g., [4])

$$Q_H = \frac{\rho c_p}{\gamma} \left( T_a - T_s \right)$$

where $\rho$ is the density of air, $c_p$ is the specific heat of air at constant pressure (1005 $J \cdot kg^{-1} \cdot K^{-1}$), $T_a$ is the surface temperature derived from satellite thermal infrared observations, $T_s$ is the air temperature recorded by the meteorological stations, and $r_a$ is the aerodynamic resistance. Analogously, $Q_E$ is expressed as

$$Q_E = \frac{\rho c_p e_s^* - e_a}{\gamma} r_a + r_s$$

where $e_s^*$ is the saturation water vapor pressure at $T_a$, $e_a$ is the atmospheric water vapor pressure, $\gamma$ is the psychrometric constant (0.67 $hPa \cdot K^{-1}$), and $r_s$ is the stomatal resistance. Stomatal resistance is calculated after [5] using the simplified equation from [6]

$$\frac{1}{r_s} = \frac{f_1(T_a)}{r_{sMIN}} f_2(PAR) + \frac{1}{r_{cuticle}}$$

where PAR is the photosynthetic active radiation, $r_{sMIN}$ is the minimum stomatal resistance, and $r_{cuticle}$ is the canopy resistance related to the diffusion through the cuticle layer of leaves ($10^5$ s·m$^{-1}$). Functions $f_1$ and $f_2$ are calculated as per [6] and $r_{sMIN}$ can be determined for each vegetation type. $Q_E$ is calculated by the land cover type and weighted by the fraction of water, vegetation, and pervious surfaces with the respective $r_{sMIN}$ in every pixel. Values for $r_{sMIN}$ used in this study are taken from [5] and listed in Table I.

The aerodynamic resistance $r_a$ for sensible heat in (2) can then be written as

$$r_a = \frac{1}{u_* k} \ln \left( \frac{z_{ref} - z_d}{z_{0m}} \right) - \psi_h \left( \frac{z_{ref} - z_d}{L} \right) + \ln \left( \frac{z_{0m}}{z_{0h}} \right)$$

and

$$u_* = U k \left[ \ln \left( \frac{z_{ref} - z_d}{z_{0m}} \right) - \psi \left( \frac{z_{ref} - z_d}{L} \right) - \psi \left( \frac{z_{0m}}{z_{0h}} \right) \right]^{-1}$$

where $u_*$ is the friction velocity, $k$ is the von Kármán constant (0.4), $z_{ref}$ refers to a reference height (usually the height of wind measurements), $z_d$ is the zero-plane displacement height, $L$ is the Monin–Obukhov length, $z_{0m}$ is the roughness length for momentum, $z_{0h}$ the roughness length for heat (accounting for the excess resistance when using radiometric surface temperatures [7]), and $\psi \left( \frac{z_{ref} - z_d}{L} \right)$ and $\psi \left( \frac{z_{0m}}{z_{0h}} \right)$ are the stability functions for momentum and heat, respectively, as documented in [8]. Equation (6) can be used to estimate $u_*$ from wind velocity $U$ by iteration, if no direct measurements of the friction velocity are available [9]. $z_{0h}$ values are usually reported as the dimensionless number $k \beta^{-1}$, defined as

$$k \beta^{-1} = \ln \left( \frac{z_{0m}}{z_{0h}} \right)$$

and $z_{0h}$ can be calculated after [4] by

$$z_{0h} = z_{0m} \left( 7.4 \exp \left( -0.25 \alpha Re^{0.25} \right) \right)$$

where $Re$ is the roughness Reynolds number and $\alpha$ is a parameter that varies with surface. $Re$ is calculated by

$$Re = \frac{z_{0m} u_*/\nu}$$

with a kinematic molecular viscosity $\nu$ of 1.461 $\times 10^{-5}$ m$^2$·s$^{-1}$.

To determine the input parameters for $r_a$, the approach of [10] is modified to the satellite data. Both, roughness length (for heat and momentum) and displacement height are needed in $r_a$ calculation. Input for the calculation of roughness parameters, i.e., the morphometry, is derived from a digital surface model, including the heights of buildings and trees, in high spatial resolution (between 1 and 5 m) using the open-source Geographic Information System software QGIS and the Urban Multi-scale Environmental Predictor (UMEP) [11]. UMEP output provides building heights (mean, standard deviation, maximum) and the morphological parameters plane area index and frontal area index aggregated to the chosen grid size. Roughness parameters $z_{0m}$ and $z_d$ are calculated by the real urban surfaces parameterization of [12] using UMEP results as an input.

B. Evaluation

The results are evaluated by the analysis of the calculated fluxes in 100 m spatial resolution in the footprint of the flux towers. For $Q_H$ and $Q_E$ the source area model of Kormann and Meixner [13] is used. Fluxes are measured by the eddy covariance method and processed with standard methods [14], [15]. Since measured $Q_H$ and $Q_E$ may vary considerably between averaging intervals (normally 30 min), the mean value of three half-hourly fluxes centered at overpass time was taken for the evaluation and is listed in Table II. Satellite-derived surface temperatures are compared to the surface temperature $T_{rad}$ calculated from the emitted longwave radiation in the radiation footprint of the flux towers. $T_{rad}$ is calculated by

$$T_{rad} = \left[ \frac{L + (1 - \varepsilon) L}{\sigma \varepsilon} \right]^{0.25}$$
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where $L_{\uparrow,\downarrow}$ is the upwelling and downwelling longwave radiation, respectively, measured by the radiometer; $\varepsilon$ is the emissivity of the surface in the radiation footprint (0.97); and $\sigma$ is the Stefan Boltzmann constant ($5.67 \times 10^{-8}$ W·m$^{-2}$·K$^{-4}$).

According to [16], 50% of the radiometer signal originates from an area below the sensor with a radius equal to the height a.g.l. of the sensor (see Fig. 1). Because the original resolution of the Landsat 8 TIRS is 100 m, an area of $3 \times 3$ cells with the flux tower in the center was taken. The center cell was weighted 20% and the adjacent cells 10% each for the evaluation of $T_s$.

### III. Study Area and Dataset

Here, results from Basel (city population 200 k, Basel agglomeration population 500 k), a typical mid-sized mid-European city right at the border triangle France–Switzerland–Germany are presented. Fig. 2 shows the land cover map and the digital elevation model for the investigated area.

Land cover types (see Fig. 2) were derived from SPOT 5 data in 2.5 m resolution, and land cover fractions used in (4) were aggregated to the URBANFLUXES standard 100 m grid. Surface temperatures were calculated from Landsat 8 TIRS in the same grid using the atmospheric correction software ATCOR [17]. Urban morphology parameters used for the calculation of atmospheric resistances in (5) are available in the same
resolution. The reference height $z_{ref}$ in (5) and (6) was taken as three times the mean building height in the 100 m resolution UMEP output. For the parameter $\alpha$ in (8) a value of $-0.8$ for built-up areas as proposed for the city of Basel in [18] and the standard value of $-2.46$ from [4] for areas with low roughness, i.e., mean building/vegetation height $<1$ m (mainly the low vegetation land cover class, e.g., agricultural land use and bare soil) was applied.

$Q_H$ and $Q_E$ were calculated for 22 Landsat 8 scenes between February 2013 and December 2015 for Basel (overpass time around 11:15 UTC+1). The analyzed scenes are listed in Table II sorted by season and with the most important meteorological measurements from the BKLI flux tower (see Fig. 6) during satellite overpass. This data are used as input for evaluation of the modeled heat fluxes in Section IV-B and for the spatial extrapolation of $T_a$ and $u_*$. Because the city of Basel is surrounded by the hills of the Black Forest in the North-East and the Jura mountains in the South, measured $T_a$ was extrapolated to the standard grid using the dry adiabatic lapse rate of 0.0098 K·m$^{-1}$ to consider the topography ranging from 240 to 800 m a.s.l. (see Fig. 2).

Friction velocity $u_*$ was extrapolated to the 100 m standard grid by iteration as in [8] using the measured wind speed and the Monin–Obukhov length $L$ at the BKLI flux tower as starting values and 100 m grid roughness parameters $z_0$ and $z_d$. Note that measurements in the same season may vary considerably between different years (see Table II) with consequences for the modeled fluxes as shown in the overview in Fig. 4. For example, $R_n$ on June 5, 2013, and June 8, 2014, are of similar amount (665 and 632 W·m$^{-2}$, respectively), but the partition between $Q_H$ and $Q_E$ is completely different, namely, 268 and 153 W·m$^{-2}$ for $Q_H$ to 63 and 172 W·m$^{-2}$ for $Q_E$, respectively, reflecting higher $T_a$ and the higher saturation deficit on June 8, 2014.

IV. RESULTS

A. Fluxes

Modeled sensible and latent heat flux for the Basel study area are shown in Fig. 3 for the Landsat overpass on August 30, 2015, at 1116 CET. $Q_H$ shows the highest values in the industrial areas, at the airport (NW of city center) and railway stations (areas with impervious land cover in Fig. 2), in the inhabited areas in the city, and in the densely populated valleys of the urban agglomeration. Negative values are calculated for River Rhine, because the surface temperature of water bodies is lower (25°C) than the surrounding air temperature (29°C). Dense forests also show low sensible heat flux, because the foliage temperature is close to air temperature.

Though the most important input to $Q_H$ in the ARM method is the difference between surface temperature and air temperature, the correlation is not always straightforward, as can be seen by the comparison of the scenes in Figs. 4 and 5. The general seasonal trend with highest fluxes for both $Q_H$ and $Q_E$ during the summer months is obvious, but interannual differences can be large when, e.g., comparing the different scenes available for months April, June, July, August, and October. A more detailed analysis of the interannual variability of flux distribution and partition may raise some interesting general relations between the modeled fluxes and atmospheric conditions, but this topic is out of the scope of this paper.

B. Evaluation

Modeled $Q_H$ and $Q_E$ from the 22 Landsat scenes are evaluated by comparison with the measured fluxes in the weighted source area of the three Basel flux towers. Fig. 6 shows the locations and the weighted source areas for August 30, 2015, in the 100 m standard grid for Basel flux towers BKLI, BAES, and BLER (from left to right).
The regression statistics of measured to modeled fluxes and tower $T_{rad}$ to $T_s$ are listed in Table III and shown in Figs. 7 and 8. Agreement between measured and modeled fluxes is generally poor though flux maps in Fig. 4 show reasonable values. Modeled fluxes in the footprint of the flux towers do mostly underestimate the measured fluxes and the scatter is large. Relative underestimation of $Q_E$ is larger than that for $Q_H$ but evaporative fluxes are of course lower in urban areas than in the rural surroundings.

Regression statistics for $T_s$ are better than that for the heat fluxes; nevertheless, differences may reach up to 4 K (see Fig. 8).

Satellite-derived $T_s$ are higher at the urban flux towers BKLI and BAES and lower at the rural/suburban flux tower BLER. This is addressed to the different fields of view, i.e., the radiation sensor mounted on an urban flux tower “sees” a considerable amount of walls (see Fig. 1), which are more influenced by shadow
C. Sensitivity Analysis

A sensitivity analysis was performed in order to estimate the influence of the input variables on the value of modeled $Q_H$. A perturbation of $T_i$ [or $(T_i - T_a)$ in (2)] by $\pm 2$ K causes a change in $Q_H$ in the range of $\pm 50 \ W\cdot m^{-2}$. A change in friction velocity $u_*$ of 20%, i.e., a variation in the range of 0.05–0.15 m$^2\cdot s^{-1}$, impacts the value of $k\beta^{-1}$ and $r_a$ and affects $Q_H$ by $\pm 25 \ W\cdot m^{-2}$. And finally, an increase/decrease of the roughness parameters $z_0$ and $z_d$ by 20%, corresponding to a variation of the original values in the range of 0.1–0.4 m for $z_0$ and 2–6 m for $z_d$, results in a change in $Q_H$ of $\pm 10 \ W\cdot m^{-2}$. In line with $Q_H$, the term $(e - e_a)$, i.e., the water vapor pressure deficit, is most crucial for the value of $Q_E$, for vegetated surfaces the value of $r_s$ (mainly determined by the specific $r_s_{\text{MIN}}$) has a similar impact. However, compared to the variations in $Q_H$ and considering the generally low values of $Q_E$ in urban environments, the impact of variations of input variables in (3) is generally small for the urban energy balance.

V. DISCUSSION AND OUTLOOK

The analysis of modeled $Q_H$ and $Q_E$ from 22 Landsat scenes for the URBANFLUXES case study city Basel shows reasonable results, but the validation with in situ measurements is generally moderately accurate. Since there is no alternative for the evaluation of EO-derived fluxes, possible reasons for the observed deviations are listed in the following:

1) The uncertainty inherent to EC measurements may range from 10% for $Q_H$ to up to 25% for trace gases [e.g., [19], [20]]. Representativeness of flux tower measurements in urban environments is reduced compared to rural areas due to the heterogeneity of urban neighbourhoods [14]. Large (inherent) variations in EC measurements between averaging intervals additionally increase this uncertainty. Using averages of the adjacent half hours (before and after the satellite overpass) for comparison with modeled fluxes reduce this uncertainty.

2) Known drawbacks of the ARM method: input parameters ($T_a, w_v$) have to be spatially derived from in-situ measurements (flux towers and/or sensor networks) and may differ from “true” values in certain areas during satellite overpass; further large uncertainties exist in the calculation of the aerodynamic resistance including $k\beta^{-1}$.

3) Uncertainties in the calculation of flux tower source areas used for comparison with modeled fluxes [21].

4) Difficulties to measure evapotranspiration in general and in urban areas in part. Spatial extrapolation of measured vapor saturation deficit.

Finally, modeled fluxes may be in a first step improved by examination of uncertainties in $T_i$ related to emissivity, thermal anisotropy and atmospheric correction in urban areas.

As URBANFLUXES will model all terms of the urban energy balance independently to derive the anthropogenic heat flux as a residual, the presented results are combined with EO-derived storage term $\Delta Q_S$ and net radiation $R_n$ towards analyzing the energy balance closure (including $Q_H$) in the framework of this project.

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REFERENCES


Authors’ photographs and biographies not available at the time of publication.