MEASUREMENT AND MODELLING OF THE GROUND HEAT FLUX IN THE CITY OF BASEL DURING BUBBLE BY DIFFERENT METHODS

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ABSTRACT:

During the **B**asel **U**r**b**an **B**oundary **L**ayer **E**xperiment (BUBBLE) in 2002, micrometeorological in-situ data (radiation fluxes, turbulent fluxes, wind speed, air temperature etc.) has been acquired at different sites by a variety of sensors. Although there were many sites for measurements, the spatial aspects of the energy and heat flux balance can only be taken into account with remote sensing methods.
Therefore multiple satellite images from different platforms (NOAA-AVHRR, MODIS and LANDSAT ETM+) covering the BUBBLE-timeslot have been acquired, processed and analysed. From atmospheric corrected thermal data, broadband albedo and SWIM (**S**hort **W**ave **I**rradiation **M**odel) the net radiation has been computed. Together with a high resolution digital elevation model (DEM) a 1 x 1 meter resolution digital city surface model of the surroundings of the urban sites has been also acquired. From these datasets, the ground heat flux of the City and its surroundings has been modelled with different methods and compared to in- situ measurements. The agreement of the modelled data to the in-situ one is promising with an average difference around 20 W/m^2 for urban and rural sites.

KURZFASSUNG:

Während des **B**asel **U**r**b**an **B**oundary **L**ayer **E**xperiment (BUBBLE) in 2002 wurden verschiedene in-situ mikrometorologische Messungen an sechs verschiedenen Orten durchgeführt (Energie- und Strahlungsbilanz, Windgeschwindigkeit, Temperatur usw.). Diese Messungen liefern jedoch nur punktuelle Daten, womit dem räumlichen Aspekt der Energie- und Strahlungsbilanz nicht genüge getan ist.
Aufnahmen von verschiedene Satellitensysteme (NOAA-AVHRR, MODIS and LANDSAT ETM+) während des BUBBLE Projektes wurden prozessiert und analysiert. Die Strahlungsbilanz wurde aus Thermaldaten, Albedo und SWIM (**S**hort **W**ave **I**rradiation **M**odel) berechnet. Neben mit einem digitalen Geländemodell (DEM) wurde auch ein hochaufgelöstes digitales Stadtmodel mit einer Auflösung von 1m x 1m für die Modellierung des Sky View Factors verwendet. Aus diesen räumlichen Daten wurde der Bodenwärmestrom räumlich modelliert und berechnet und mit den in-situ Messungen verglichen. Die Überreinstimmung zwischen den modellierten und in-situ Daten ist mit einer durchschnittlichen Differenz von 20 W/m^2 für urbane und rurale Stationen sehr gut und liegt im Rahmen von ähnlichen Studien.

1. INTRODUCTION

During the Basel Urban Boundary Layer Experiment (BUBBLE) in 2002, micrometeorological in-situ data has been acquired at different sites by a variety of sensors from mid June to mid July. Although there were many sites for measurements, the spatial aspects of the energy and heat flux balance can only be taken into account with remote sensing methods. Therefore multiple satellite images from different platforms (NOAA-AVHRR, MODIS and LANDSAT ETM+) have been acquired, processed and analysed. This paper focuses on the calculation and modelling of the ground heat flux in inhomogeneous urban and rural areas from remotely sensed data combined with in situ ground measurements, including accuracy assessment of the models. In a first step, the net radiation was modelled for each satellite overpass and compared with the in situ measurements and then three different approaches were used to calculate the ground heat flux and to compare it with the in situ measured data.

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2. STUDY AREA AND DATA

The City of Basel lies in the Upper Rhine Valley at the French, German and Swiss border in Switzerland. The City holds about 200 000 inhabitants, with the surrounding area its about 350 000. In 2002, a joint international project “Basel Urban Boundary Layer Experiment” (BUBBLE) has took place where all kind of micrometeorological measurements were conducted. There have been 7 micrometeorological sites in the City and its surroundings but these data show only punctual measurements. The whereabouts of the sites Sperrstrasse (Ue1), Spalenring (Ue2), Messe (Ue3) Allschwil (Se1), Lange Erlen (Re3), Village-Neuf (Re2), Grenzach (Re1) can be seen in Fig. 1. All the “U” sites are urban, the “S” stands for suburban and “R” for rural sites. The urban sites Sperrstrasse and Spalenring were in typical urban street canyons and Allschwil was situated in a vegetated suburban backyard. The rural sites Grenzach and Lange Erlen were over grassland whereas the site Village-Neuf was over agricultural fields. The Messe site was a special case and situated on the roof of a parking lot.
In combination with remote sensing data from Landsat ETM+, MODIS, NOAA-AVHRR and ASTER it is targeted to bring

these data of radiation and energy fluxes into the spatial domain. In addition to these data, also a digital elevation model (DEM) of 25m resolution and a digital city model with 1m resolution is available. A land use classification has been calculated from a 2001 ASTER scene.

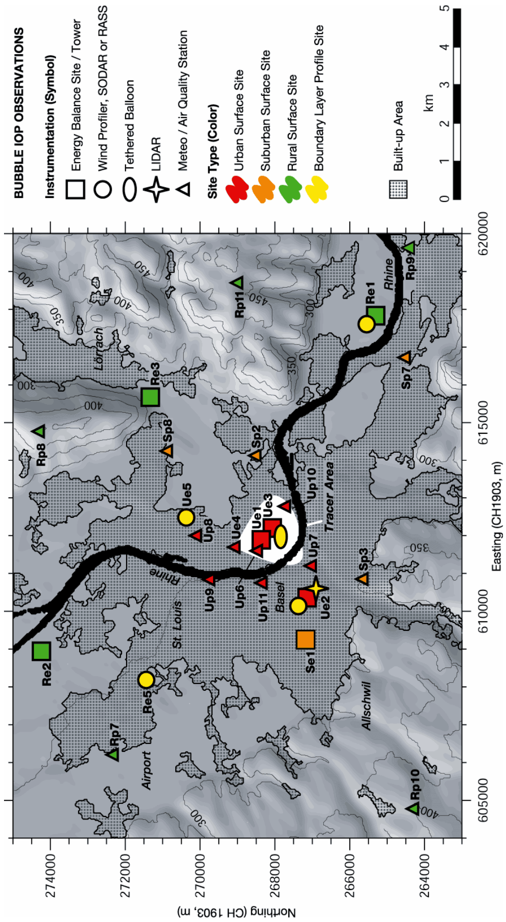


Figure 1: Map of the measurement sites during BUBBLE-IOP

3. DATA PREPROCESSING

After georeferencing of all the data, as a first step, the net radiation has to been calculated.

$$Q^* = Q_{SU} - Q_{SD} + Q_{LU} - Q_{LD} = Q_s + Q_E + Q_H \qquad (1)$$

all in [W/m^2] where

Q^*	is the net radiation
Q_{SU}	is the shortwave upward radiation
Q_{SD}	is the shortwave downward solar radiation
Q_{LU}	is the longwave upward terrestrial radiation
Q_{LD}	is the longwave downward radiation
Q_S	is the ground or storage heat flux
Q_E	is the latent heat flux
Q_H	is the convective sensible heat flux

The solar irradiation was calculated with the DEM for different dates and times with SWIM (Shortwave Irradiation Model). The longwave upward radiation was calculated from the different satellite sensors as was also the albedo which leads to the shortwave upward radiation. The longwave downward radiation was assumed to be the average of all the in situ measured values at the given time for the whole scene. From there the ground heat flux Q_S can be calculated as part of the net radiation.
For the calculation of the ground heat flux, three approaches were used and compared with the in situ measurements which are available as one hour averaged data for the different sites.

The three following approaches were used:

a) The NDVI approach

The first approach bases on the fact, that the surface temperature is dependent form the Normalized Different Vegetation Index (NDVI) (Munier & Burger 2001, Rigo 2001) Therefore the surface temperature rises when the NDVI shrinks which means less energy is going into the latent heat flux. More detailed descriptions can be found in Kustas & Daughtry (1990) and Baastiansen et al. (1997). Because the equations by Baastiansen are based on rural field measurements, they are not very suitable for the urban environment. Parlow (1999) proposed the following equations for urban and rural environments:

$$Q_{S\,(urban)} = -\,(0.3673 - 0.3914 \bullet NDVI) \bullet Q^* \qquad (2)$$

$$Q_S(rural) = (0.3673\text{-}0.3914 \bullet NDVI) \bullet Q^*_{SW} \bullet (-0.8826 \bullet \ln(Q^*_{SW}) + 5.0967) \qquad (3)$$

Where Q* is the net radiation, NDVI the NDVI values and Q^*_{SW} the shortwave net radiation. The NDVI can be calculated from the Landsat image and the net radiation (Q^*) has been modelled and calculated as described above. eq. 2 was used for the urban sites and eq. 3 for the rural ones.

b) The objective hysteresis model (OHM) approach

There the Objective Hysteresis Model based on Oke & Cleugh (1987) and Grimmond & Oke (1999) has been applied to remote sensing data. Oke & Cleugh (1987) used a hysteresis-type equation to characterize the storage flux as

$$\Delta Q_S = a_1 Q^* + a_2 \frac{\partial Q^*}{\partial t} + a_3 \qquad (4)$$

where t is time [h].

The parameter a_1 indicates the overall strength of the dependence of the storage heat flux on net radiation. The parameter a_2 describes the degree and the direction of the phase relations between ΔQ_S and Q^*. The parameter a_3 is an intercept term that indicates the relative timing when ΔQ_S and Q^* turn negative.

For this reason the thirteen land use classes from the ASTER derived land us classification have been summarized to the following six classes and binary masks have been made:
a) water, b) dense built-up settlements and industrial areas, c) medium and light built-up settlements, d) forest, e) grassland and f) agricultural fields.

The parameters a_1, a_2 and a_3 were derived from in situ measurements at the seven sites and from Grimmond & Oke (1999) and were applied with the different binary land-use class masks.

Parameters/Land use class	a_1	a_2	a_3
Water (Grimmond & Oke 1999)	-0.5	-0.21	29.1
Forest (Grimmond & Oke 1999)	-0.11	-0.11	12.3
Industrial (Ue3)	-0.46	-0.16	49
Medium (ø Se1 + Ue1 + Ue2)	-0.42	-0.27	36
Agricultural (Re2)	-0.21	-0.34	25
Grassland (ø Re1 + Re3)	-0.16	-0.05	16

Table 1: The OHM parameters for the different land use classes

c) The complete aspect ratio approach (CAR)

This approach is based on the calculation of the complete aspect ratio. This can be done with a high resolution (1m) city elevation model. As a first step the sky-view-factor has been calculated from the model (see Fig. 2)

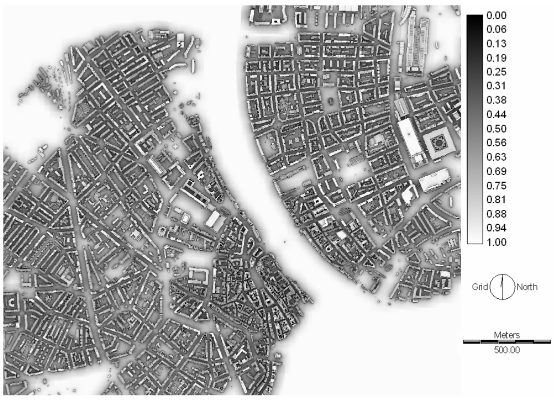


Figure 2: Sky-View-Factor of the City of Basel

As a second step, the complete aspect ratio λ_C was calculated after a downsampling of the data to 30m resolution. The complete aspect ratio describes the enlargement of the surface due to the 3-D structure of the city, which almost doubles the surface where storage can take place. There is a relationship between λ_C and $\Delta Q_S/Q^*$ which can be described as an hysteresis and which suggest the following equation:

$$\Delta Q_S/Q^*(\lambda_C)=\frac{(\Delta Q_S/Q^*_{rural})-(\Delta Q_S/Q^*_{\max})}{\lambda_C+\lambda_C f-f}+\Delta Q_S/Q^*_{\max} \quad (5)$$

Where $\Delta Q_S/Q^*_{rural}$ is the ratio measured or modelled over rural surfaces, λ_C the complete aspect ratio and $\Delta Q_S/Q^*_{max}$ the theoretical value asymptotically reached with increasing λ_C. It is set to a constant value of -0.45. f is a factor to describe the curvature that is highly dependent on daytime due to the diurnal hysteresis. f is set to values between 10 (morning) and 0 (evening) to fit best the observations.

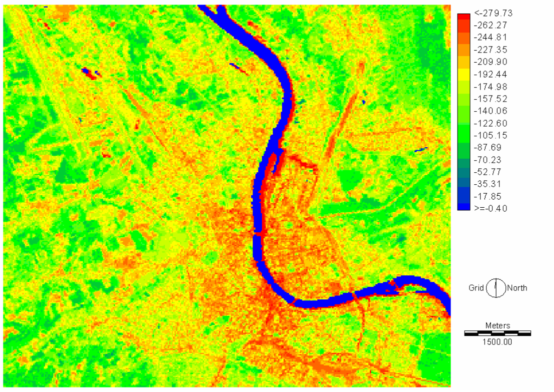
4. RESULTS

The in situ-measurements during the BUBBLE-IOP yielded ground heat flux measurements for all the seven sites mentioned above. The data was collected as hourly average. At some sites the ground heat flux has been measured directly (Allschwil, Grenzach, Village-Neuf), for the other sites it has been calculated from sonic-radiometer measurements. For the 8th of July 2002, many satellite overpasses have been available (MODIS at 11.07 UTC and 22.10 UTC, Landsat at 10.10 UTC, AVHRR-14 at 5.07 UTC and AVHRR-16 at 2.30 UTC). For the daytime images (from 4 UTC to 21 UTC when the short wave part of eq. 1 is also needed) the net radiation has been modelled with the respective satellite data together with SWIM (Short Wave Irradiation Model) whereas for the night time scenes only the longwave radiation was taken in account for the calculation of the net radiation.
Due to limited available ground heat flux measurements data, the hourly values for the respective times (3, 5, 10, 11 and 22 o'clock UTC) for all sunny days during IOP have been averaged for the comparison with the results from the three different approaches. For the complete aspect ratio only the urban sites could be used for comparison. The different satellite overpasses and their modelled ground heat fluxes were compared to their corresponding hourly in situ values.
In advance, the accuracy of the modelled net radiation values have been compared to the in situ measurements and there the overall accuracy for the 8th of July scenes of AVHRR 14,16 MODIS and LANDSAT ETM+ yielded the following average differences: 2.4%, 4.3%, 7% and 3% respectively (without the Messe site) One has to keep in mind, that AVHRR and MODIS have only a spatial resolution of 1.1 km and 0.93 km respectively whereas Landsat has a 30 m spatial resolution.

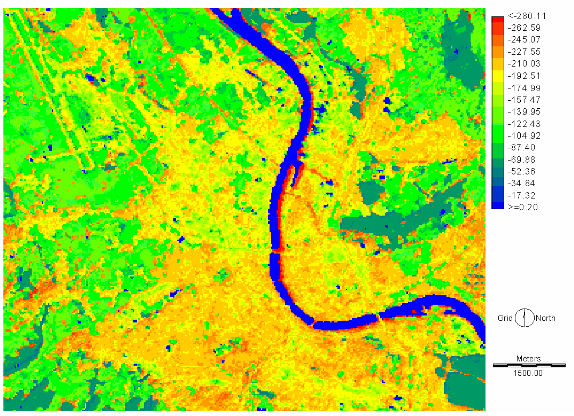
When we compare the modelled ground heat flux values with the in-situ measured ones, it shows the following differences:

Sites	Ue1	Ue2	Ue3	Se1	Re2	Re3
a) with Landsat	3	26	1	18	2	69
a) with MODIS	1	25	3	9	3	74
b) with Landsat	6	12	7	12	3	38
b) with MODIS	26	19	75	10	16	49
c) with Landsat	4	19	(103)			
c) with MODIS	1	32	(96)			
Overall Difference	7	22	47	12	6	58

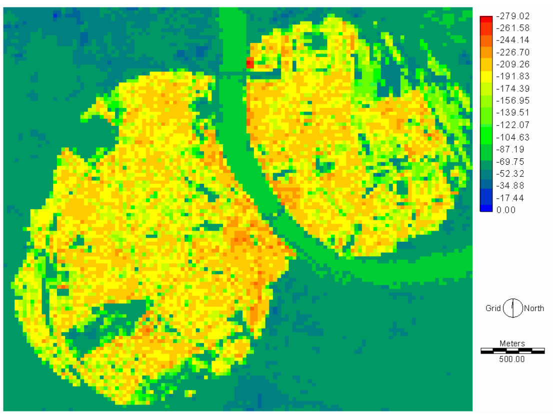
Table 2: Absolute differences between in situ and the modelled ground heat flux in W/m^2 at six sites.



a)



b)



c)

Figure 3: Ground heat flux in W/m^2 in the city of Basel. a) modelled with the NDVI approach, b) modelled with the OHM approach applied on AVHRR 14 and Landsat ETM+ data and c) modelled with the complete aspect ratio approach.

5. DISCUSSION AND CONCLUSIONS

As we can see in fig. 3, the results show the same patterns and about the same values for the city and its surroundings (except c) where the surroundings cannot be calculated).

As the results in chapter 4 shows, the differences are in the average around 10 W/m^2 (except the Lange Erlen and the Messe site), without much difference between the methods. This is an very good correlation, because the measurement of the ground heat flux is still a difficult task and even the measurements have an error of more than 10%, depending on the method which is used (heat flux plate or calculation with eddy covariance from Sonics measurements).

But when the differences at the net radiation calculations are looked at in chapter 4, the difference already are between 5 W/m^2 and 44 W/m^2. Night time overpasses are generally more accurate than daytime ones and the higher the resolution the better the agreements get. The daytime AVHRR overpasses (4 a.m. UTC to 9 p.m. UTC) are all about 20 W/m^2 to 25 W/m^2 mean difference, whereas the night time overpasses are about only 10W/m^2.

With these differences within the modelled net radiations, the differences with the ground heat flux measurements yields good results, especially if the instrumentation error on net radiation itself is about 10% for daily totals (Kipp & Zonen CNR 1 net radiometer manual)

For the NDVI approach, the spatial resolution of the thermal data doesn't matter as the results in table 2 show. The differences between the modelled Landsat and MODIS scene ground heat fluxes are minimal but the Lange Erlen site shows far too high differences when compared to the other sites, even the Spalenring site which has an average difference of 25 W/m^2.

Most problems with the ground heat flux at the Messe site arise with the OHM approach to MODIS daytime. Because the site is situated on a parking lot, the explication for the big differences with the MODIS OHM approach can be found in the far coarser spatial resolution of 1km, where smaller local extreme values cannot been detected that accurate.

For the Lange Erlen site, it is remarkable that, no matter which approach is used, the differences are above an average of 40 W/m^2. The problem appears only when daytime approaches are used, when the OHM approach with the MODIS night time image is used, the differences are much smaller and approach the average values of the other sites. The contrary happens when MODIS and any other daytime OHM approach is used on the Messe site (see tab. 2) and the differences rise above even 70 W/m^2 for the site. Higher differences result also at the other sites when they are calculated for the MODIS daytime overpass. It seems that due to the lower spatial resolution, the local differences submerge and therefore the differences grow. Because the spatial differences of local ground heat flux peaks are smaller during night time than daytime, this problem doesn't arise when night time MODIS date is used for the ground heat flux modelling.

The best results can be found at the Sperrstrasse, Allschwil and Village-Neuf sites, where even with the MODIS daytime scenes the differences stay around 20 W/m^2.

The CAR approach results are a little bit limited, because of the availability of the data, which covers only the built-up areas. The results for the urban sites Sperrstrasse and Spalenring are about the values which we got from the other models, but the Messe site shows the highest differences of an average 100 W/m^2.

The explanation for these high differences at the Messe site is the following. The in situ measurement equipment at the Messe site was located on the roof of a parking lot. When the calculation of the complete aspect ratio from the sky view factor was applied, the resolution was diminished to 30 m instead of the original 1 m. Therefore the roof shows an aspect ratio about 1.01, which qualifies it for an open space, where the aspect ratio is exactly 1. Because the aspect ratio for vegetated areas is taken as the one for open space, therefore the result shows an ground heat flux, which is typical for vegetated areas like the Lange Erlen or Grenzach sites (the difference would be here about 10 W/m^2 too when the Messe result is compared with the measured values at these sites). This explains the big difference and also shows that on open and not vegetated spaces or areas the CAR-model is useless, whereas in high density areas, where we have a high complete aspect ratio, the results are good.

As this paper shows, the modelled values (with help of in situ derived data) correspond very well with the measured ones, but it enables us to calculate the ground heat flux on a spatial scale, not only punctual. It's not easy to measure ground heat flux in urban areas and a combination of these three approaches could help to model it more exactly in the spatial domain in future.

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