ENERGY FLUX DENSITIES WITH REMOTE SENSING AND IN-SITU DATA IN AN URBAN ENVIRONMENT

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ABSTRACT

The impacts of climate change and also the modification of the urban climate of the cities itself cannot be neglected and affects also human life. With more and more people living in urban areas, urban climatology becomes more and more important. Remote sensing can help to analyze the spatially distributed radiation and heat fluxes in complex environments like urban areas.

During the Basel Urban Boundary Layer Experiment (BUBBLE) in 2002 a wide set of micrometeorological measurements of an international research team took place in the City of Basel in northern Switzerland. The acquired dataset enables us to validate the radiation and energy flux densities which were computed and modelled with remote sensing data from different satellite systems (MODIS, ASTER, NOAA-AVHRR, Landsat ETM+). After validation of the radiation fluxes, the ground heat flux was modelled and validated also with the in-situ measurements. A combined NDVI-Bowen-Ratio regression approach was used to compute the turbulent fluxes in the spatial domain.

The results presented in this paper are very promising and encourage us to pursue the further use of remote sensing data for the assessment of radiation and heat flux densities.

1. INTRODUCTION

During the Basel Urban Boundary Layer Experiment (BUBBLE) in 2002 a wide set of micrometeorological measurements of an international research team took place in the City of Basel in northern Switzerland. During the BUBBLE-IOP (Intensive Observational Period) from mid June to mid July 2002, a total of eight measurement sites were selected in and around the city. All these sites were equipped with a complete set of instruments for measuring the radiation and heat fluxes.

The available satellite data consisted of MODIS Terra, NOAA-AVHRR and Landsat ETM+ scenes from which the two-day period of 7th and 8th of July was selected for the modelling and validation of the energy and radiation fluxes.

The net radiation Q* can be described as:

$$Q^* = S\downarrow - S\uparrow + L\downarrow - L\uparrow \quad (1.1)$$

Where S is the shortwave and L is the longwave radiation respectively, directed towards and away from the Earth's surface. From there, the energy fluxes can be calculated because

$$Q^* = Q_E + Q_H + \Delta Q_S + (Q_F) \quad (1.2)$$

Where Q_E is the latent heat flux, Q_H is the sensible heat flux, ΔQ_S is the ground heat flux, or in the case of impervious surfaces the storage heat flux. In urban areas also Q_F which stands for the anthropogenic heat flux can be present but due to the small amount it can be neglected for this model.

The left part of the equation corresponds to the net radiation, the right side gives the heat fluxes and together these terms keep the balance. The heat fluxes are dependent on the surface material, the structure of the material and density of vegetation. The method of distribution of the available energy in these heat fluxes has a large influence on the climate of an area.

2. METHODS

2.1 Remote sensing data

In a first phase, the thermal infrared datasets from all the satellite platforms were atmospherically corrected and validated with the in-situ measured longwave upward radiation with an overall accuracy around 3% (3).

The short wave radiation was modelled with SWIM (Short Wave Irradiance Model) and a digital elevation model (DEM) of 25m resolution. Together with the shortwave albedo, which was derived from the Landsat ETM+ scene, it was possible to calculate the net radiation.

The results showed an average difference of below 25 Wm^{-2} for Q*. With the two worst sites (Messe and Village-Neuf, see Figure 1) omitted, the results are eve more accurate with an average difference of 20 Wm^{-2}. This is about the accuracy as mentioned by (4), which lies between 10-20 Wm^{-2}.

For further processing of the data and the modelling of the ground heat flux, the Objective Hysteresis Model (OHM) approach first developed by (5) and applied to remote sensing data by (6) was used. Also an NDVI approach of (7) was considered and validated, but the possibility of daily multi-temporal ground heat flux density calculations (day and night-time) made the OHM approach superior. There the overall accuracy yielded a result of a difference of less than 20 Wm^{-2}. For this paper, this processing was applied on four scenes taken on the 8^{th} of July 2002 from Landsat, MODIS and AVHRR 16.

With these components of radiation and heat fluxes all available now only Q_E and Q_H are unknown in the equation 1.2. There, a Bowen-Ratio approach is used. Beneath the Eddy-Covariance approach the Bowen-Ratio approach is one of the few possibilities to calculate the latent and sensible heat flux (8).

The Bowen-Ratio (β) is described as:

$$\beta = Q_H / Q_E \quad (2.1)$$

Typical values for β are between 0.3 and 0.8 for vegetated areas and forest and 1 to 5 for urban environments, depending on the density of the buildings and vegetated areas. Together with the Normalized Difference Vegetation Index (NDVI) and in-situ derived Bowen-Ratios, the Bowen-Ratio for the spatial domain can be calculated from a regression with an R^2 of 0.95. In a second step Q_E and Q_H can be calculated when we assume that the energy flux density balance should be closed.

2.2 In-situ data

The in-situ data was acquired at seven sites in and around the City of Basel of which three were situated in urban areas, one in suburban and three in rural areas. The whereabouts of the sites can be found in Fig. 1.

Sensible heat flux density Q_H and latent heat flux density Q_E were directly derived from eddy correlation measurements using three-dimensional ultrasonic anemometer-thermometers combined with humidity fluctuation measurements (see Table 1). Q_H and Q_E were calculated from block averages of 20 Hz raw data averaged over one hour. All instruments were checked and outputs compared with each other in the wind tunnel (except the instrument at U3). Q_H was calculated from the covariance of acoustic temperature and vertical wind $\overline{\omega' T'_S}$, which was corrected for crosswind either internally by the sensor electronics or during post processing and for special loss (9).

Additionally, Q_H is corrected for humidity effects (10). This humidity correction reduces the magnitude of the raw $\overline{\omega' T'_S}$ by 3% at the urban sites and by 13% at the rural sites, because the rural sites have higher evapotranspiration. Q_E was calculated from the covariance of absolute humidity and vertical wind $\overline{\omega' \rho'_v}$ including a correction for O_2-sensivity (11) and a small vertical wind component (WPL-correction, (12)). Furthermore, a spectral correction was calculated taking into account sensor separation (9).

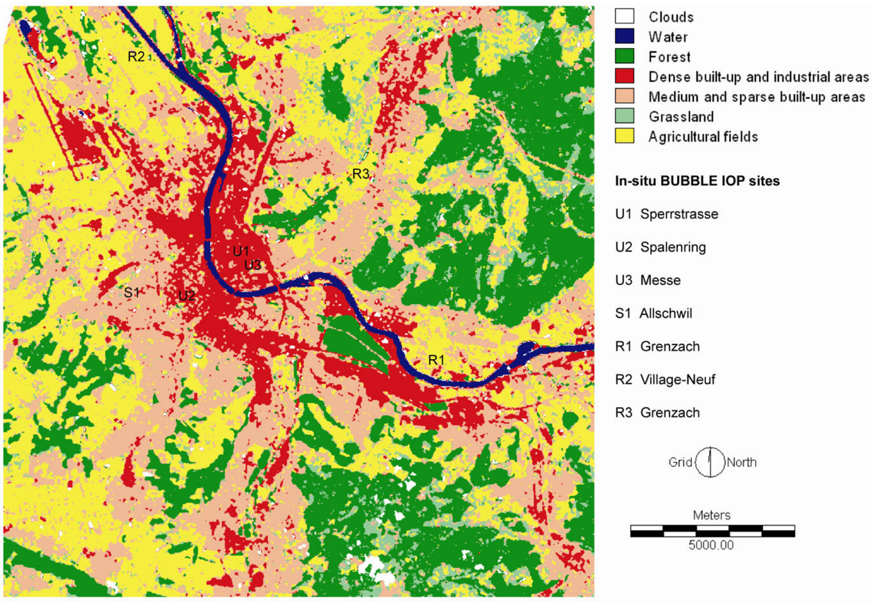
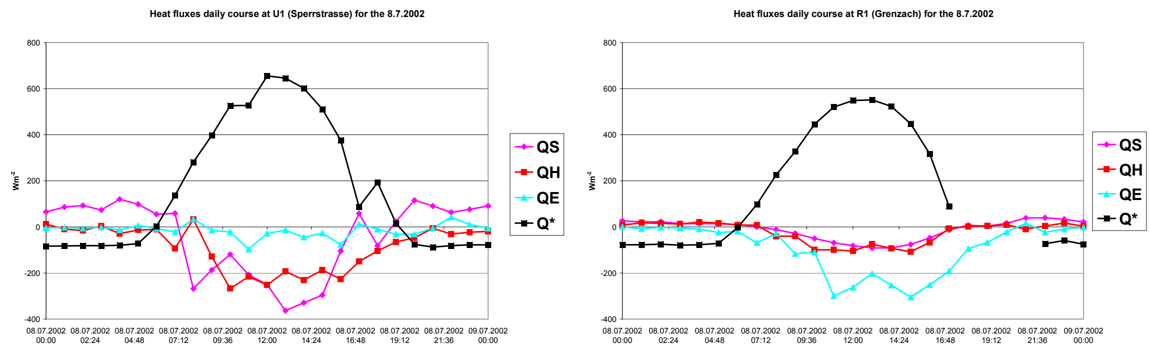


Fig. 1: Map of all surface sites during the BUBBLE-IOP in June-July 2002 on a land-use classification derived from a LANDSAT-ASTER mixed image from the 12.06.2001

3. RESULTS

The averaged components of the heat flux densities for the 8th of July 2002 are show in Fig. 3 for two sites (U1 and R1). The same day was also the focus of the remote sensing modelling of the heat flux densities. The graphs show clearly the differences of the heat flux densities depending on land use at the different sites. All sites have in common the negative fluxes during daytime and the slightly positive ones during night time. Clear differences can be found at Q_H and Q_E between the urban and rural sites, whereas the Allschwil site lies somewhere between the two.



a) b)

Fig. 2: In-situ heat flux densities for the 8th of July 2002 for a) U1 and b) R1

As for the satellite data the results show a mean difference of below 30 Wm^{-2} for Q_H whereas for the Q_E the values are around 50 Wm^{-2}. For rural sites the differences in Q_E are generally higher than for urban sites. An overview of the mean absolute differences (MAD) for each of the stations can be found in the Table 1 below.

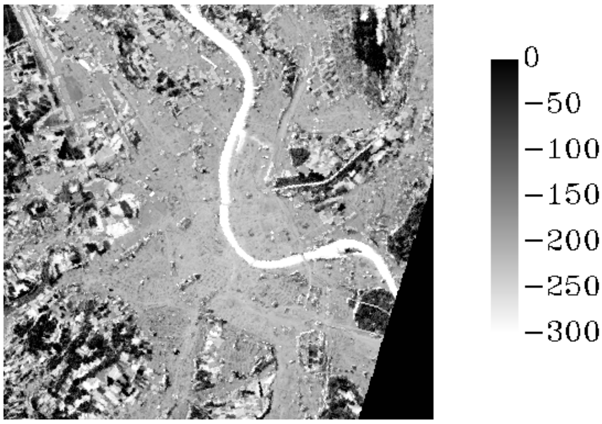
Tab. 1:Mean absolute differences (MAD) for energy flux densities for the in-situ sites in Wm^{-2}

Site	U1	U2	U3	S1	R1	R2	R3
MAD Q_S	10	24	13	12	19	17	37
MAD Q_H	28	14	-	12	17	16	-
MAD Q_E	18	25	-	37	42	78	-
Mean for all fluxes densities	19	21	13	20	26	37	37

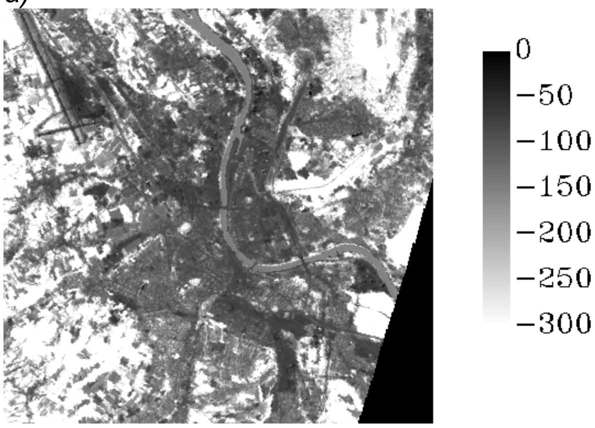
The coefficient of determination (R^2) is 0.77 for the sensible heat flux density and 0.92 for the latent heat flux density.

The following figure (Fig. 3) shows an example for the Landsat overpass. It must be pointed out that for night time modelling of Q_E and Q_H this NDVI-Bowen-Ratio approach is not useful and yields completely wrong results. For the River Rhine the modelled values are not representative in Fig. 2 due to the specific thermal properties of water which were not included in the Bowen-Ratio / NDVI approach.

In Figure 4 a) the urban areas are clearly distinguishable due to their very high sensible heat flux densities (below -200 Wm^{-2}), whereas the rural areas are higher than -100 Wm^{-2}, with forests showing even lower values. As for Figure 4 b) the results change completely and the highest negative values can be found in the rural areas, whereas the urban surface clearly shows very low latent energy fluxes.



a)



b)

Fig. 3: a) Shows the Q_H distribution at the time of the Landsat overpass (10.10 UTC) and b) shows the Q_E distribution. All values are in Wm^{-2}.

4. DISCUSSION AND CONCLUSIONS

According to the model of (13), the differences for the sensible heat flux are sensitive to errors in air and surface temperatures. They showed, for example, that a 10% error in surface temperature can result in an error of over 50% in predicted heat flux. When we assume, that our accuracy according to (3) is on the order of 3% to 4% the errors in sensible heat flux could be expected to range between 20 Wm^{-2} to 40 Wm^{-2} with the approach of (13). Authors (14 & 15) use also a Bowen-ratio approach for the modelling of Q_E and Q_H, others (16, 17 and 18) use models based on the two-source energy balance model proposed by (19). Other models are two source-models like (20) describing the relationship between surface radiant temperatures and energy fluxes.

The common thing on all these publication is the fact that they are mostly focused on homogenous rural areas. On the other hand, evapotranspiration in urban areas with impervious surfaces can be almost neglected. Therefore some of the models mentioned which apply vegetation indices, evapotranspiration or height of vegetation are not suited for urban environment. Because of the inhomogeneity of the urban surface and the very low evapotranspiration in urban areas therefore another approach was used in this paper. As an example for a local scale non remote sensing model the results from (21) for the UBL/CLU-ESCOMPTE with the TEB (Town Energy Balance) Model show also an RMSD of above 40 Wm^{-2} for Q_E and above 60 Wm-2 for Q_H and Q_S, whereas the biases are below 20 Wm^{-2}.

The advantage of Eddy-covariance measurement and modelling of the heat flux densities with sonic anemometers is described by (22), which were used here as mentioned in chapter 2. They give an uncertainty of 10% for their measurements over a grassland site.

As for the remote sensing imagery, there is a clear relationship between Bowen-ratio and NDVI. The used NDVI / Bowen-Ratio approach shows very promising and good results for daytime heat flux densities, whereas for night time imagery it is not useful due to its dependency on the NDVI and daily Bowen-Ratio values which differ strongly from the night time ones. The mean difference for the modelled Q_H is 25 Wm^{-2} and for Q_E it is 46 Wm^{-2} with an RMSD of 19 Wm^{-2} and 39 Wm^{-2} respectively. For Q_E the differences are higher at the rural sites whereas for Q_H urban sites show slightly higher differences.

The achieved accuracy of this approach is high when compared to results from (17) (with an RMSD of 26 Wm^{-2} for Q_H and 38 Wm^{-2} for Q_E) or (18) which also show differences in of about the same order over homogeneous surfaces whereas we deal here with different land use and surface inhomogeneity. (20) found an RMSD of above 50 Wm^{-2} with TSTIM (Two Source Time Integrated Model) and also a mean difference of 45 Wm^{-2} for Q_H and Q_E.

Although the approach used hereby is quite simple and bases on the Bowen-Ratio, it is still requires a very exact in-situ measurement network for measuring and calculating the necessary energy fluxes either with an eddy-covariance approach or combined with a heat flux plate. On the other hand, the crucial validation of the source data with the in situ data, starting with the longwave upward radiation (see (3)) followed by the net radiation and the computation and modelling of the ground heat fluxes (see (6)) enables us to model the energy balance components in a spatial distribution based on validated basic datasets.

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