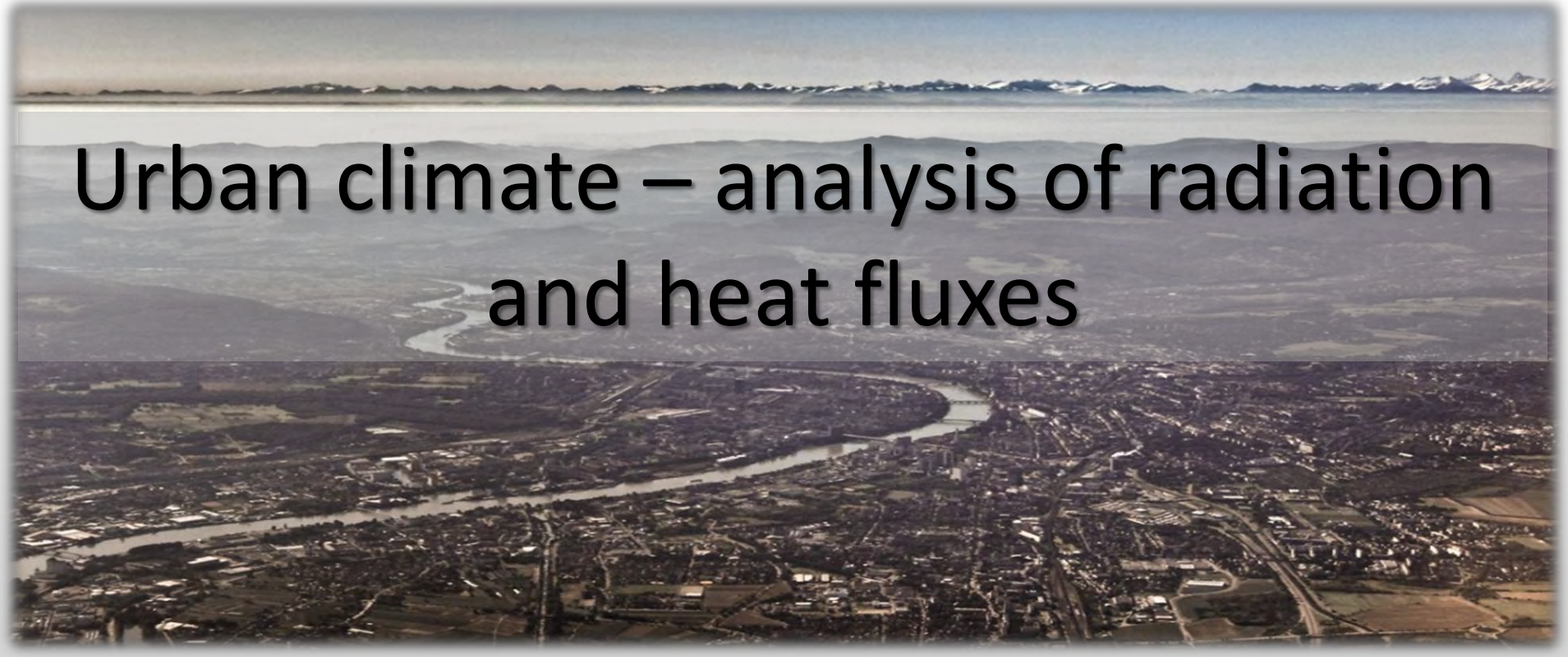

Urban climate – analysis of radiation and heat fluxes

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Topics of today

- The urban heat island (UHI) effect
- Methodologies to measure urban climate
- Urban heat island effect (UHI) versus surface urban heat island (SUHI)
- Urban temperatures versus rural temperatures
- Urban radiation and heat budget
- Spatially distributed satellite data analysis
- Vertical analysis of UHI

Urban heat island UHI

- An urban heat island (UHI) is a city or metropolitan area which has significantly warmer air temperatures than its surrounding rural areas due to human activities.
- The phenomenon was first investigated and described by Luke Howard in the 1810s.
- The temperature difference usually is much larger at night than during the day, and is most apparent when winds are weak.
- The main cause of the urban heat island effect is from the modification of land surfaces (LULC-changes) and their physical properties.
- Waste heat generated by energy usage (AC, traffic) is a secondary contributor.
- It has strong implications on: Human bio-climate and heat stress, vulnerability to increased mortality rate (2003)

The Pioneer of Urban Climatology:
Luke Howard (1772 – 1864)

Luke Howard (1833)
"The Climate of London"
(IAUC-Reprint (2006)).

He also invented the Latin names of our clouds !!

- Discoverer of urban heat island (UHI) of London
- He already wrote:
  ... **Night is 3.7° warmer and day 0.34° cooler in the city than in the country ...**

Mean Temperature of each Month, on an average of observations continued from 1807 to 1816.

Mo.	In the Country.	In London.	London warmer.
1. Jan.	34·16°	36·20°	2·04
2. Feb.	39·78	41·47	1·69
3. Mar.	41·51	42·77	1·26
4. April	46·89	47·69	0·80
5. May	55·79	56·28	0·49
6. June	58·66	59·91	1·25
7. July	62·40	63·41	1·01
8. Aug.	61·35	62·61	1·26
9. Sept.	56·22	58·45	2·13
10. Oct.	50·24	52·23	1·99
11. Nov.	40.93	43·08	2·15
12. Dec.	37·66	39·40	1.74

Urban Heat Island (UHI) – "it's so simple" ??!??

General perception is that UHI is apparently:

- Easy to measure – thermometry isn't expensive or difficult to operate
- Easy to explain – the 1st study 200 years ago essentially got it right (materials store heat well; weaker ventilation; radiation traps; air pollution changes radiation exchange; waste heat ….)
- Easy to find - every settlement exhibits it
- Effect is relatively large - usually whole degrees
- Great utility – energy and water conservation, human comfort, mortality, air pollution chemistry, plant/animal life, other weather (fog, snowfall, cloud, icing, humidity, local circulations, convective weather)
- Seems easy to illustrate – e.g with satellite T-IR data ??

So what's the problem with UHI ?

Perhaps due to this apparent simplicity many people (even mature scientists and large agencies) seem to rush into UHI studies:

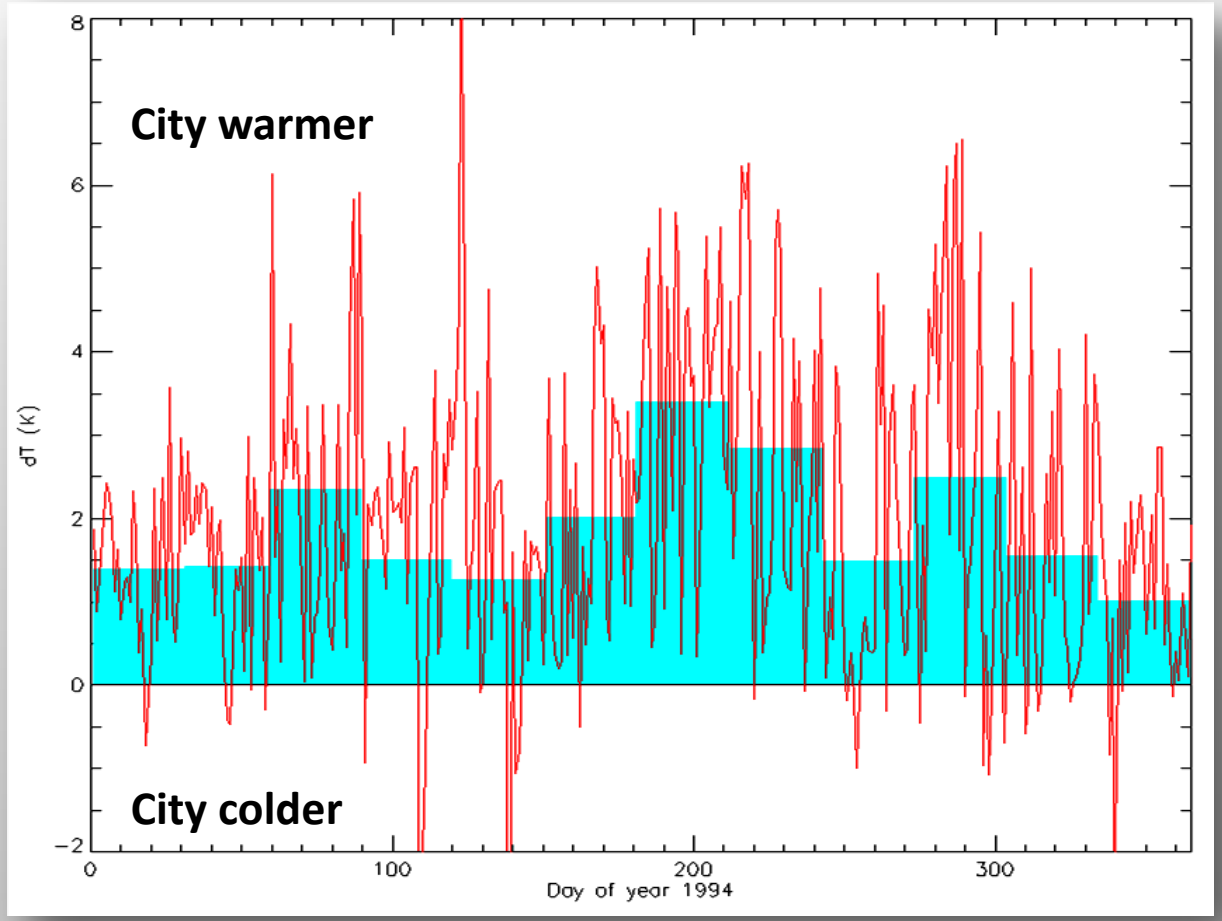
- without fully understanding the nature of the phenomenon (its time and space scales and physical processes)

These oversights have led to:

- a huge, but unstructured and commonly flawed literature
- a database lacking in scientific comparability
- models that omit the correct processes
- models tested against the wrong data
- agencies using the wrong data or models, to design measures to counter negative aspects of the UHI
- satellite data analysis often do not consider the relevant processes.

Monthly and daily mean temperature differences

Temp (Basel Spalenring - urban) minus Temp (Fischingen - rural) for 1994



Monthly mean

Daily mean

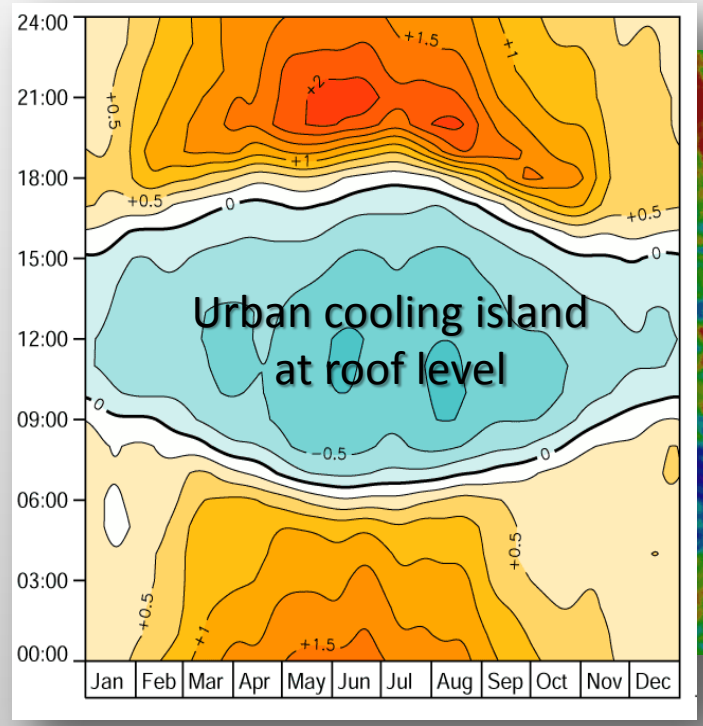
1. The statistical analysis of the UHI effect depends very much on temporal integration steps (annual, monthly, daily, hourly or even 10-min integrations).
2. An «urban» station is not necessarily an «urban» station !! Many are airport stations or at parks,

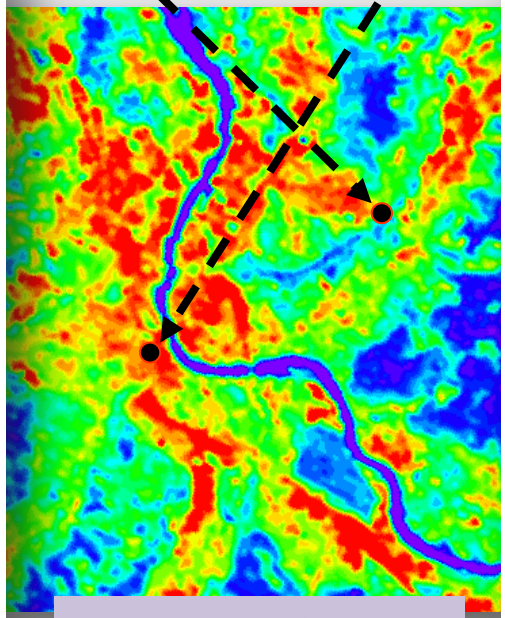
botanical gardens etc. and mostly on a lawn surface, but this surface type is NOT urban. Urban climate stations are only a few. Long term measurements very rare.

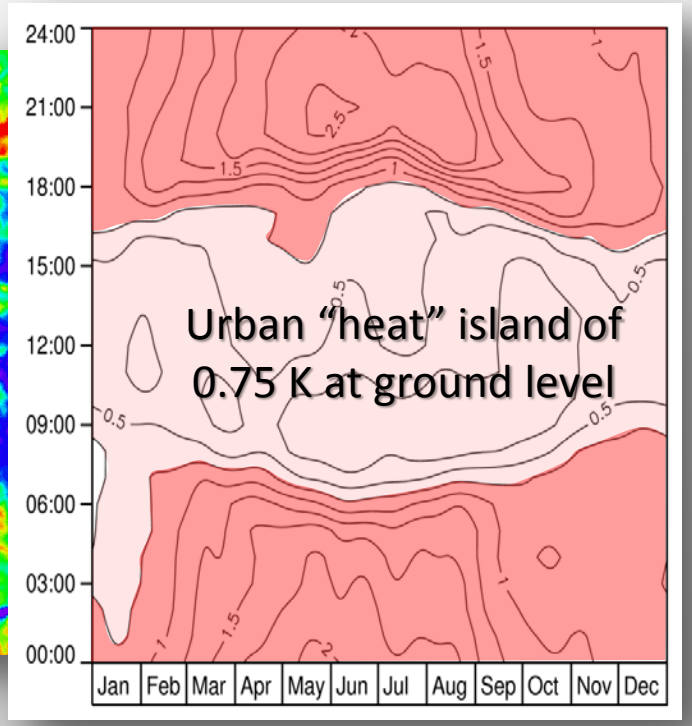
Thermo-isopleths of air temperature differences (urban – rural)

Basel–Spalenring (**32 m**) – Lange Erlen (2m)
(1994 – 2002)

Basel–Spalenring (**3 m**) – Lange Erlen (2m)
(1994 – 2003)



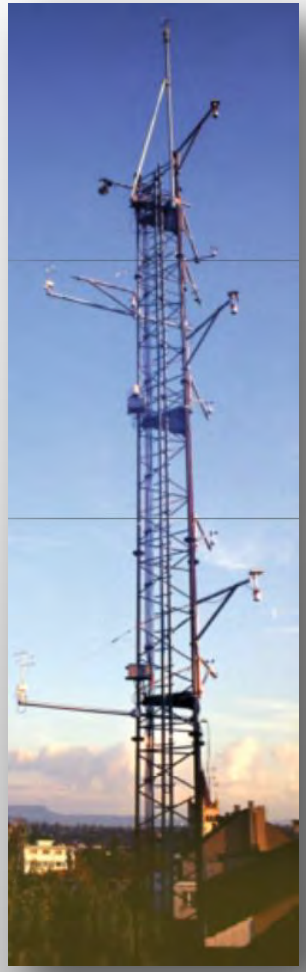




At roof level we have the highest surface temperatures but an urban cooling island at day. At ground level we have colder surface temperatures and a slight urban heat island at day. The urban heat island is primarily a night time phenomenon.

(Parlow, Vogt & Feigenwinter 2014, Erde, Vol. 145, No. 1-2, 96 – 110)

The urban climate flux towers in Basel



Spalenring
1990 – 2002

Klingelbergstrasse
Street side

Sperrstrasse
BUBBLE-Site 2002

Klingelbergstrasse
Roof level since 2002

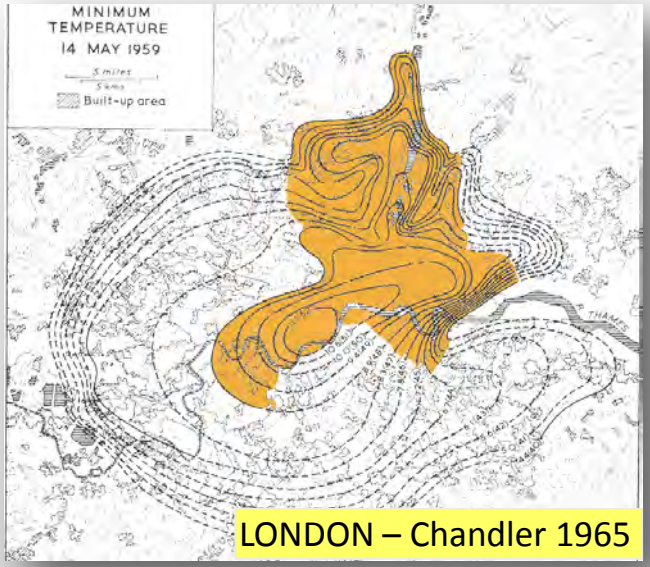
BUBBLE: Basel Urban Boundary Layer Experiment 2002 (Rotach et al. 2005)

The rural station Lange Erlen (since 1990)

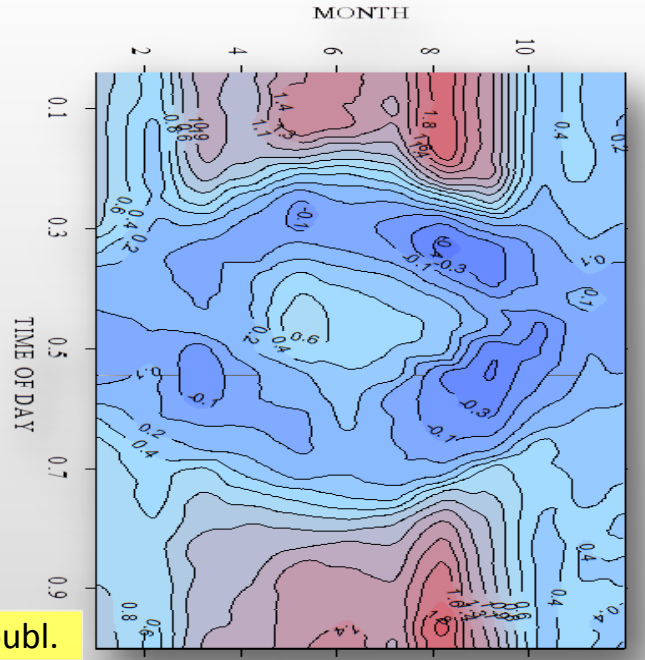
Instrumentation:

- Vertical profiles of air temperature & humidity (ventilated psychro-meters), wind speed, turbulence (EC) and CO_2-concentration & fluxes
- All radiation fluxes and net radiation at 2 m
- Wind direction at 10 m
- Precipitation
- Soil heat flux at various depths
- Soil temperatures at various depths
- Soil humidity by TDR sensor
- Partly additional instrumentation during field experiments

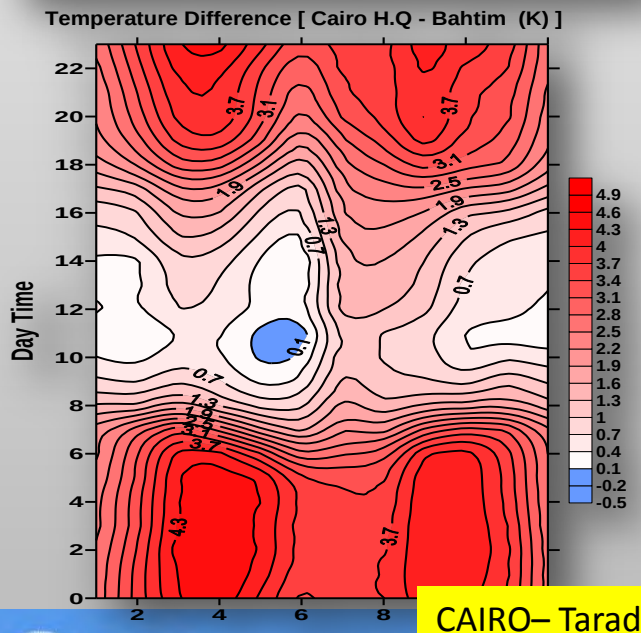
Urban heat island studies



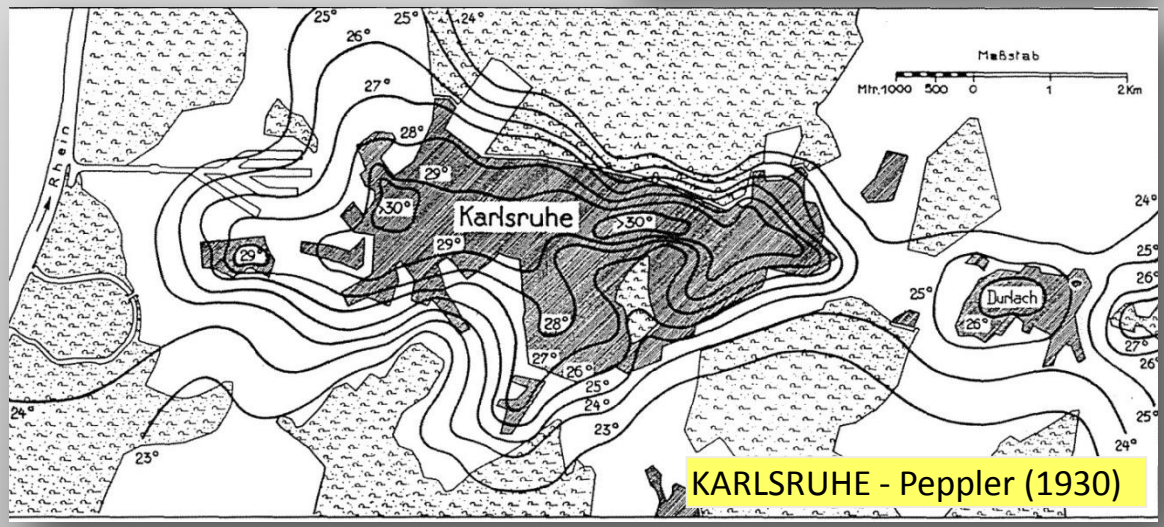
LONDON – Chandler 1965



ŁÓDŹ – Klysik & Fortuniak, unpubl.



CAIRO– Tarad 2010

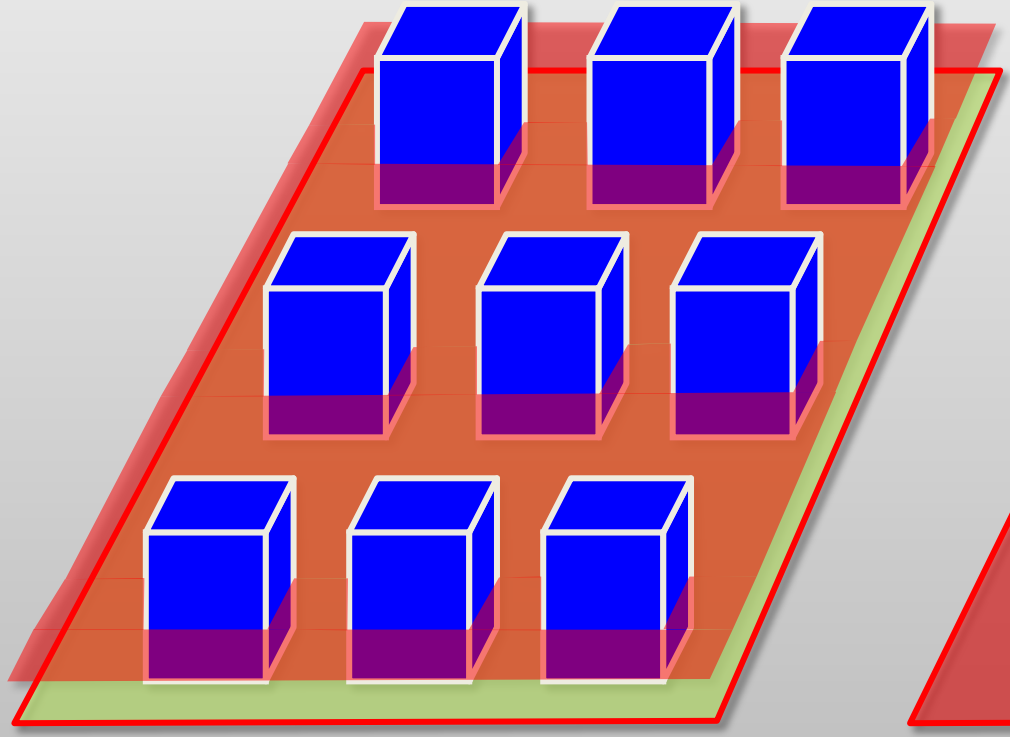


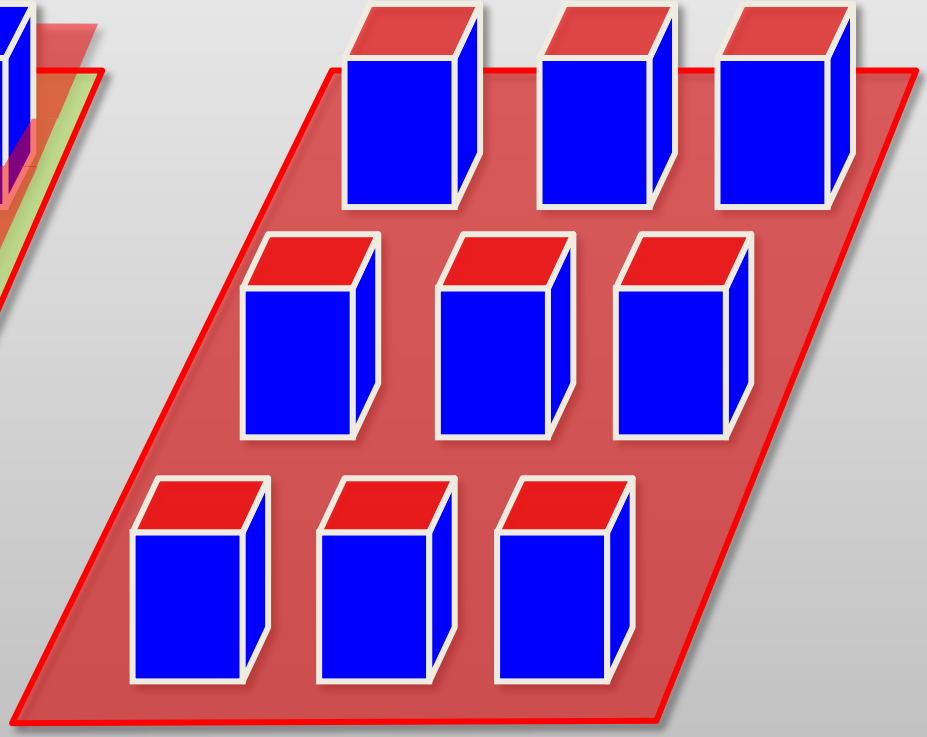
KARLSRUHE - Peppler (1930)

Observation strategies in urban climatology

The classical climatological view (2 m above ground): Urban heat island (UHI)

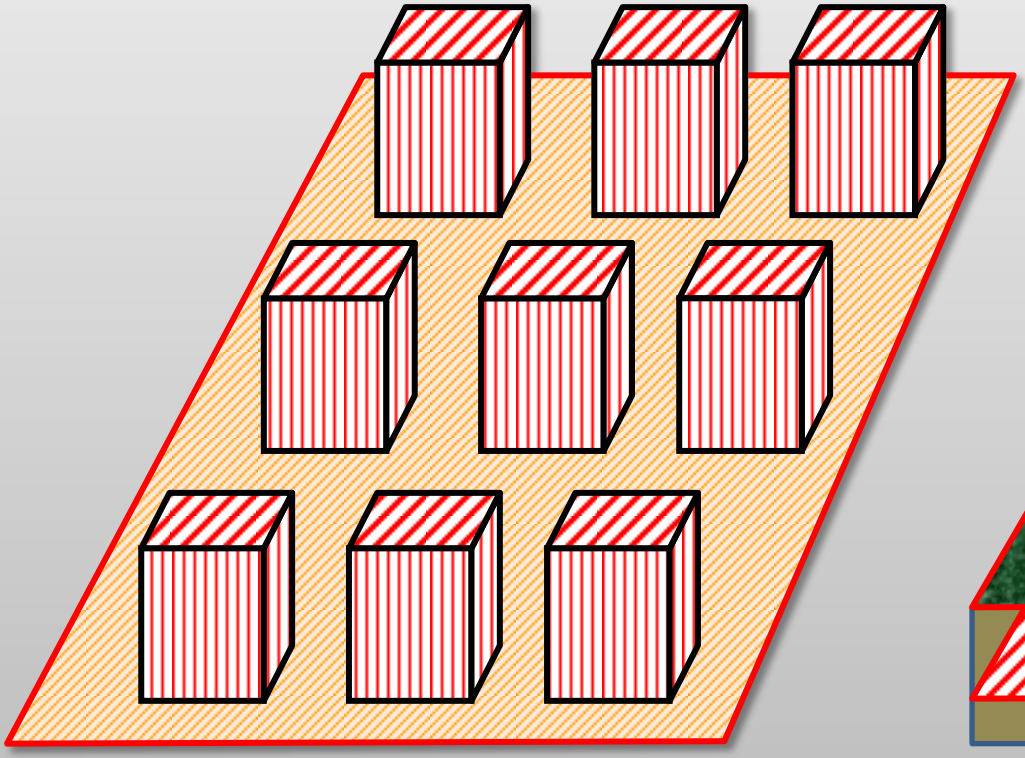
The remote sensing view (bird-eyes-view): Surface urban heat island (SUHI)



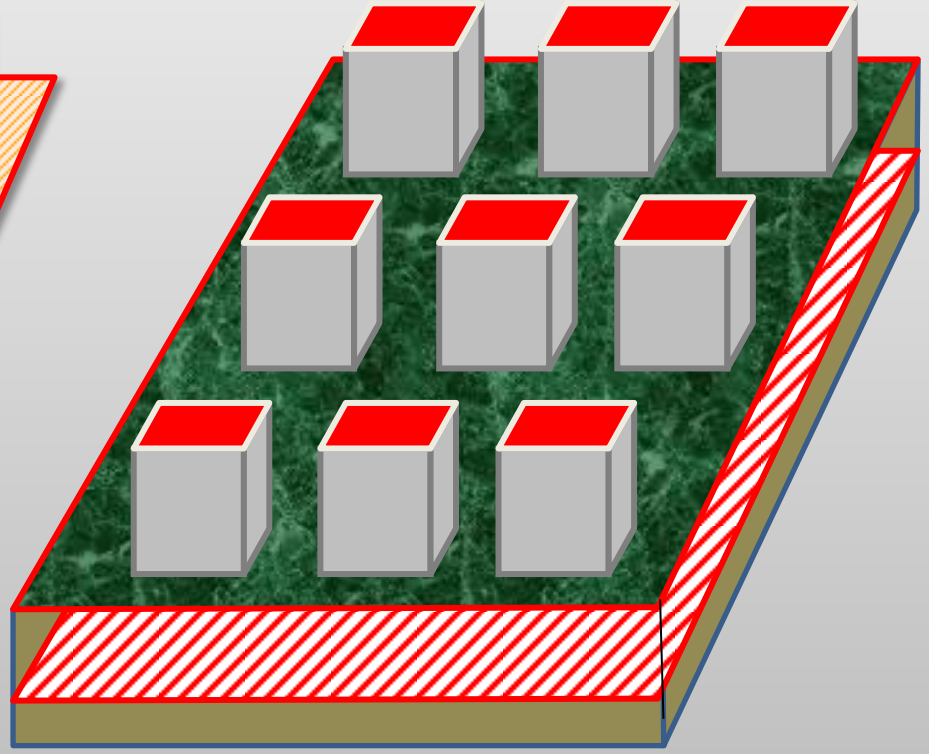


Observation strategies in urban climatology

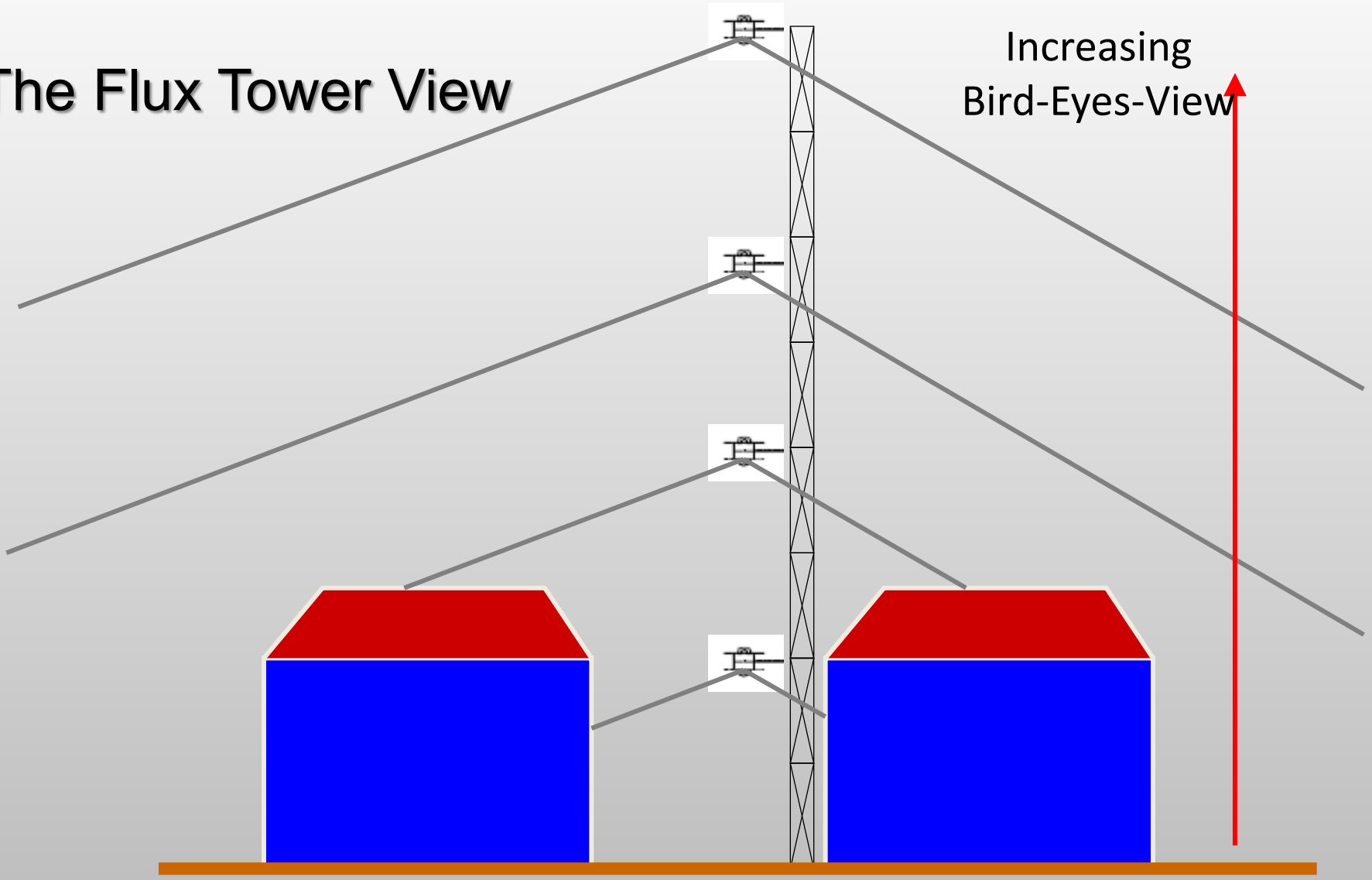
The full 3D-view



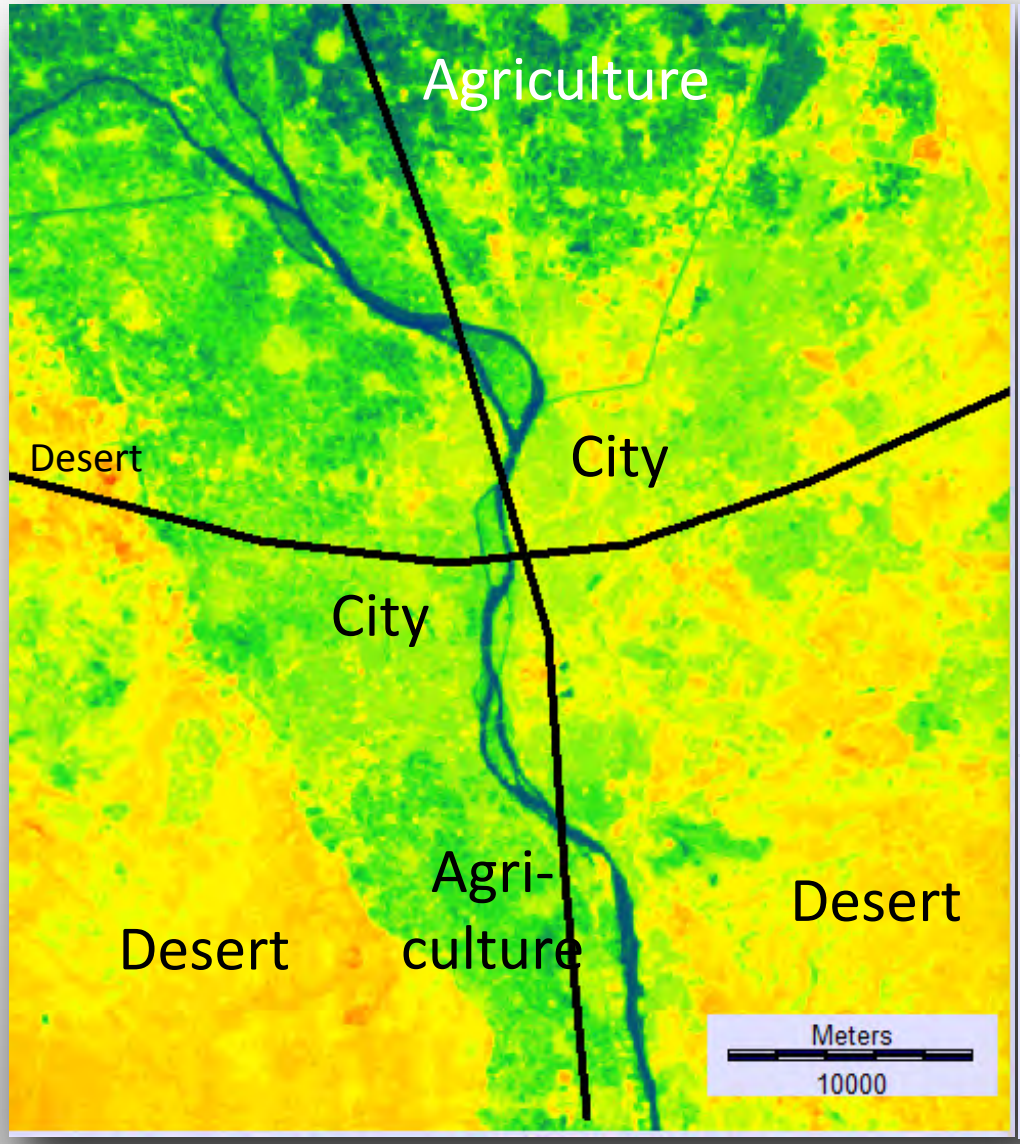
The sub-surface urban heat island (SSUHI) at x m depth

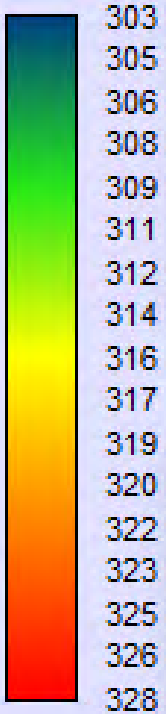


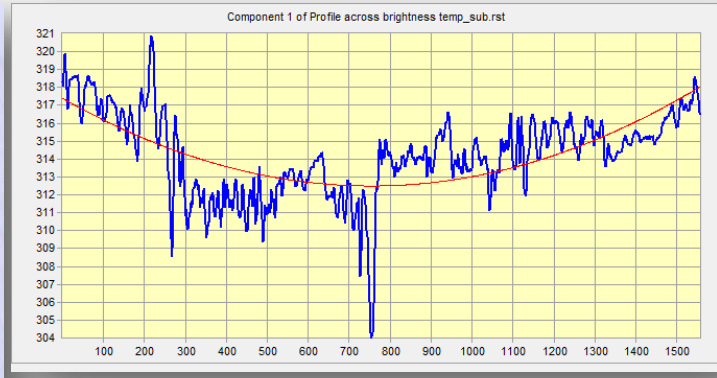
Observation strategies in urban climatology



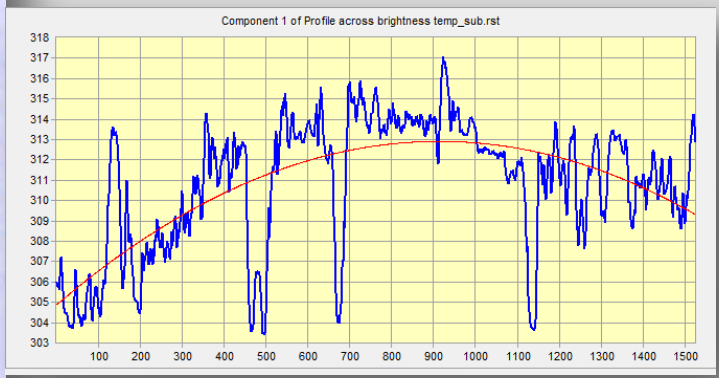
What is an urban or a rural site for UHI studies ?







W-E profile

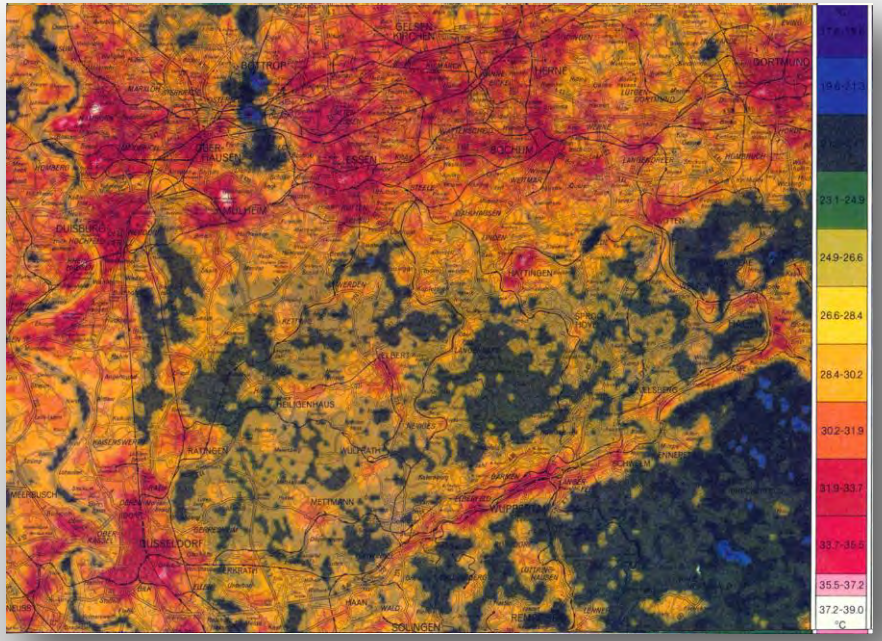


N-S profile

Day LST Cairo
03.08.2013

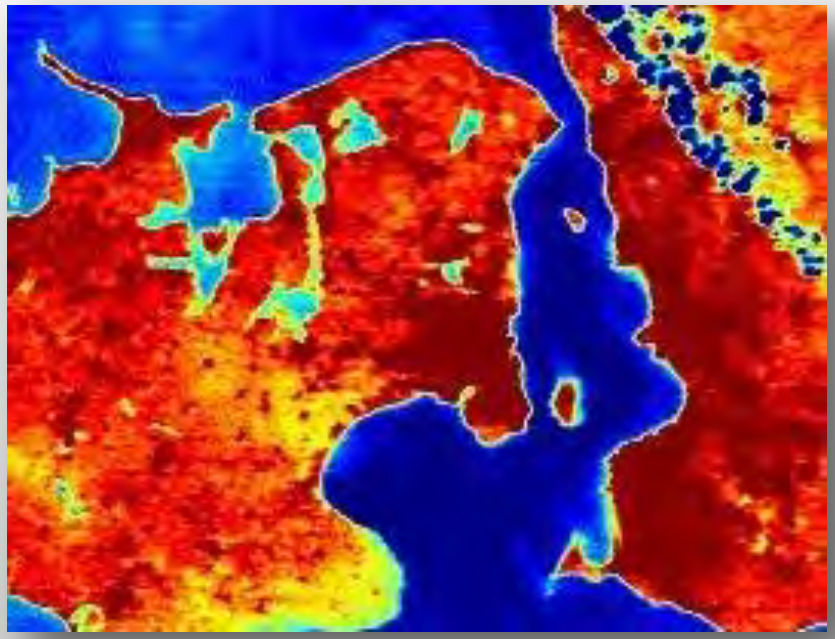
1978–80: Heat Capacity Mapping Mission (HCMM)

One of the first satellite data based urban climatologies



Ruhr-region (Germany)
Night and day orbit
What is what ??

Goßmann, H. et al. (1981).



Copenhagen-Öresund-region
Day orbit

Parlow, E. (1985)

Interactions of radiation and heat fluxes

The complete heat budget

$$Q^* + Q_H + Q_E + Q_S + Q_A + Q_P = 0 \quad [W\ m^{-2}]$$

Q^* : net radiation (sum of all short- and longwave radiation fluxes)

Q_H : sensible heat flux density (temperature)

Q_E : latent heat flux density (evapotranspiration)

Q_S : storage heat flux density / ground heat flux density

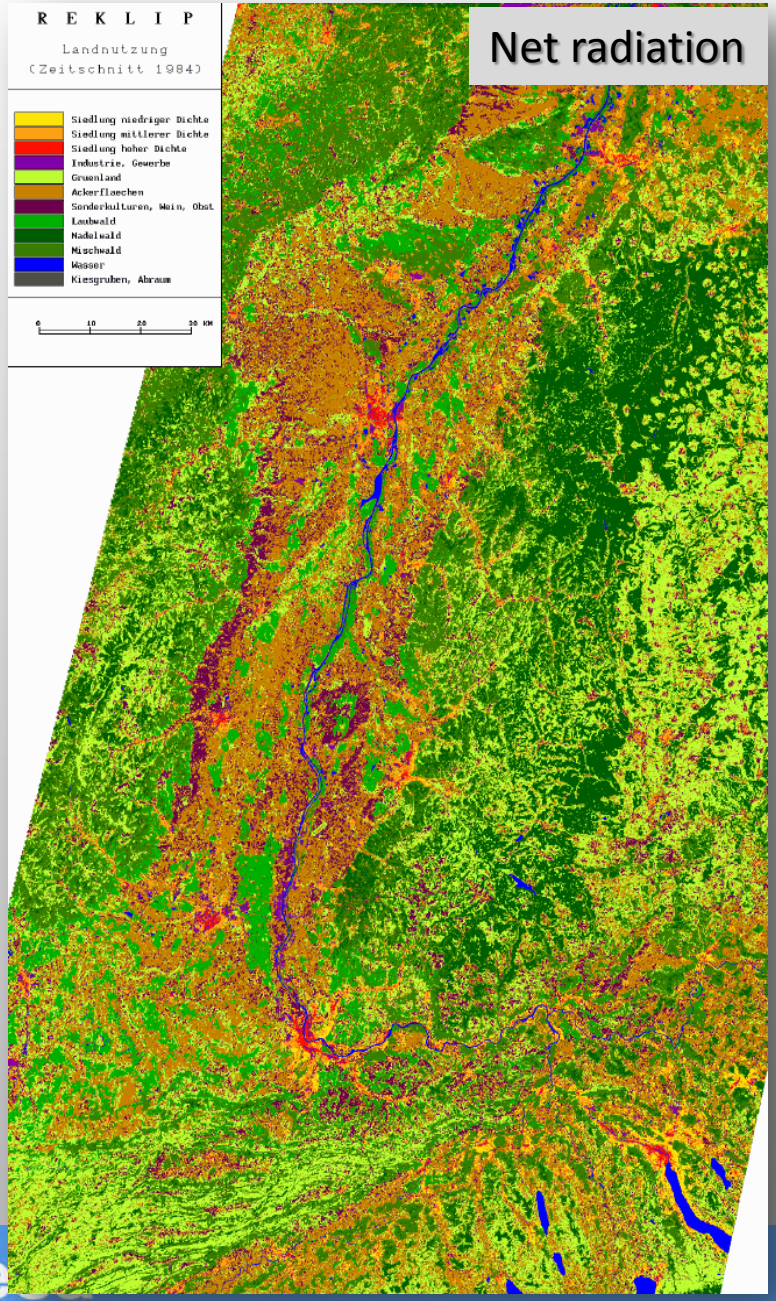
Q_A : anthropogenic heat flux density (the great unknown)

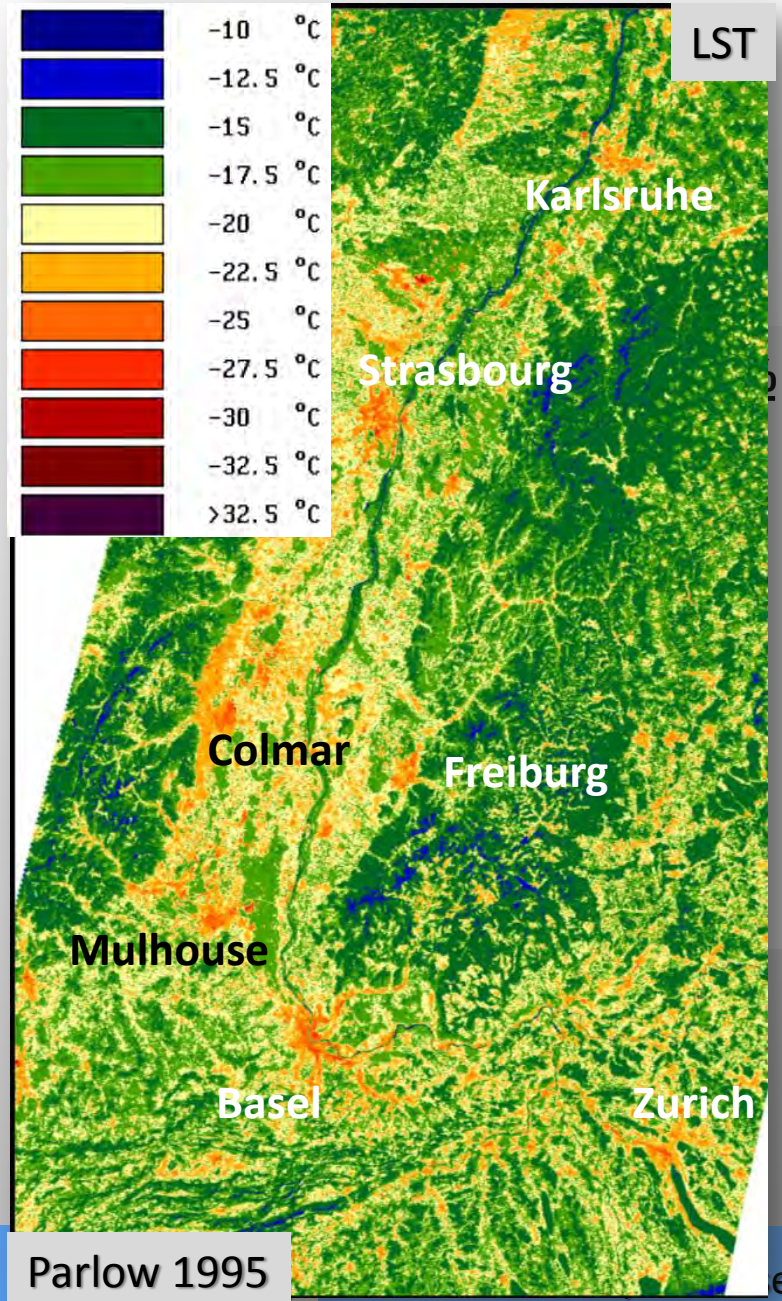
Q_P : photosynthetic heat flux density (very small)

$Q^* - Q_G$: available energy „for turbulent heat exchange“

The equation is 0 because it refers to a surface which has no mass !!

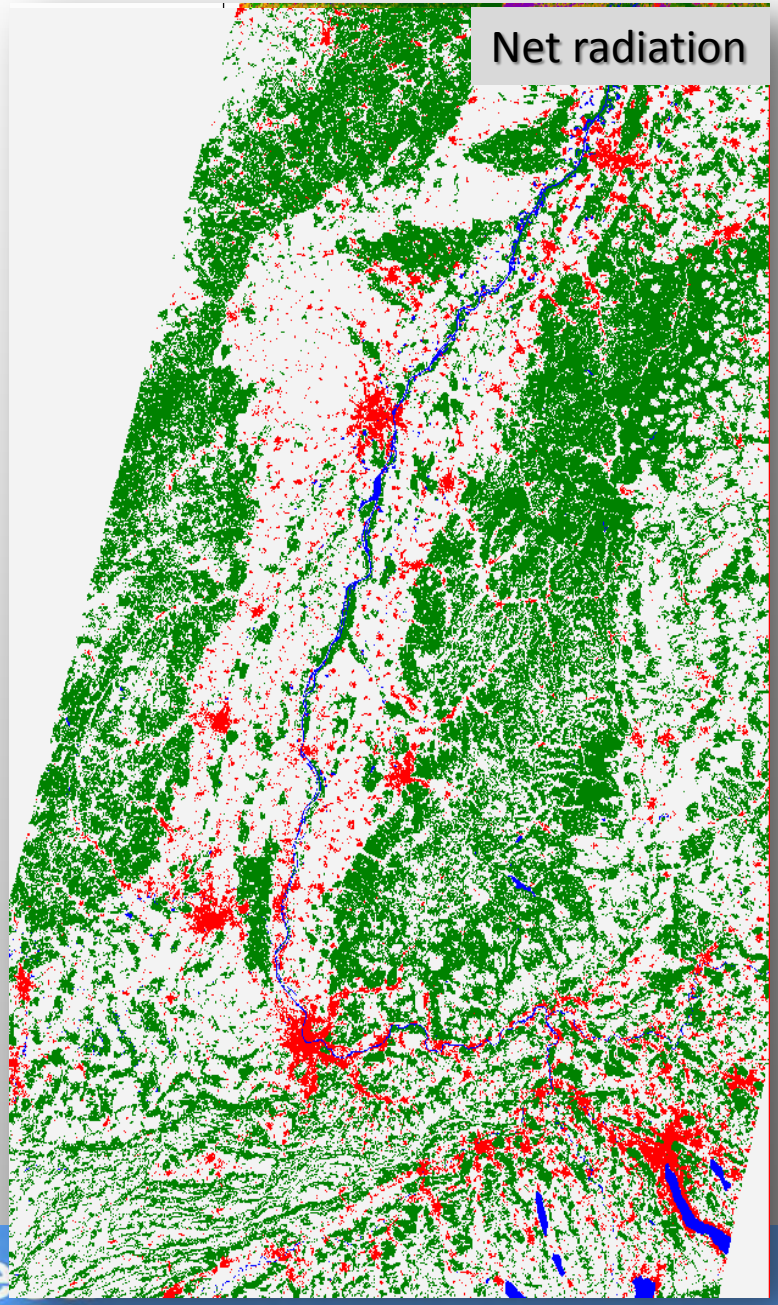
Landuse, surface temperature and net radiation

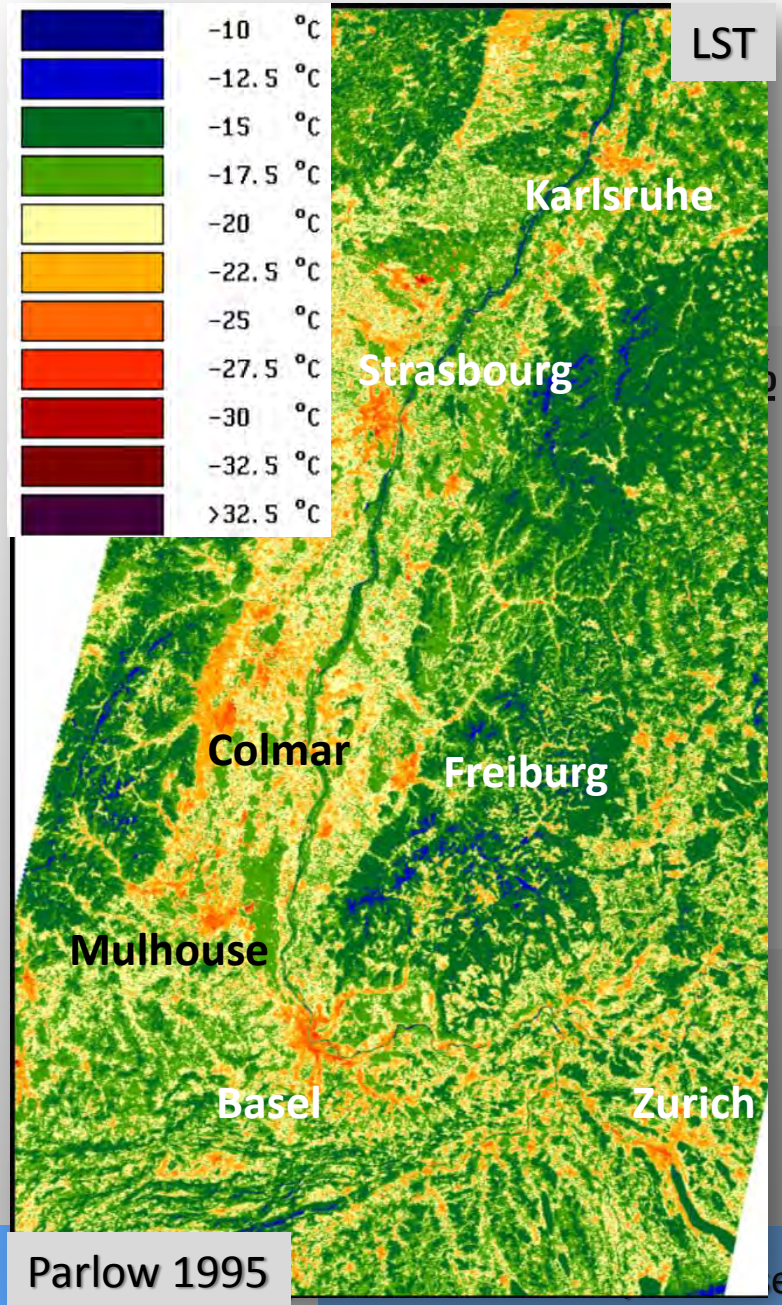




Parlow 1995

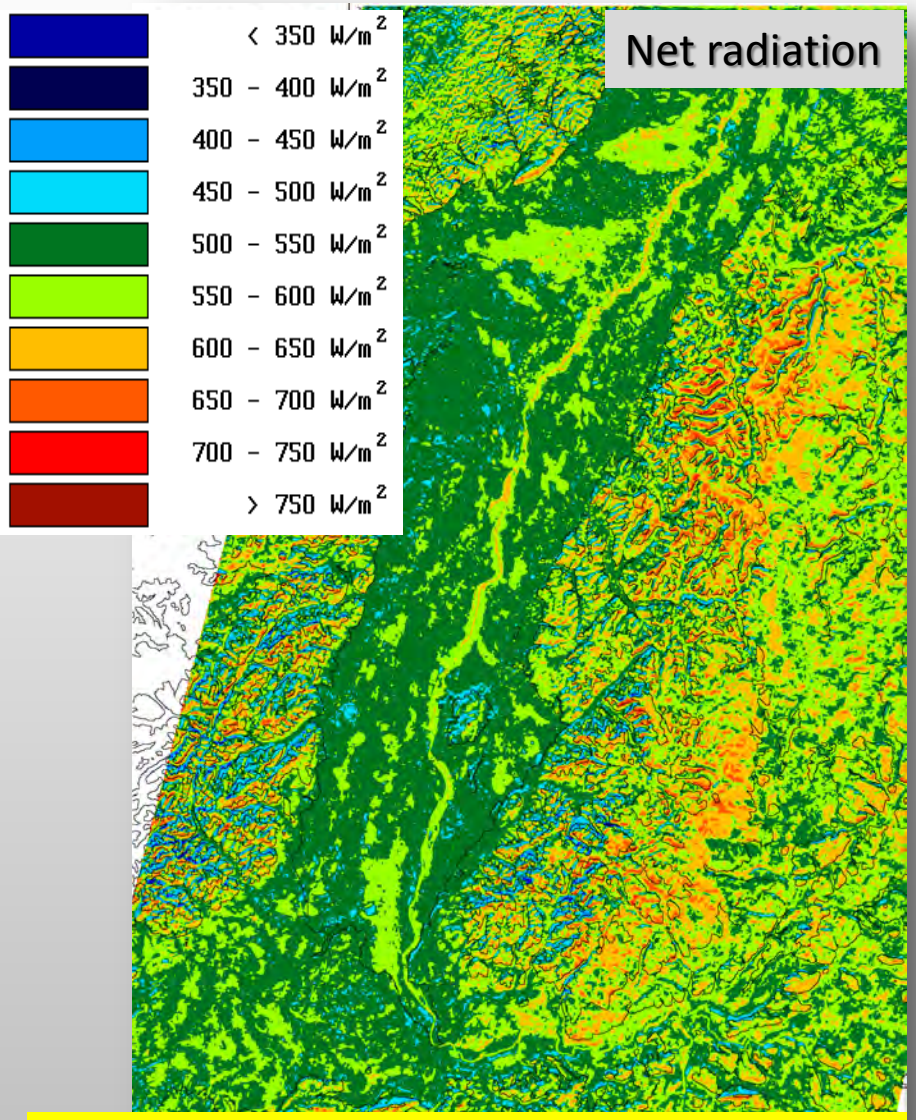
Landuse, surface temperature and net radiation

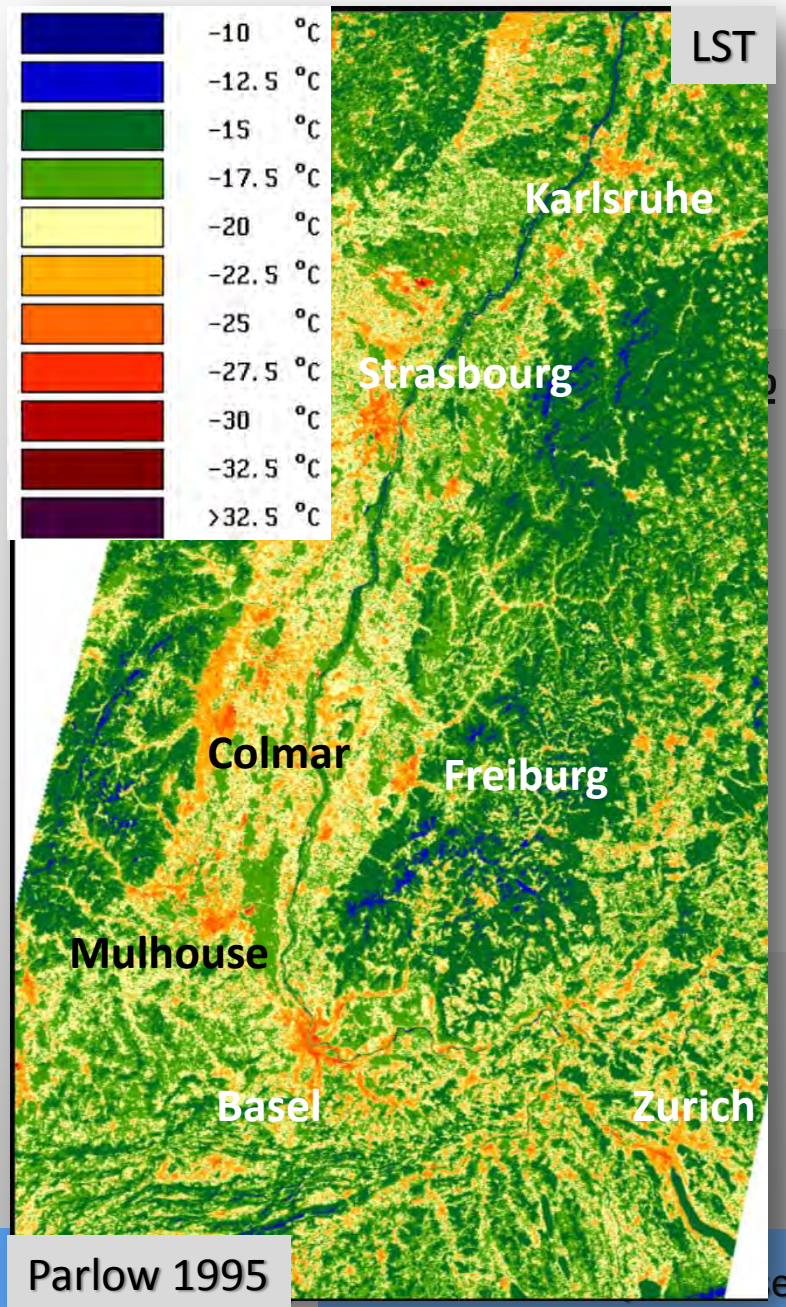




Parlow 1995

Landuse, surface temperature and net radiation

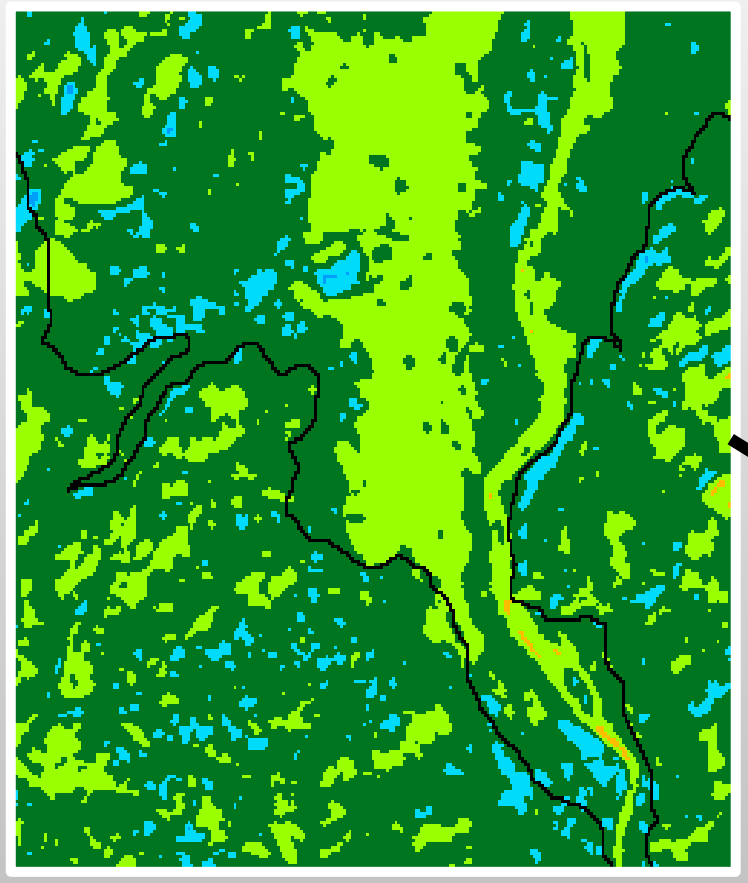


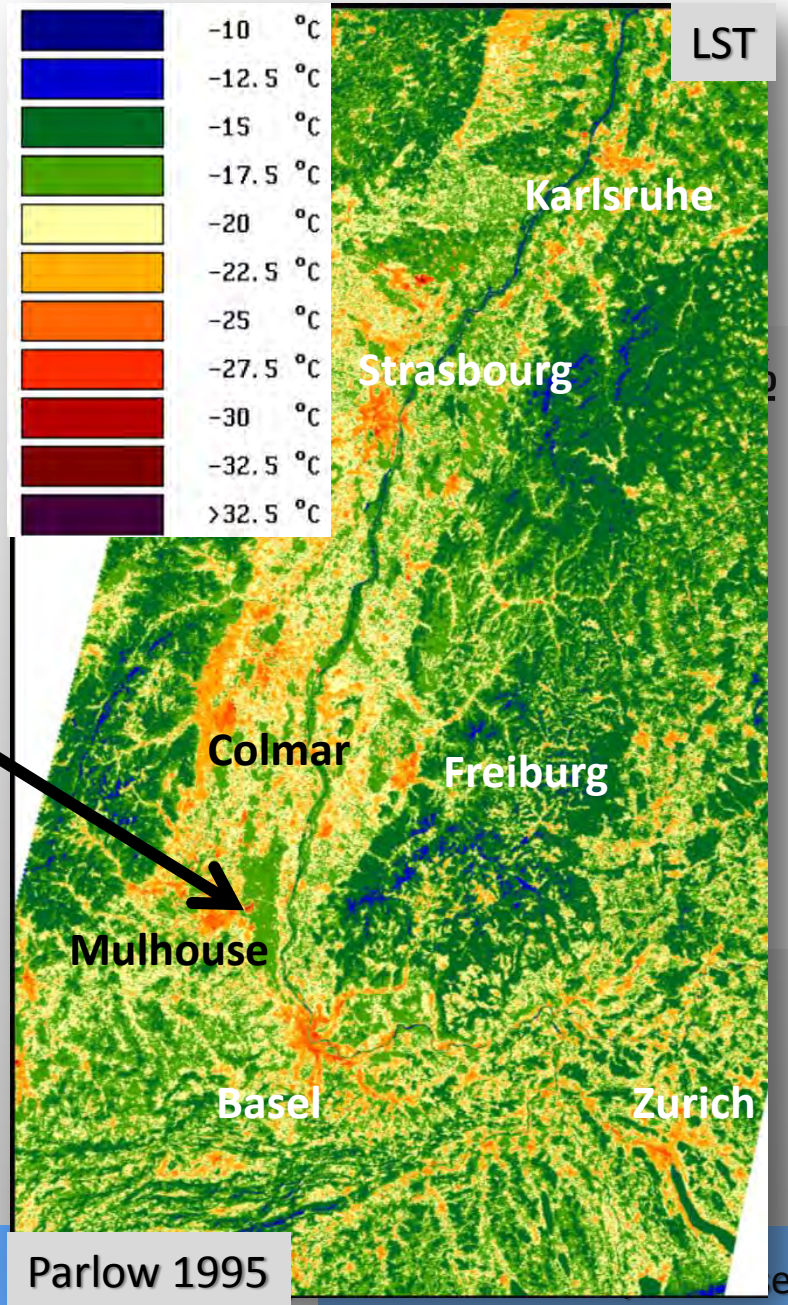


"Where have all the "cities/SUHIs" gone?" following Pete Seeger's famous song (also by Joan Baez and many more !!)

Parlow 1995

Landuse, surface temperature and net radiation

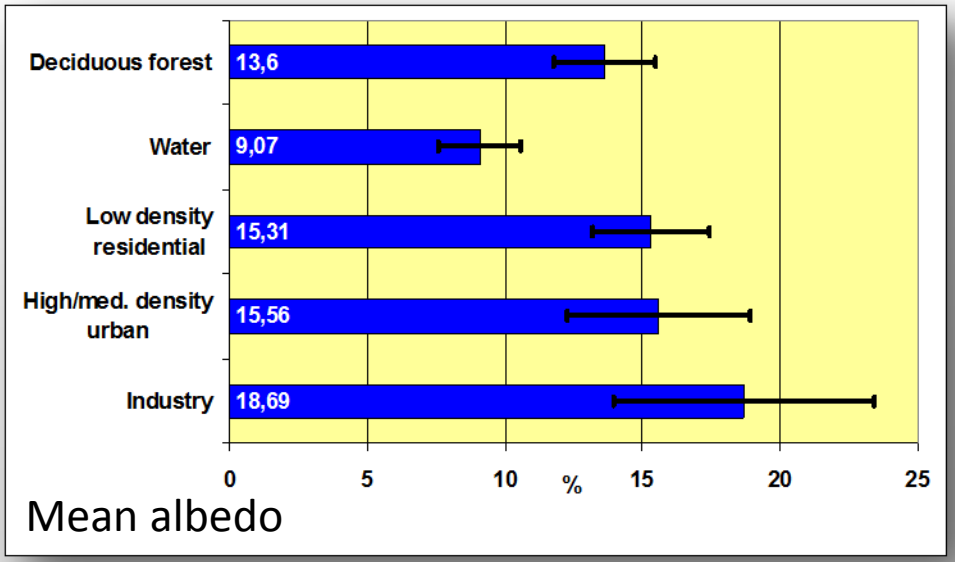




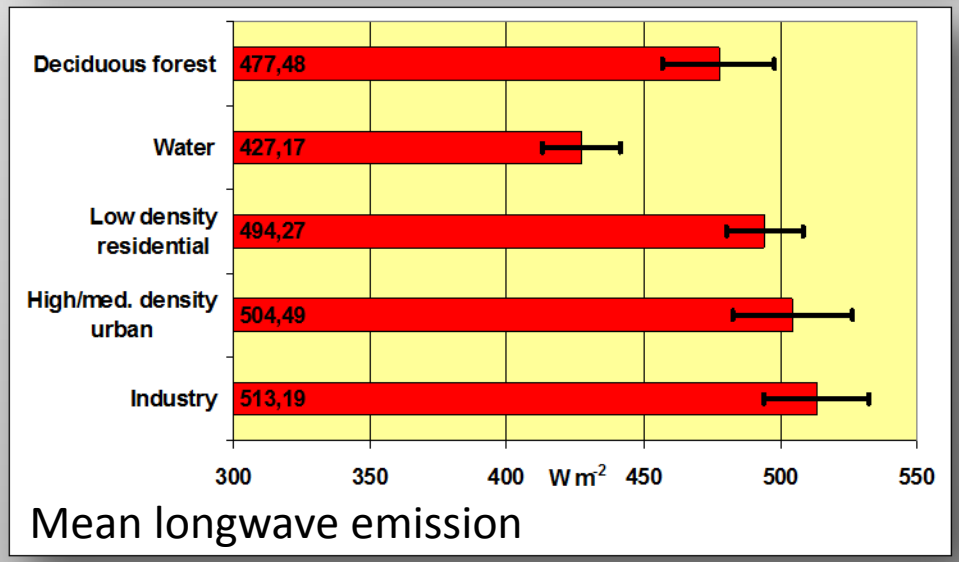
Albedo, longwave emission and net radiation

(mean values as $f_{(landuse)}$ and $\pm \sigma$)

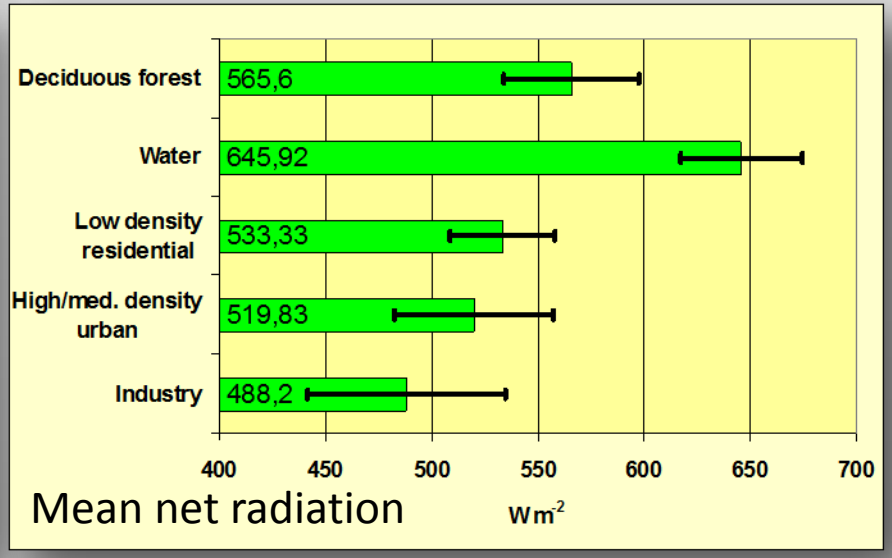
Since urban areas have higher surface temperatures and often higher albedo their net radiation is lowest and therefore the available energy for the heat fluxes is 50 – 80 Wm^{-2} smaller.



Mean albedo



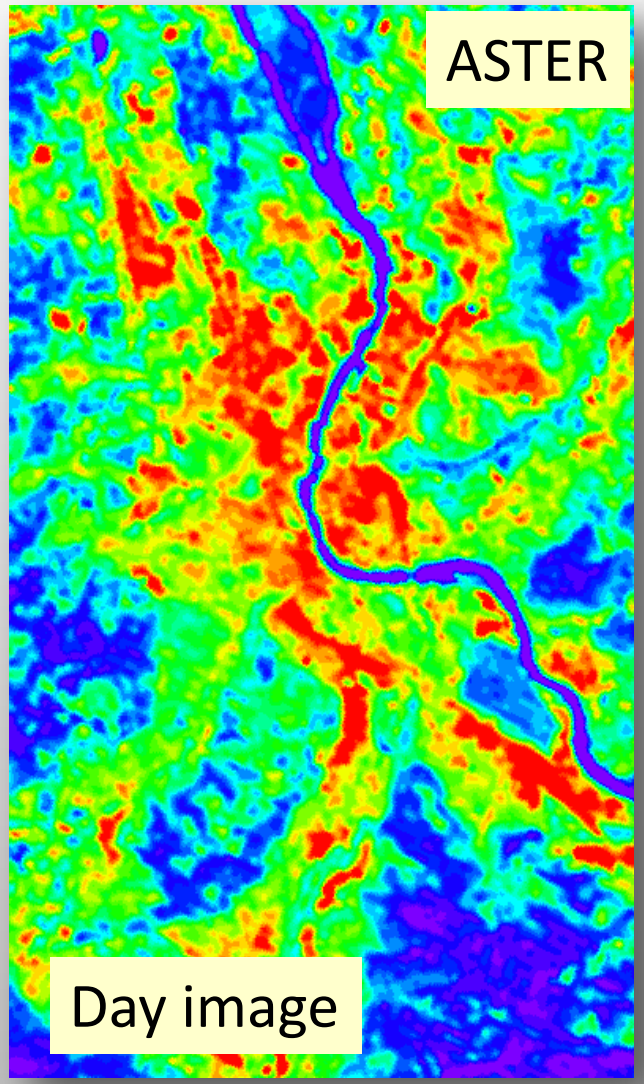
Mean longwave emission

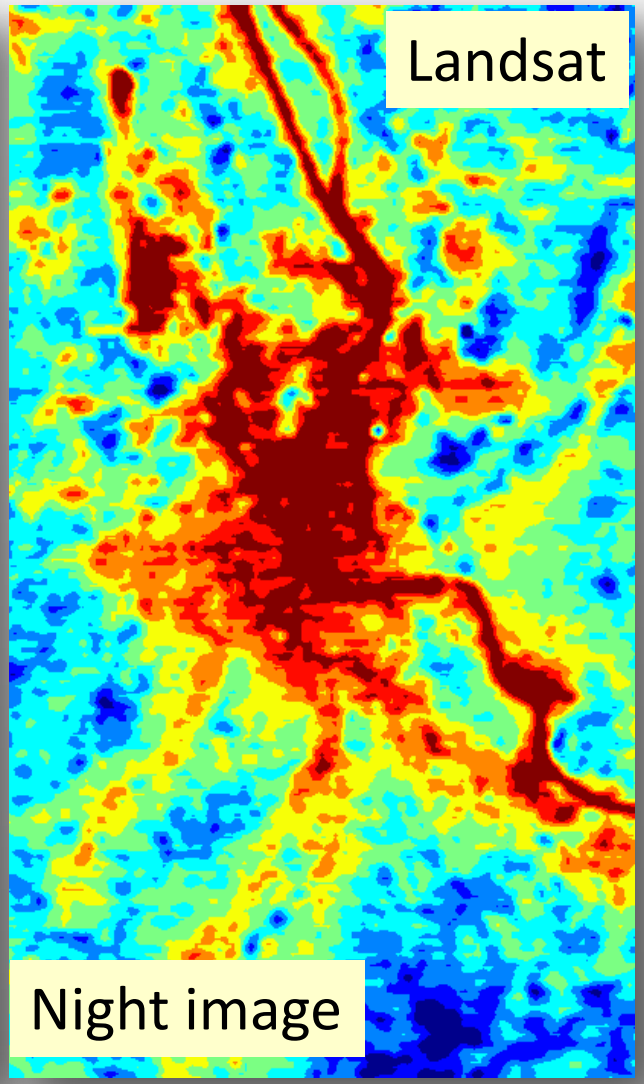


Mean net radiation

What about (S)UHI ? - T-IR satellite data Basel

(satellite data from ASTER and LANDSAT-5)



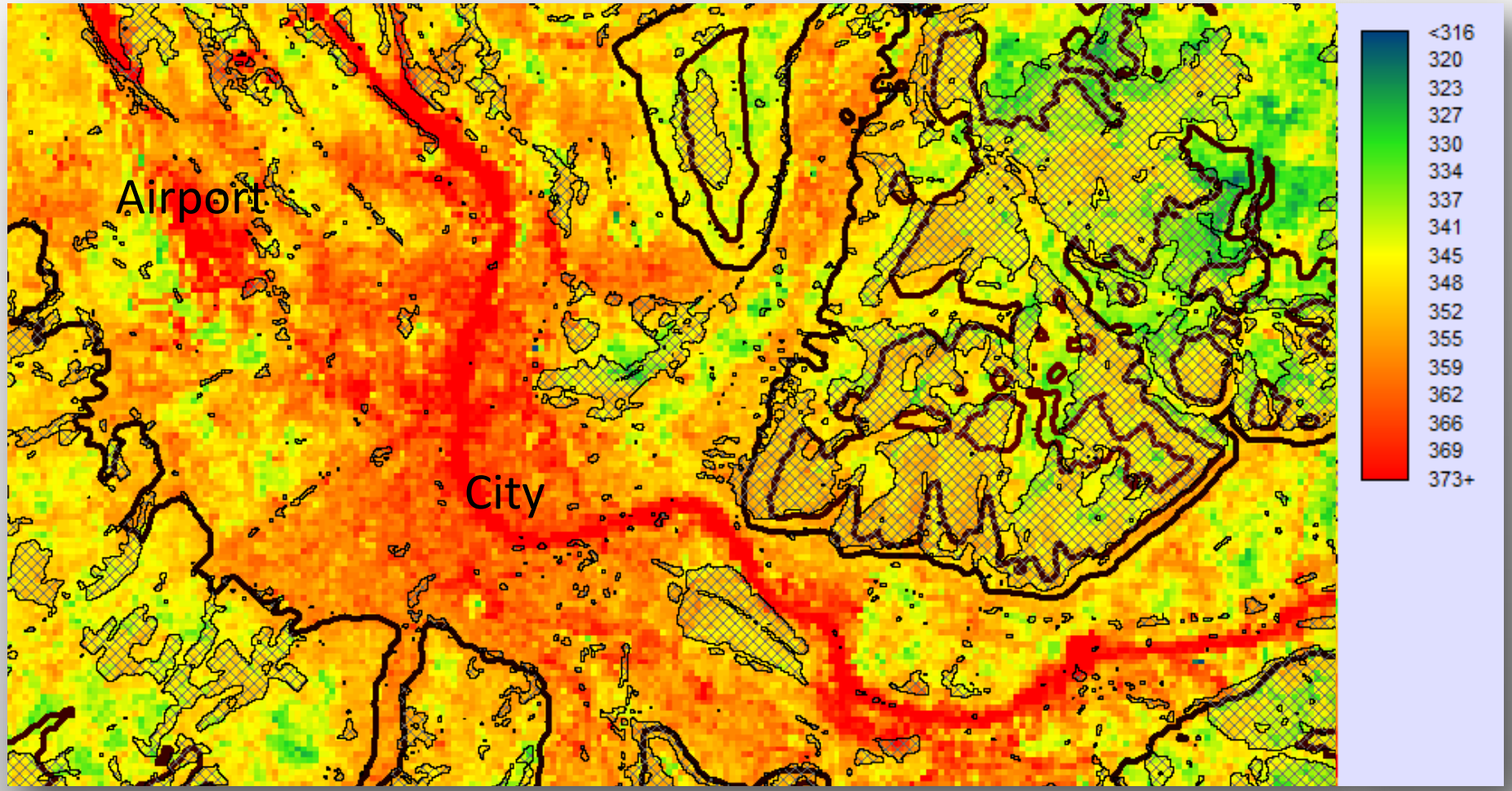


In urban areas thermal infrared satellite data always show high surface temperatures during daytime and night-time.

These images show the surface urban heat island (SUHI).

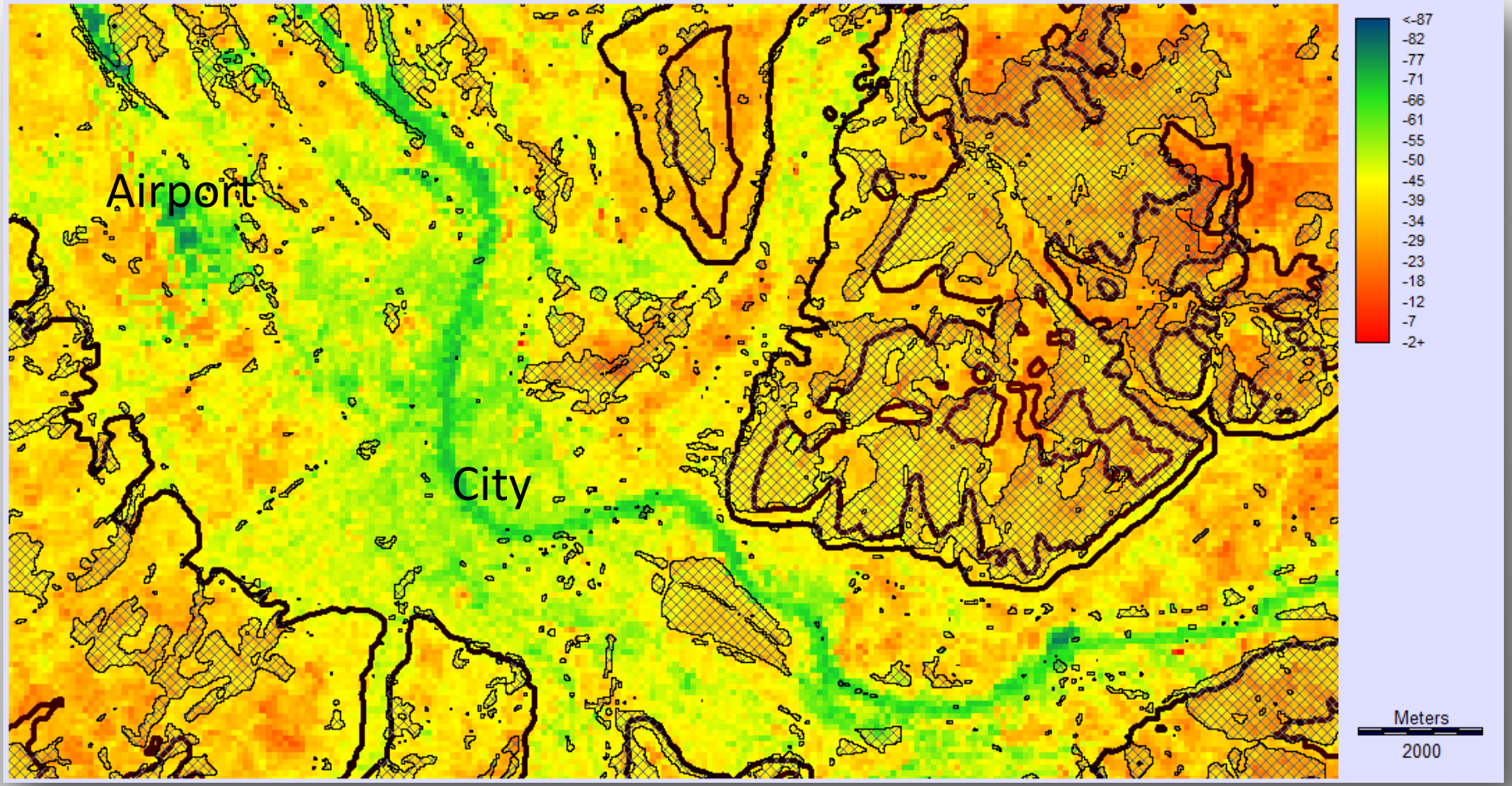
High surface temperatures mean high emission (longwave radiation loss) which often reduces net radiation

LW emission Basel region – ASTER-Night-IR data 13.5.2012 at 22:30 CET



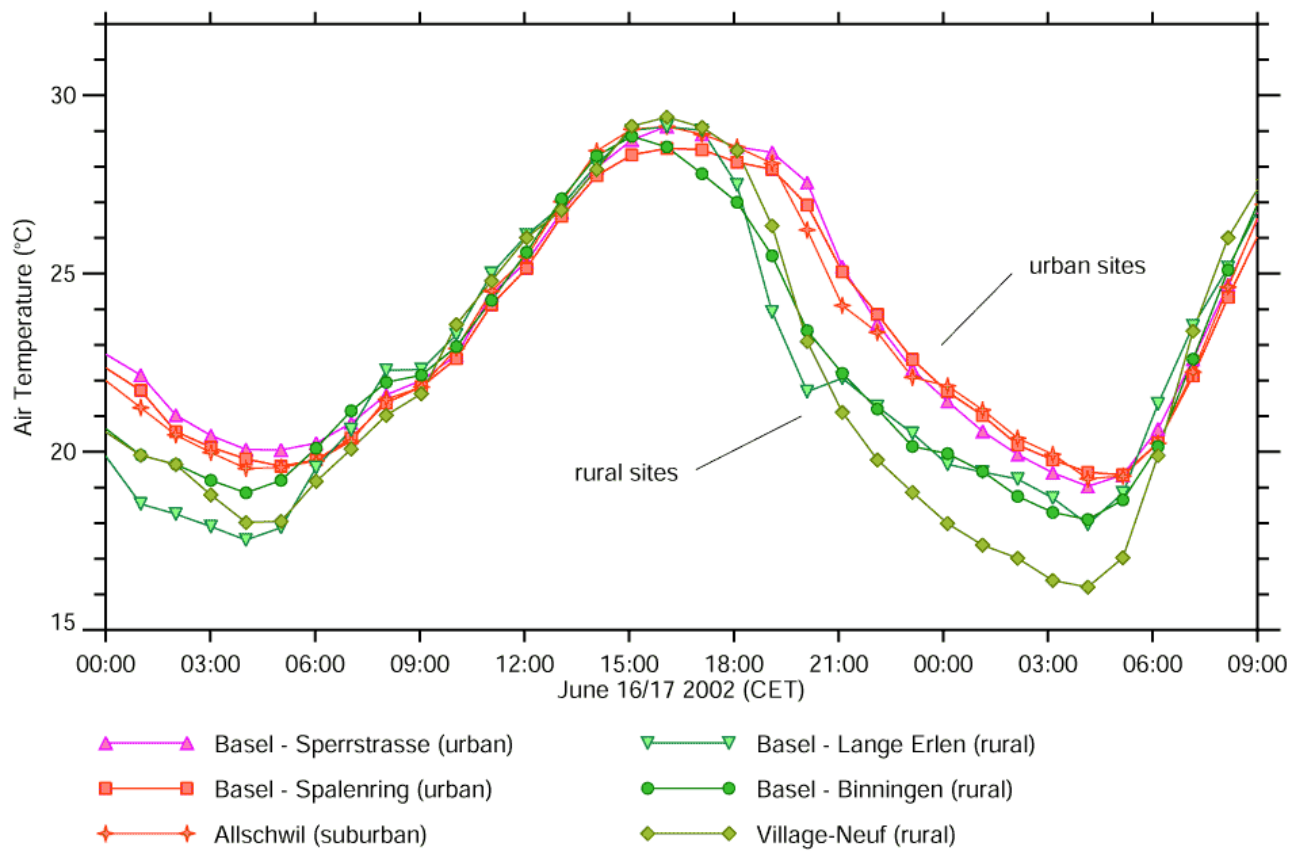
Longwave emission – surface temperatures – Law of Stefan-Boltzmann

Net radiation Basel region – ASTER-Night-IR data 13.5.2012 at 22:30 CET



Urban at night: High longwave radiation loss – very negative net radiation

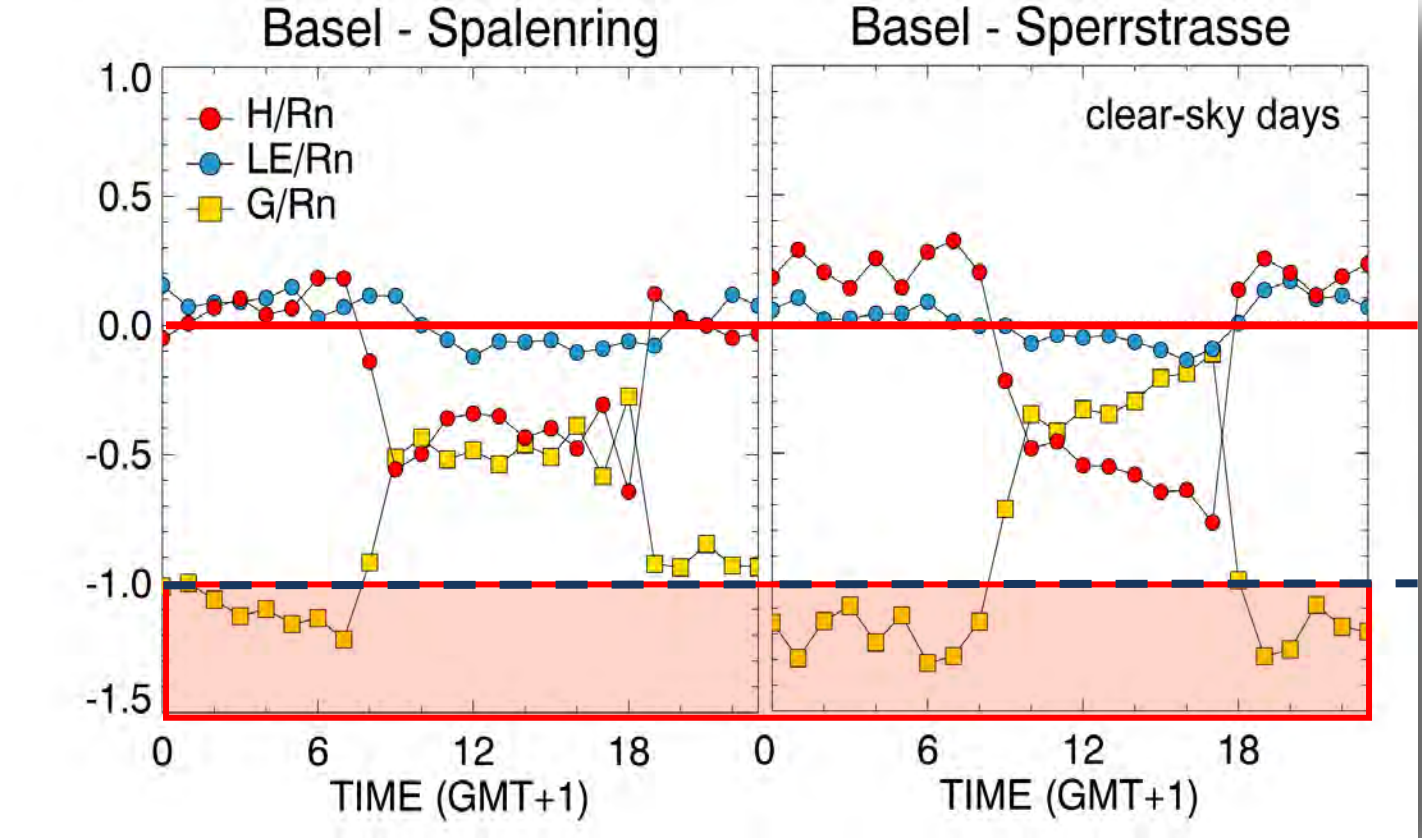
Mean diurnal trend of air temperatures for different LULC



- During daytime air temps are quite similar
- During night time air temps at rural sites are cooling down some degrees more compared to urban sites

- We just experienced that at urban sites net radiation during night is more negative than at rural sites (-50 – -80 Wm^{-2} vs -10 – -40 Wm^{-2}).
- Urban areas must compensate more radiation loss !
- What keeps the urban air temp on a higher level during all night ?

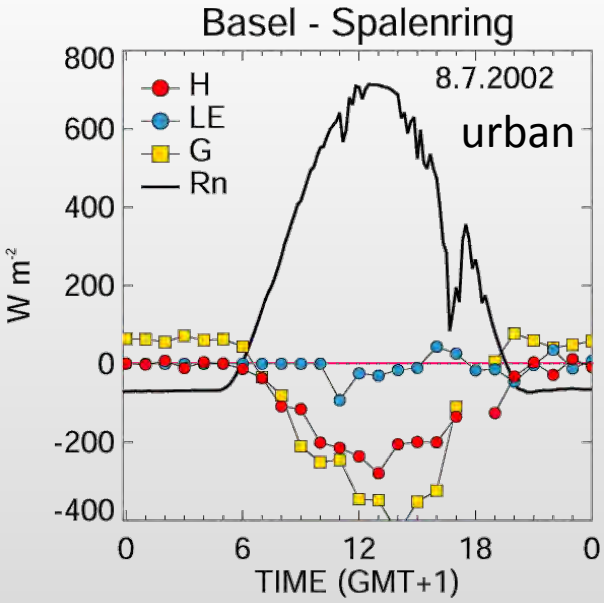
BUBBLE – results: heat fluxes normalised by Rn

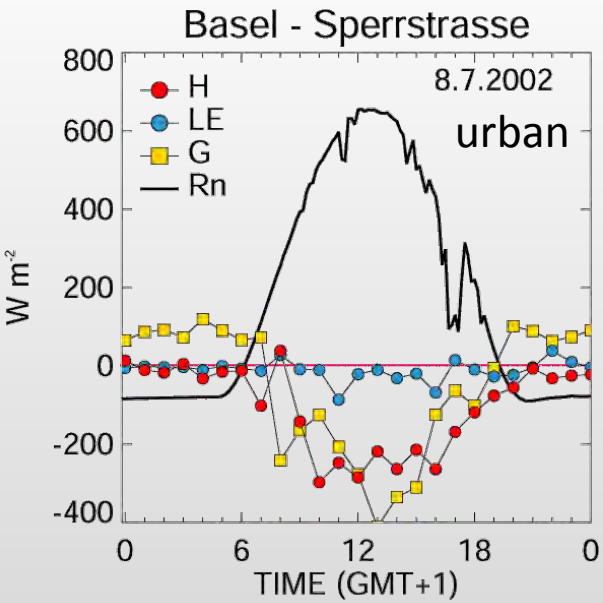


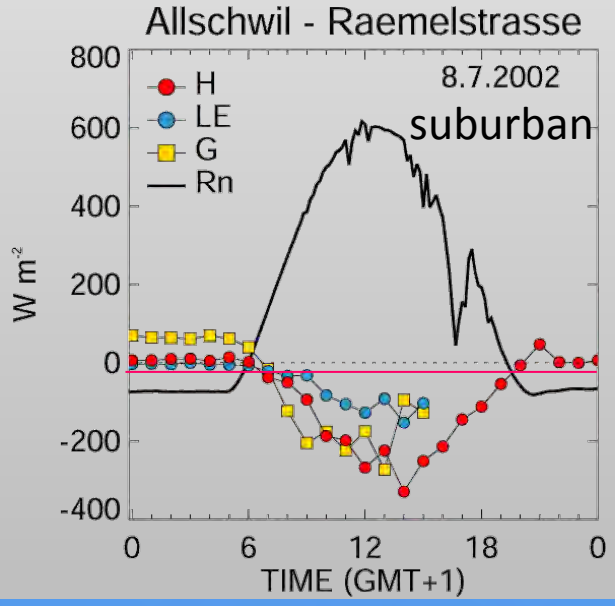
Rn : net radiation
H : sensible heat flux
LE : latent heat flux
G : storage heat flux

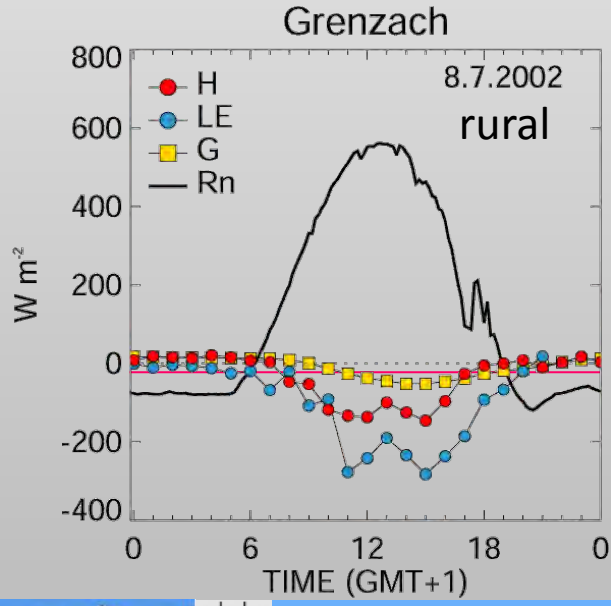
Mean diurnal course of heat fluxes for **20 clear sky days**, normalized with net radiation *Rn,* for Basel-Spalenring (left) and Basel-Sperrstrasse (right) (1.12.2001 - 30.4.2002). Graphic shows the percentage of heat fluxes of net radiation (0.5 = 50%, 1.0 = 100%). Sign convention: **fluxes from the surface into atmosphere or ground are negative !!**

Diurnal courses of heat fluxes (urban – suburban – rural)

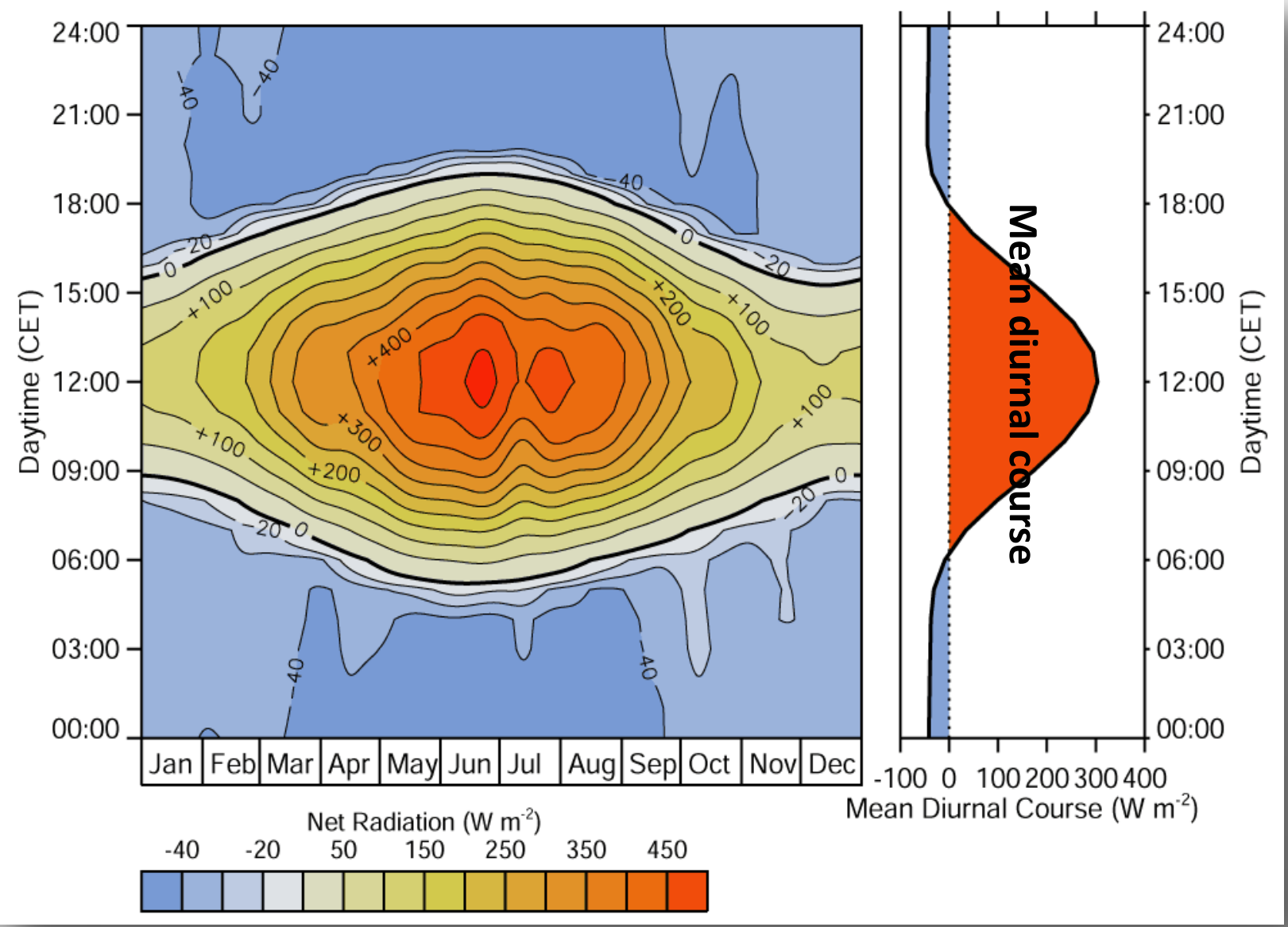




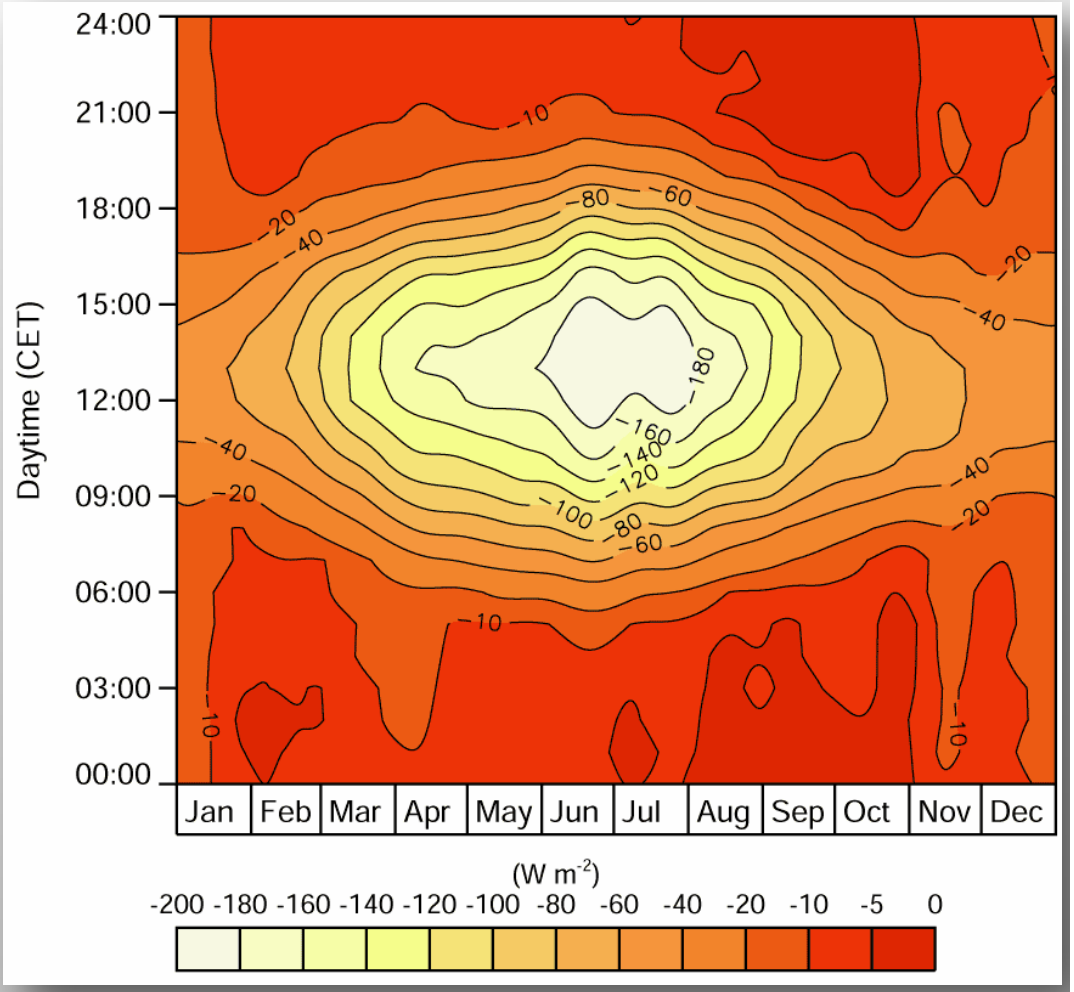




Mean net radiation Q* (1998 – 2002)



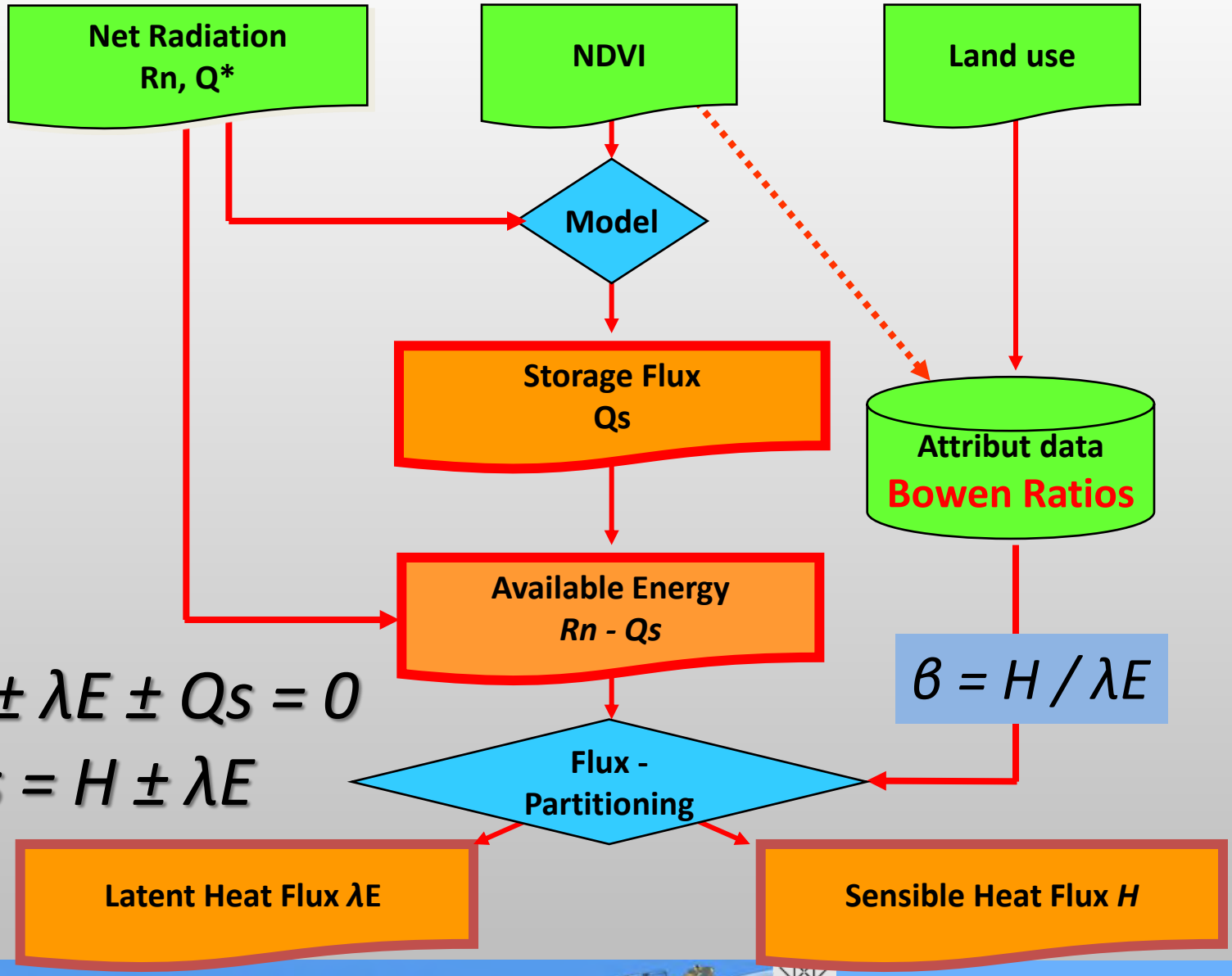
Mean diurnal and annual course of sensible heat flux *H* at urban station Basel-Spalenring (1994 – 2002 (9 years))



Data from EC-measurements

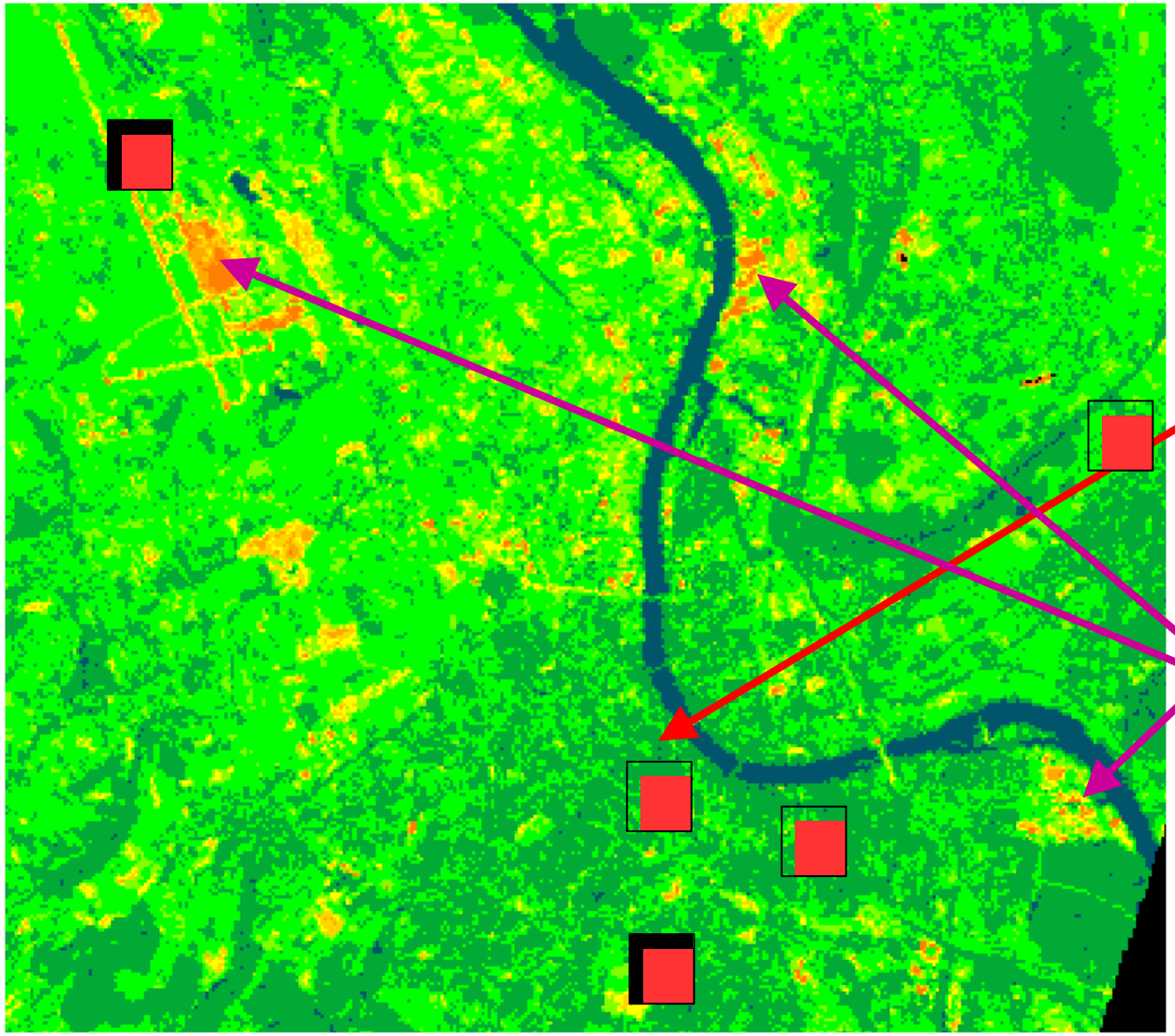
- During night : Net radiation Q* < 0
- Then **normally** heat fluxes (LE, H und G) are directed towards the surface, to compensate negative net radiation (**sign should be positive** !)
- **But** in the urban system the sensible heat flux remains at daytime **AND** night-time directed from the surface into the atmosphere ! (**negative sign**)
- During night a small sensible heat flux into the atmosphere still exists
- This means that negative net radiation is fully compensated by storage heat flux (even over-compensated).
- This prevents that air temperatures decrease strongly during night like in rural areas.

Modeling the heat fluxes using satellite data



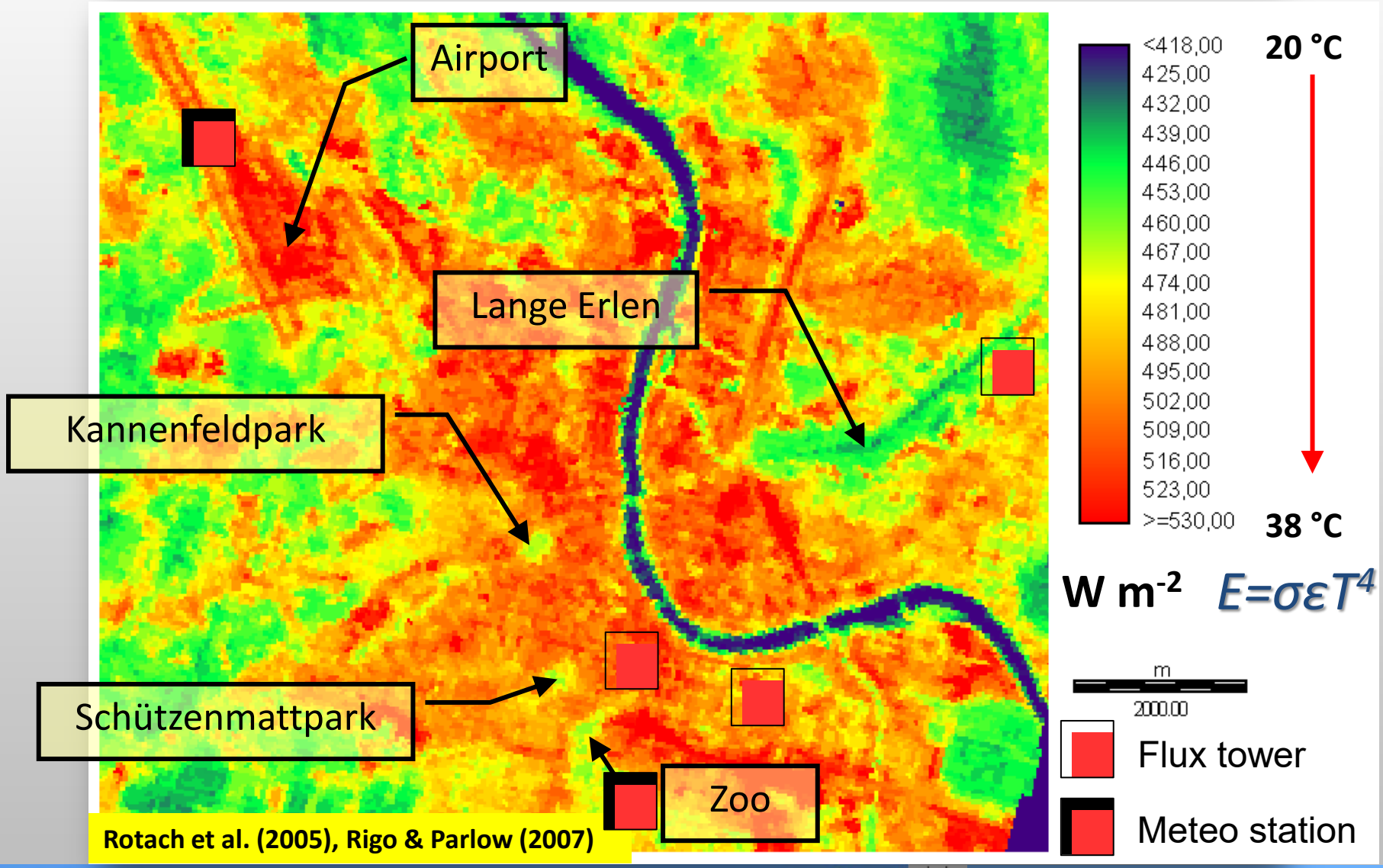
Albedo (proportion of reflected vs. solar radiation)

computed from Landsat-ETM VIS/NIR-Data



Longwave emission / surface temperature

BUBBLE – computed from Landsat-ETM-Daten (2. August 2002, 11 CET)



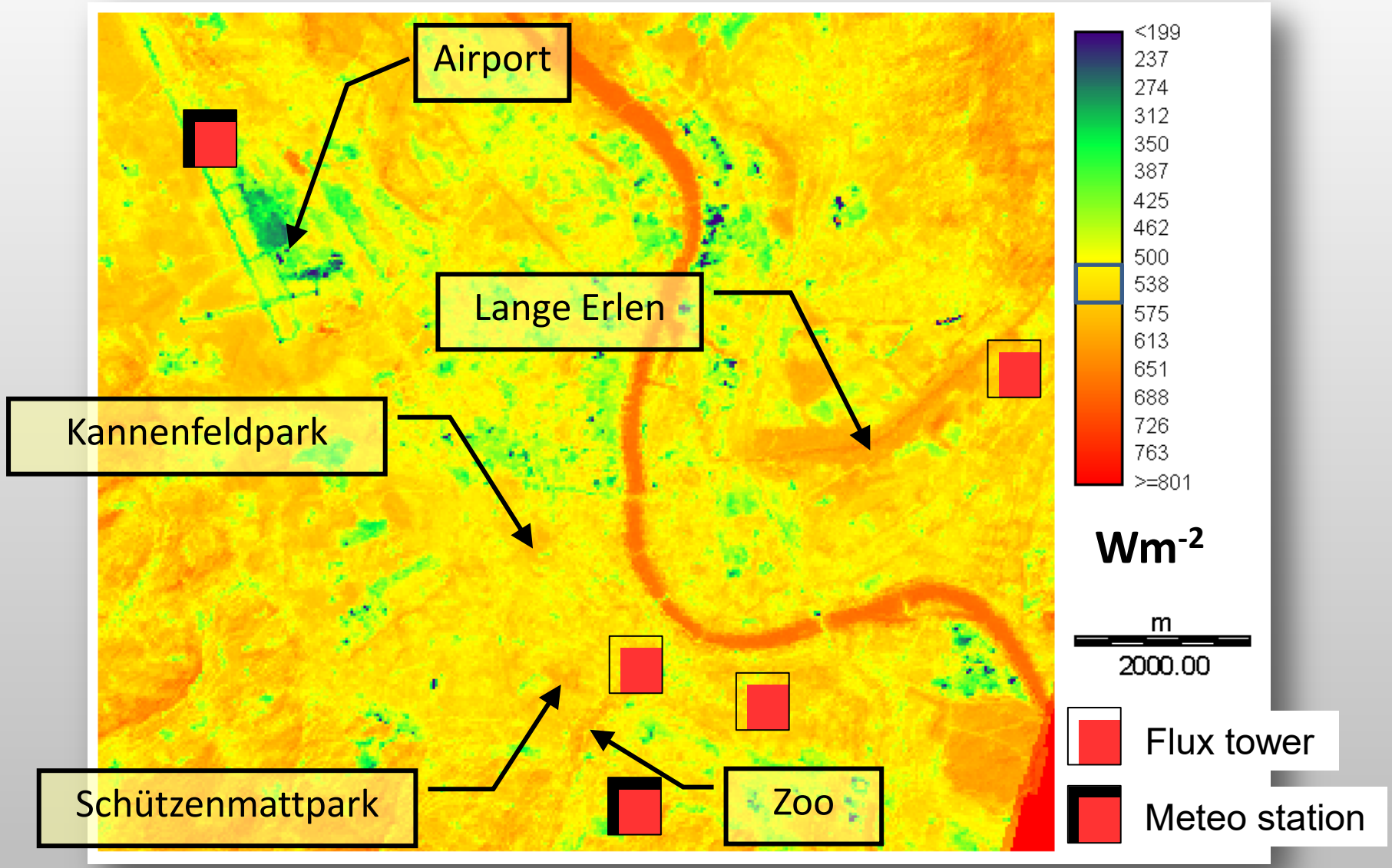
Rotach et al. (2005), Rigo & Parlow (2007)

Net radiation daytime

2. August 2002 at satellite overpass 11:04 CET

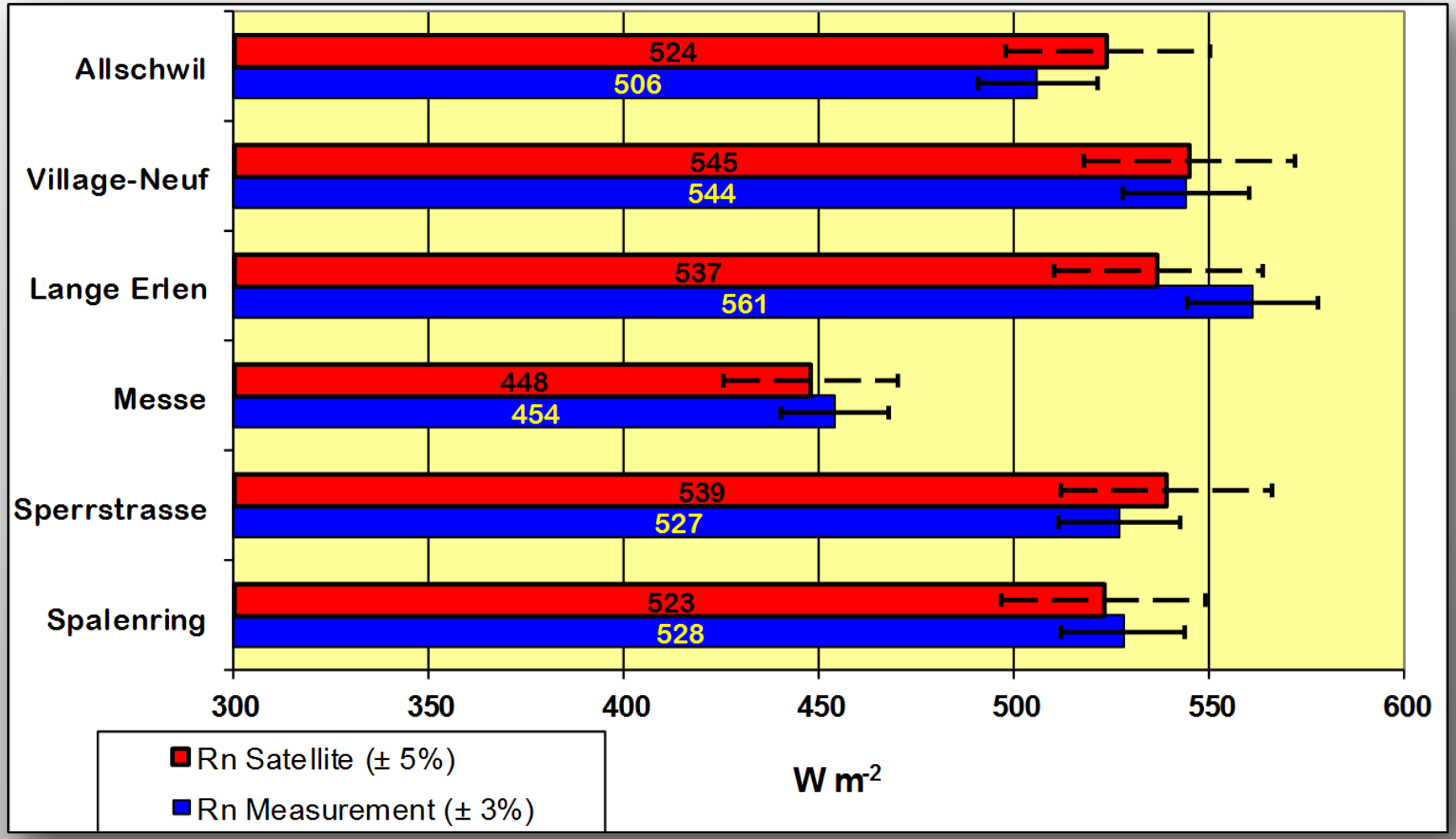
City Q* ≈ 550 Wm^{-2}

Airp Q* ≈ 250 Wm^{-2}



Validation of results

Net radiation during BUBBLE-field campaign 2002



Storage heat flux Q_s: NDVI-approach

$$Q_S \text{ (urban)} = -(0.3673 - 0.3914 \bullet \text{NDVI}) \bullet R_n$$

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

with NDVI : Normalized Difference Vegetation Index
(IR-Red)/(IR+Red)

Rn : net radiation

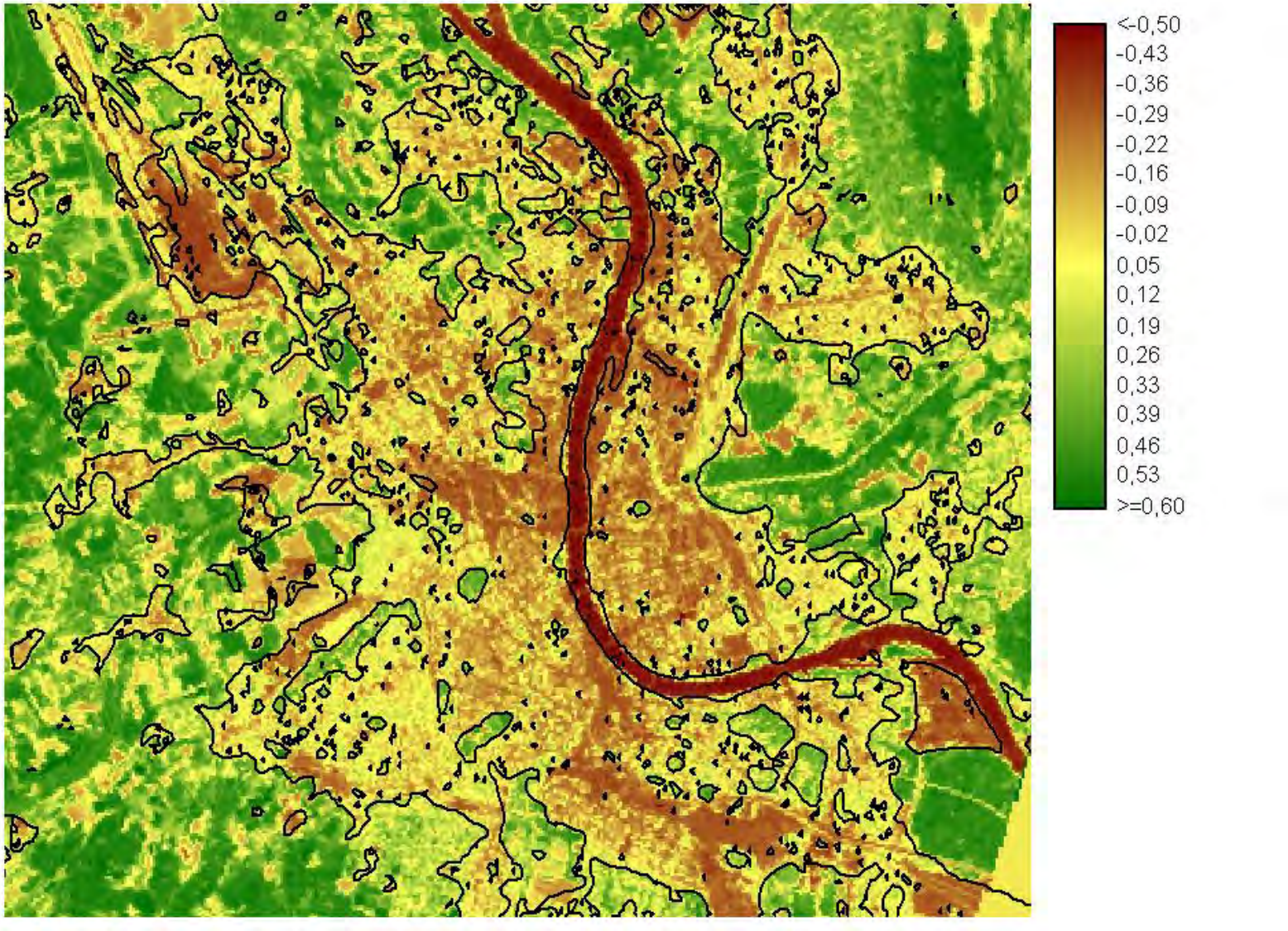
Q^*_{SW} : shortwave net radiation (= (1 – α) KW))

α : albedo

This empirical approach delivers very good results !

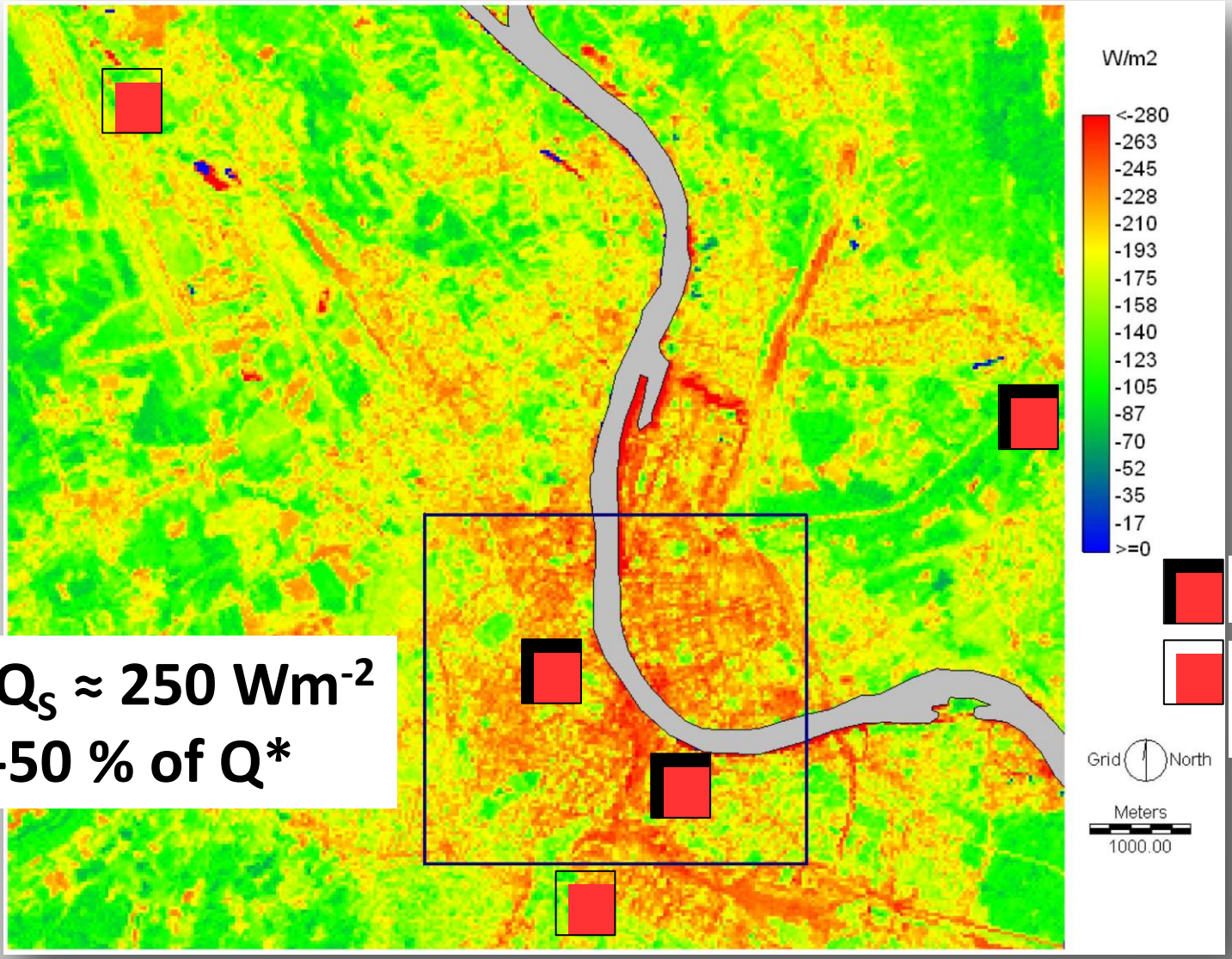
Parlow (1999), Rigo & Parlow (2007)

NDVI Basel from Landsat data



BUBBLE – Storage heat flux during satellite overpass

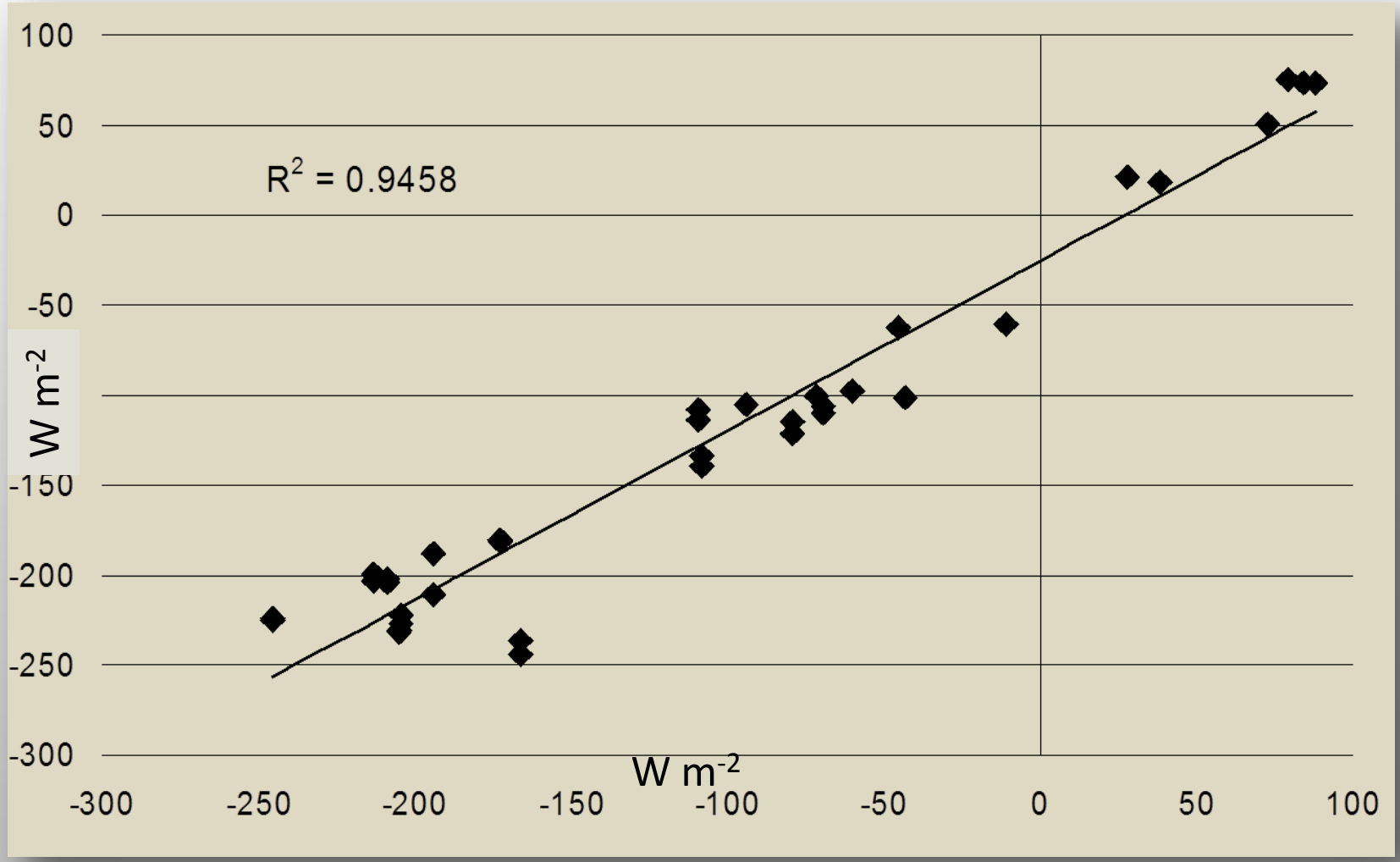
Computed using NDVI-Approach (Parlow 1999, Rigo & Parlow 2007)



City Q_S ≈ 250 Wm^{-2}
≈ 40-50 % of Q*

Validation of results

Modelled vs measured storage heat flux at BUBBLE sites



Partitioning of turbulent heat fluxes using Bowen-Ratio (β) method (I.S. Bowen 1926)

$$\beta \equiv \frac{H}{\lambda E} = \frac{k_H}{k_E} \cdot \frac{c_p}{\lambda} \cdot \frac{\frac{\partial \theta}{\partial z}}{\frac{\partial q}{\partial z}} \approx \frac{c_p}{\lambda} \cdot \frac{\Delta \theta}{\Delta q}$$

H : Sensible heat flux

λE : Latent heat flux

c_p : Heat capacity of air at constant pressure (4185.5 J $kg^{-1}K^{-1}$)

k_H and k_E : Turbulent exchange coefficients for air and water vapour (assumed to be equal)

Θ : Potential temperature -> $\partial\theta/\partial z$: vertical potential temperature gradient

q : Specific humidity -> $\partial q/\partial z$: vertical specific humidity gradient

λ : Heat of evaporation (≈ 2300 J/g)

z : Height of measurement of vertical profile

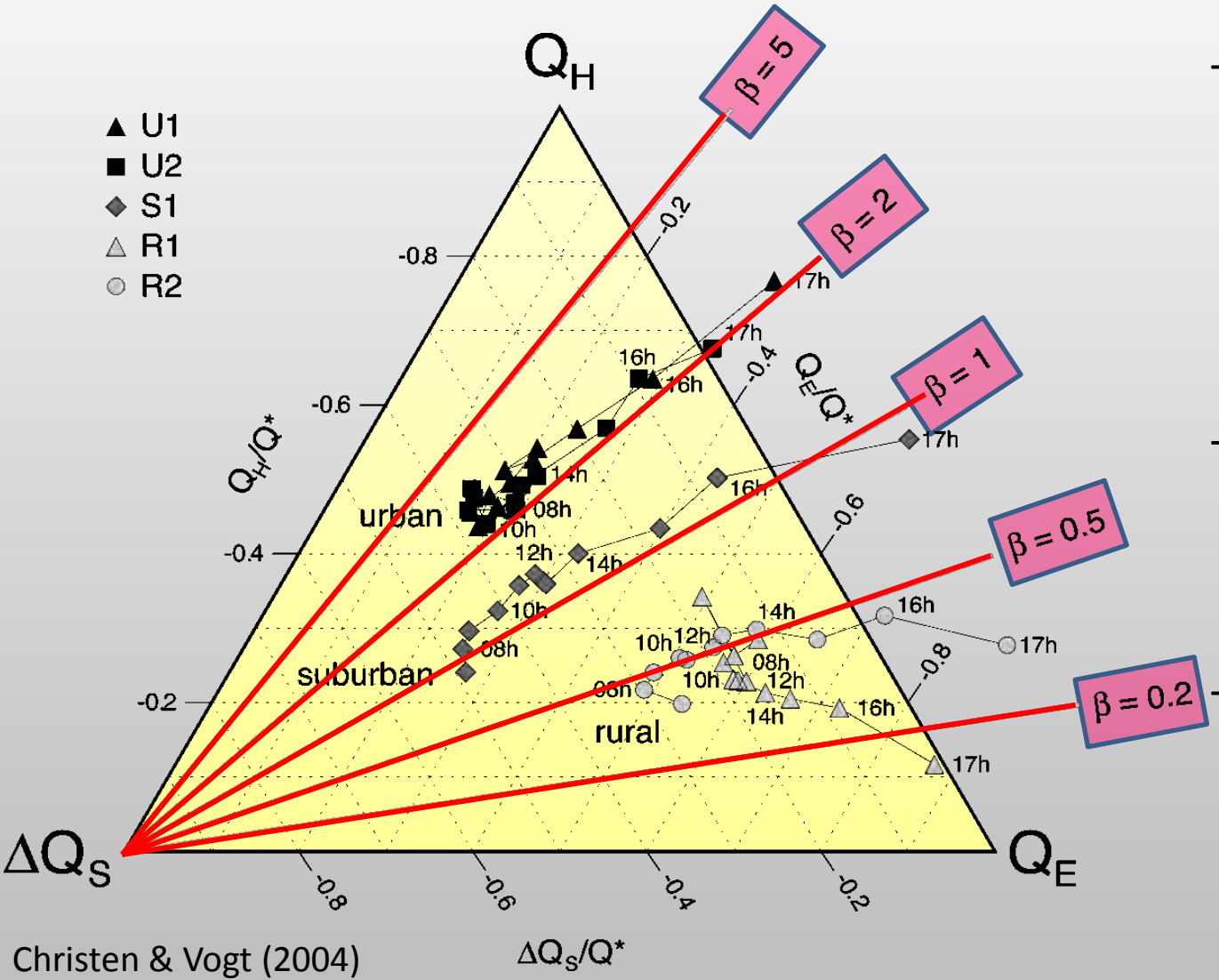
Mean Bowen-ratio-values H/LE (literature)

Land use	Bowen-Ratio	relation
Residential, high density	1.8	$Q_H > Q_E$
Residential, medium density	1.0	$Q_H = Q_E$
Residential, low density	0.8	$Q_H < Q_E$
Industry	2.5	$Q_H > Q_E$
Coniferous forest	0.7	$Q_H < Q_E$
Mixed forest	0.5	$Q_H < Q_E$
Deciduous forest	0.4	$Q_H < Q_E$
Fallow	0.5	$Q_H < Q_E$
Horticulture, vineyards	0.5	$Q_H < Q_E$
Grass land	0.6	$Q_H < Q_E$
Agricultural use	0.7	$Q_H < Q_E$

(various sources)

Heat budget

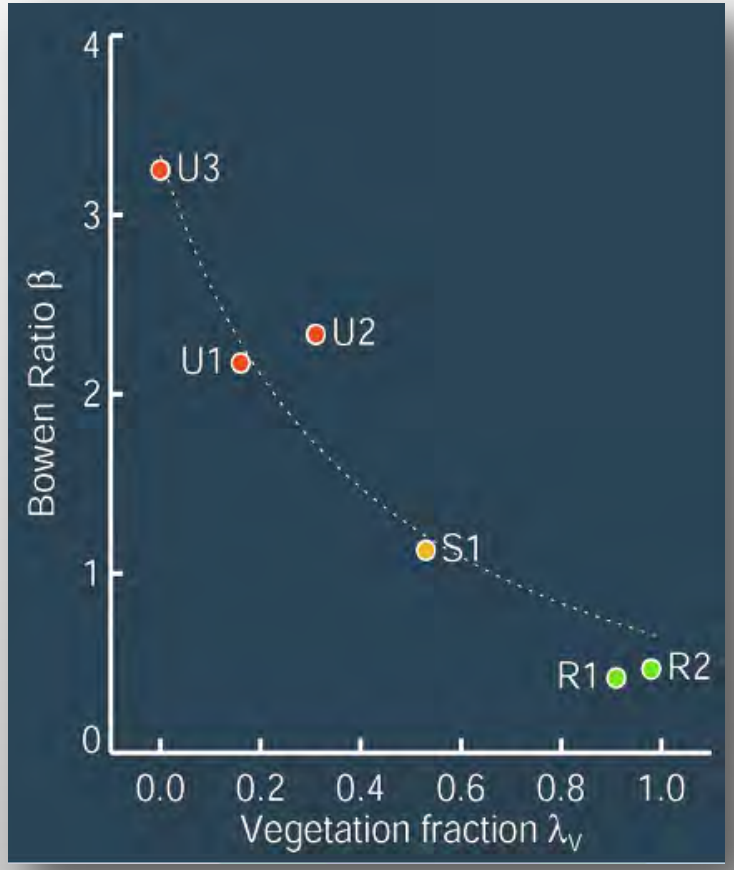
"The flux partitioning tri-angle"

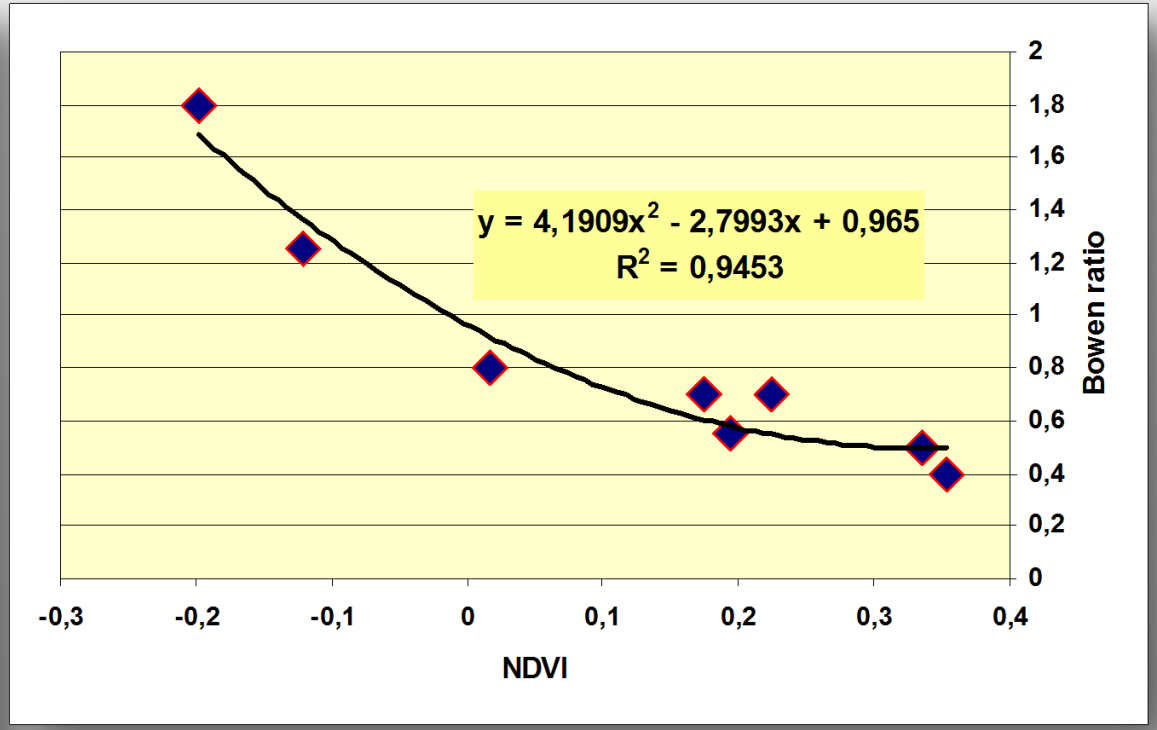


Christen & Vogt (2004)

- Bowen ratios of urban and suburban surfaces remain very stable over the day with minor variations only
- At suburban sites this depends much on the vegetation fraction
- Rural areas show more variation especially at late afternoon

Vegetation fraction & NDVI vs Bowen ratio

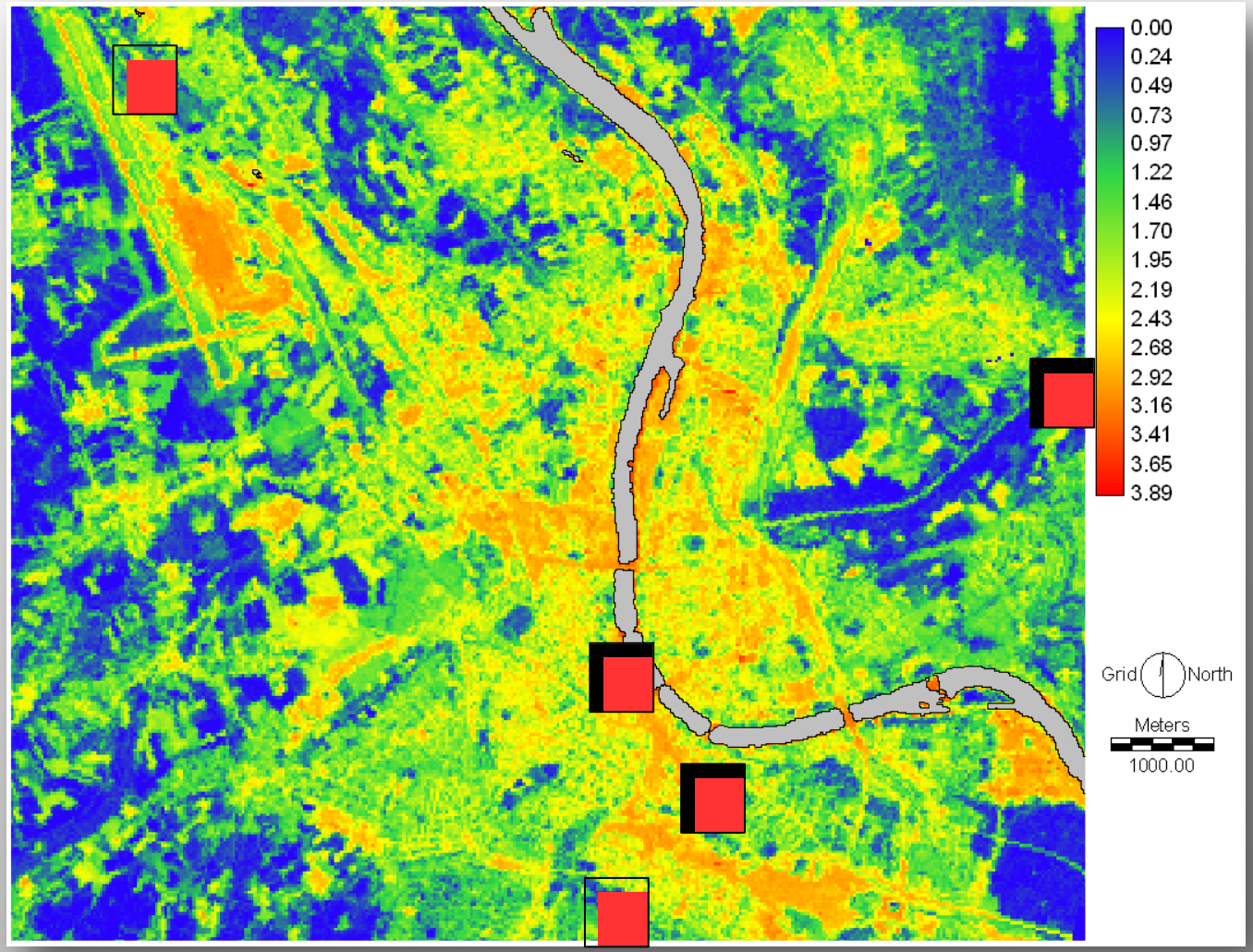




Dots are spatially integrated mean NDVI values for landuse classes in the Basel region

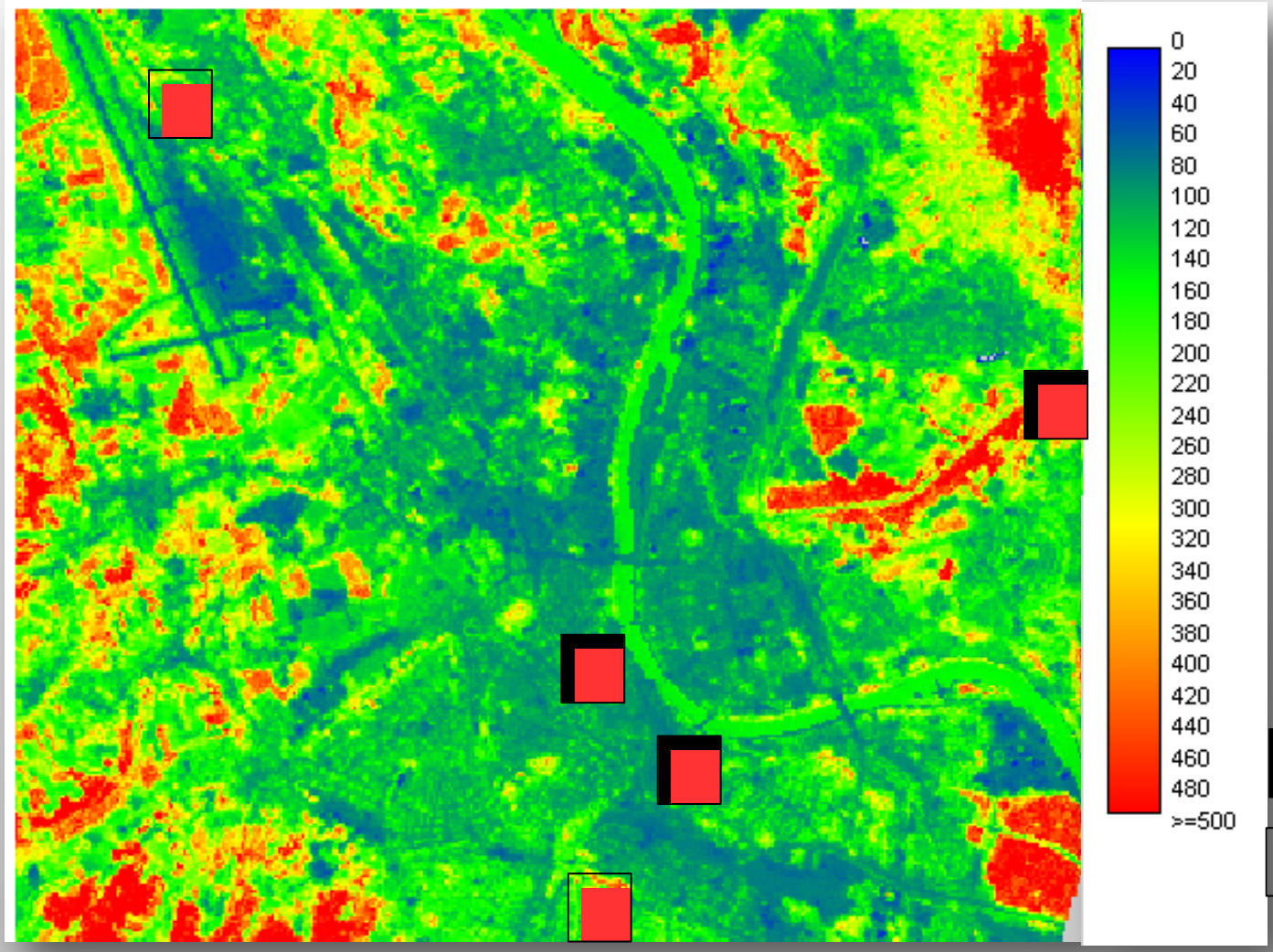
Bowen ratio during satellite overpass

Computed using NDVI-Approach



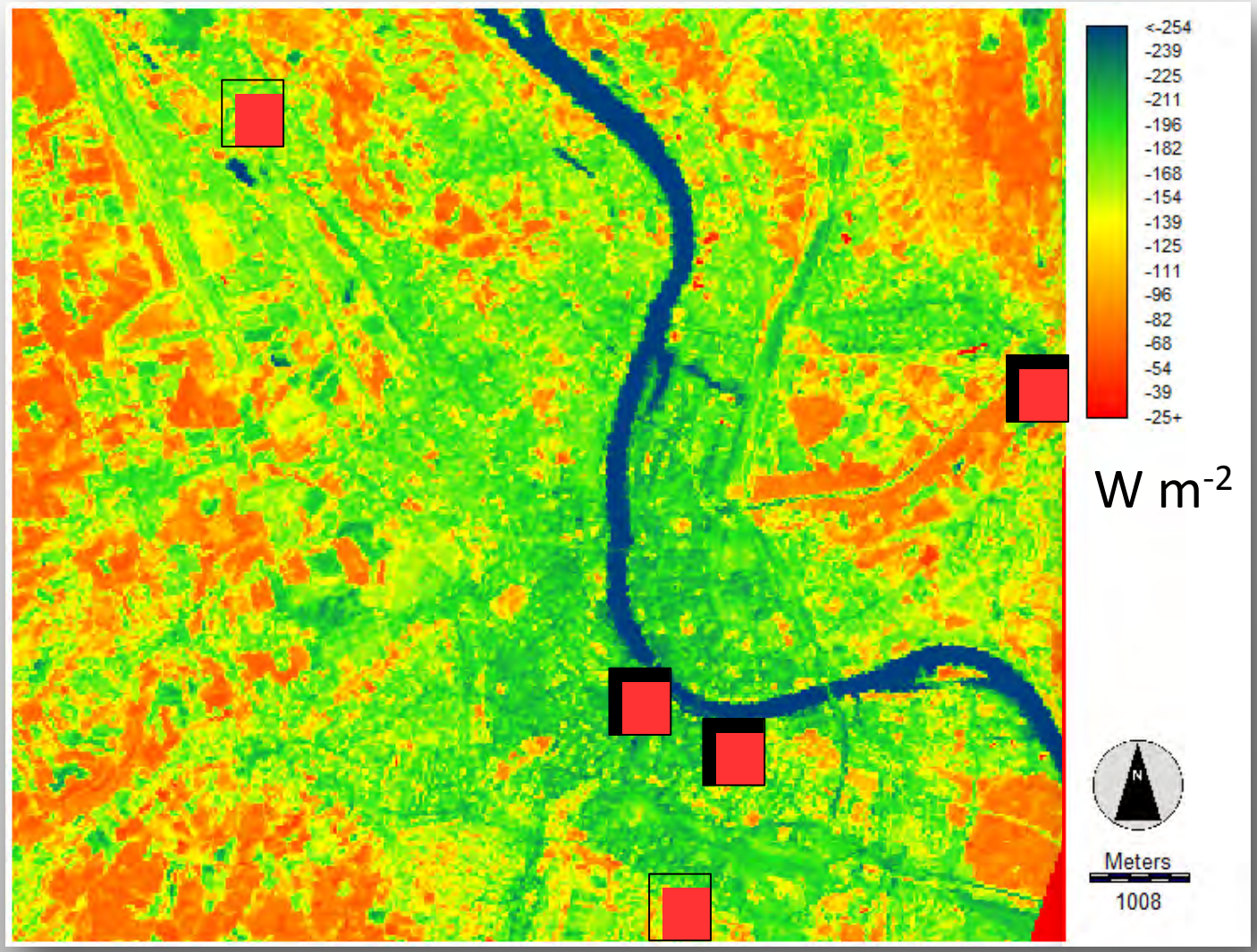
Latent heat flux (λE) during satellite overpass

computed using Bowen-Ratio-Method



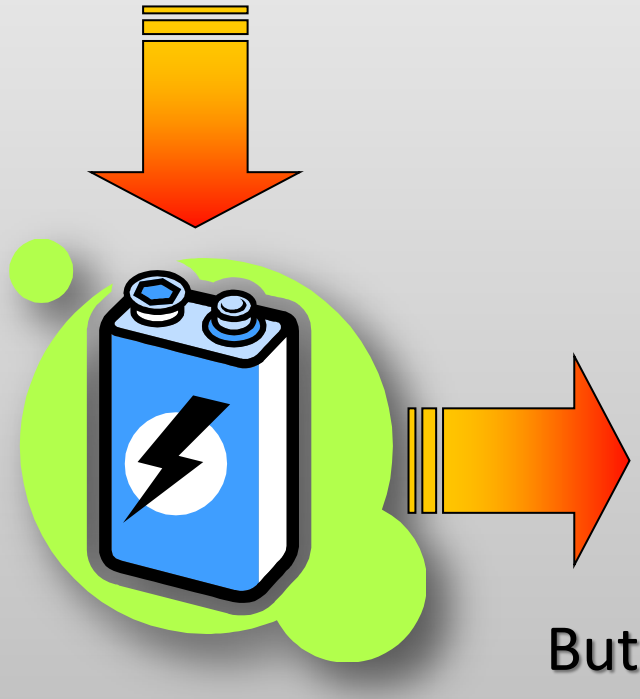
Sensible heat flux (H) during satellite overpass

computed using Bowen-Ratio-Method



Urban heat budget brought to the point

During daytime much of the received radiative energy is stored in the storage heat flux (building structure, concrete, asphalt). It is stored like in a battery and therefore is not fully available for the instantaneous sensible heat flux to increase air temperatures.

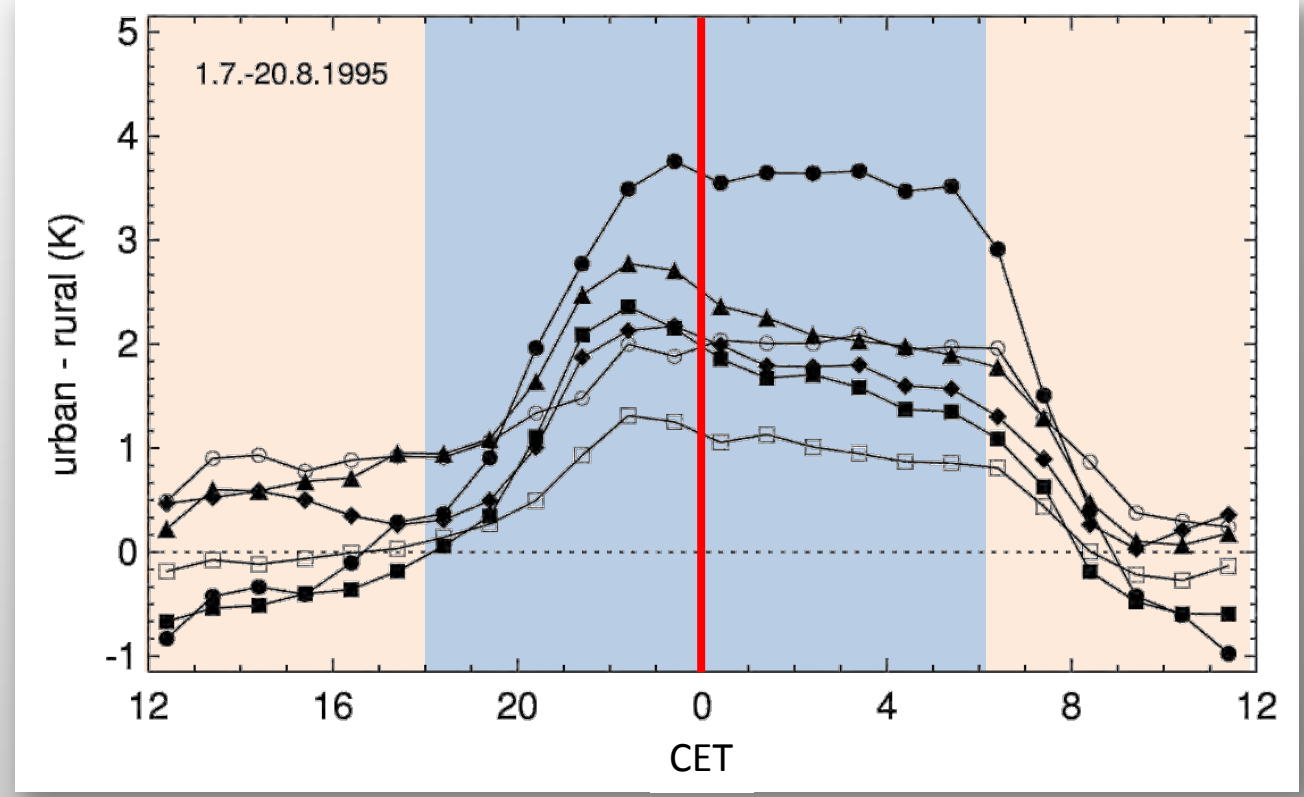


During night time this „battery energy “ is used to compensate negative net radiation at night and therefore reduces the decrease of night air temperature, resulting in higher night air temperature than at rural sites.

But what about vertical profiles of UHI and what can we learn from surface temperatures ?

Mean diurnal course of temperature differences (urban – rural)

between urban station Basel Spalenring (BSPA) and two rural stations Fischingen (FISG) and Lange Erlen (BLER) at different heights



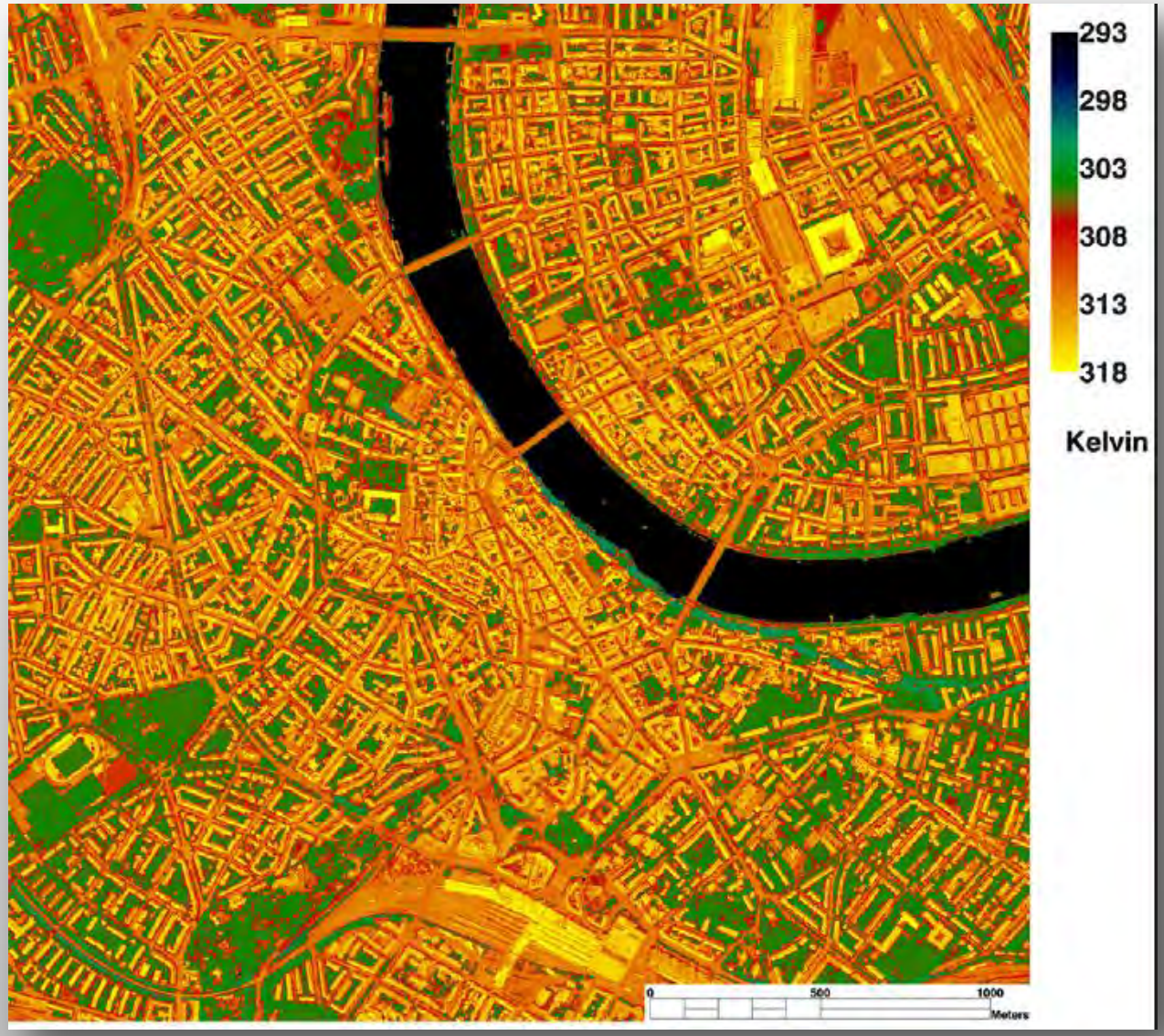
The UHI intensity is strongly influenced by measurement height:
See :
○● comparison or
□■ comparison

!!! Night is centered in grafic !!!

_s = BSPA street side _h = backyard

○ = BSPA_4m_s - FISG_10m
□ = BSPA_33m - BLER_10m
▲ = BSPA_4m_s - BLER_2m
● = BSPA_4m_s - FISG_2m
■ = BSPA_33m - BLER_2m
◆ = BSPA_2m_h - BLER_2m

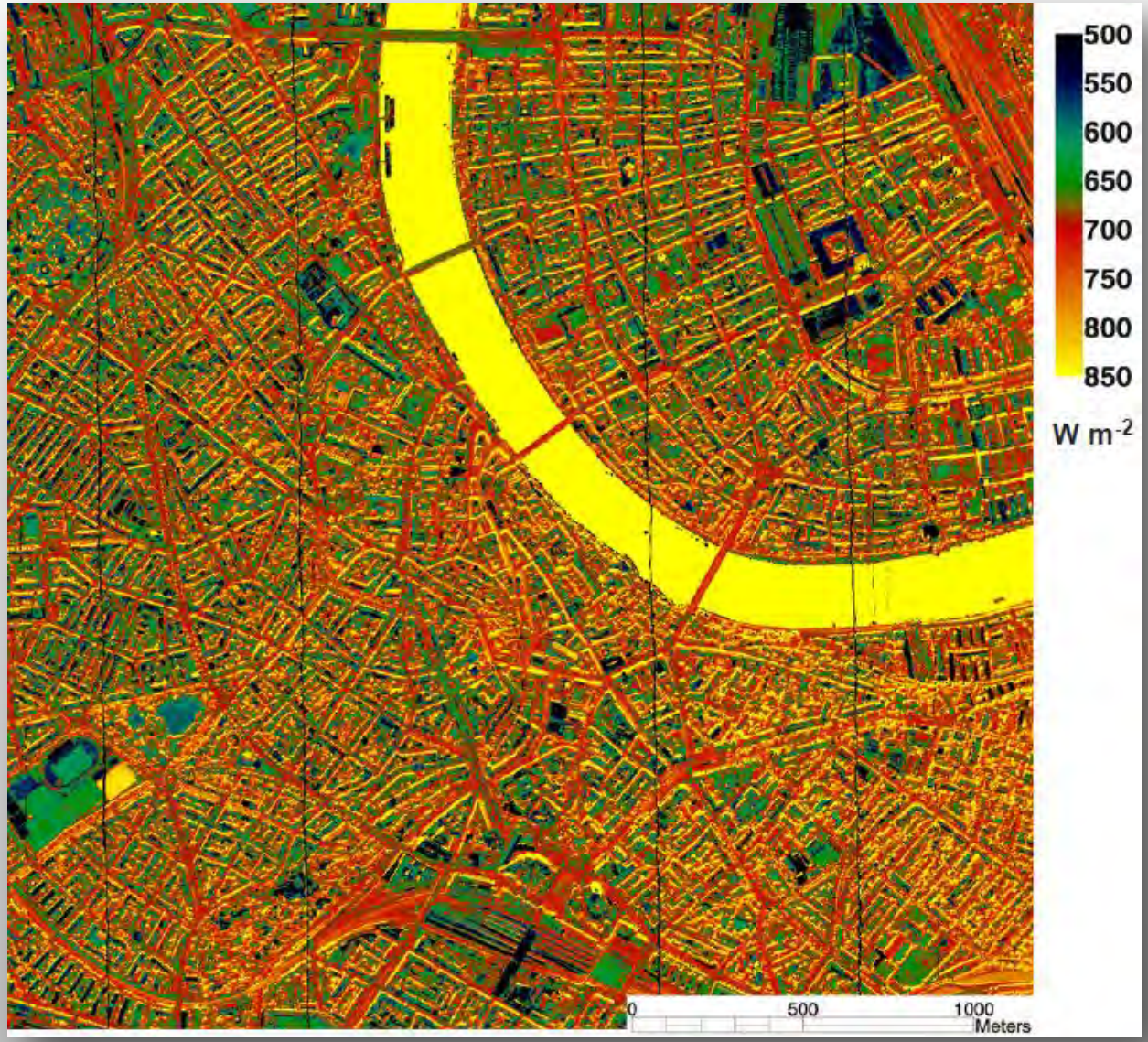
Surface temperatures: helicopter flight (1 m pixel)



This pixel resolution gives a much more detailed spatial difference of which surface types contribute to the SUHI.

The most dominant contribution to the surface temperatures pattern comes from the roofs of the buildings.

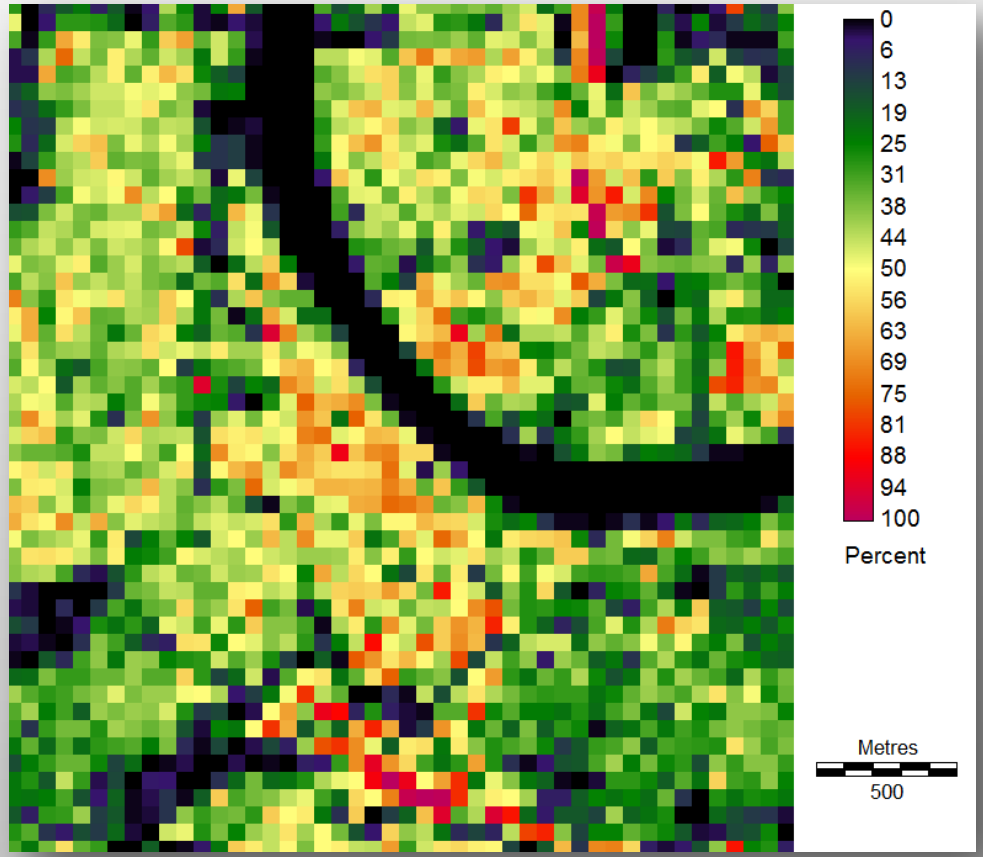
Net radiation in 1 m resolution



High resolution net radiation computed from hyperspectral airborne remotely sensed data during APEX-flight campaign, helicopter-borne TIR-data and numerical models.

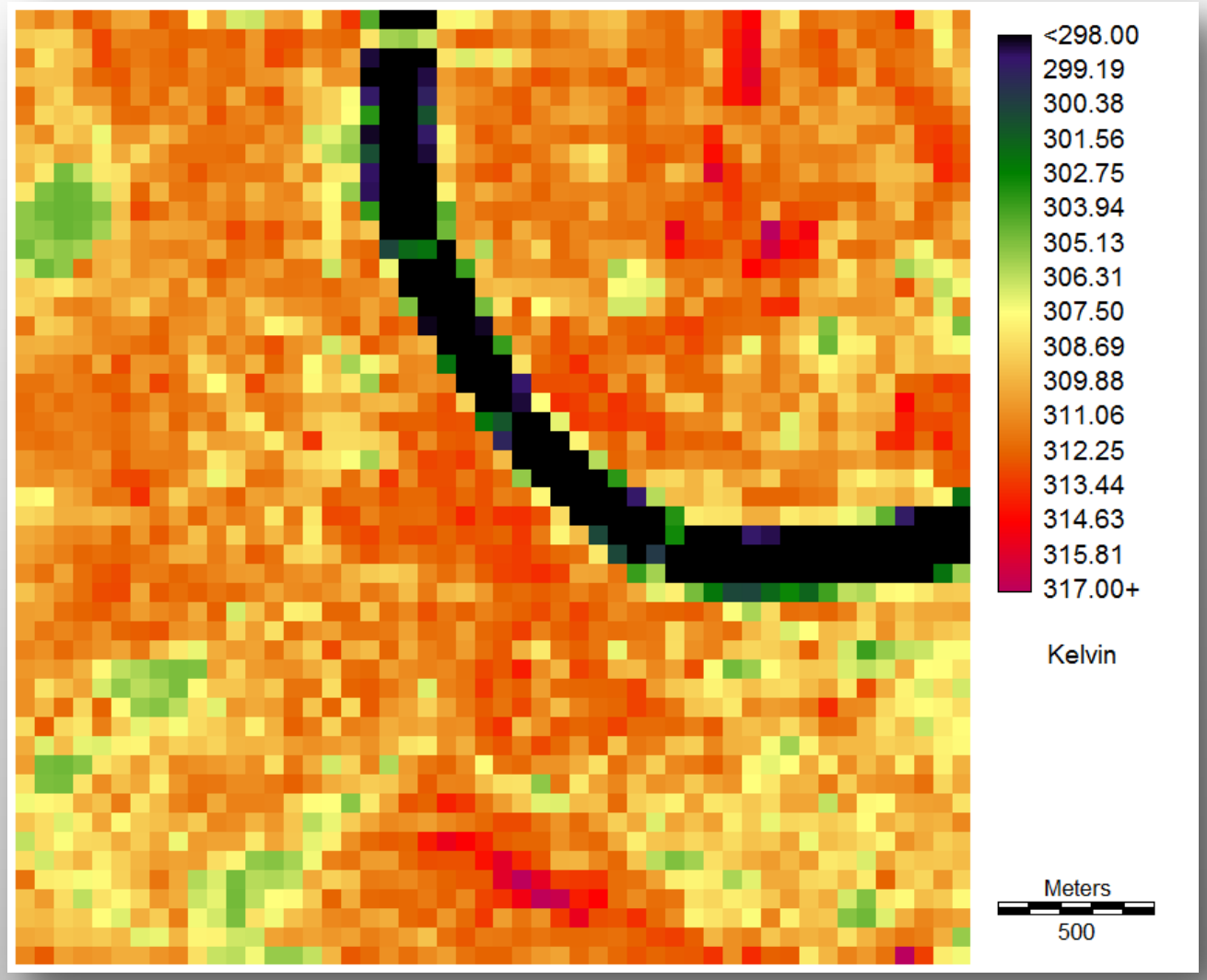
Buildings from digital surface model (1m resol.) and % of roof pixels in a Landsat-ETM TIR-pixel (60 m resol.)

Building mask



% of roof pixels

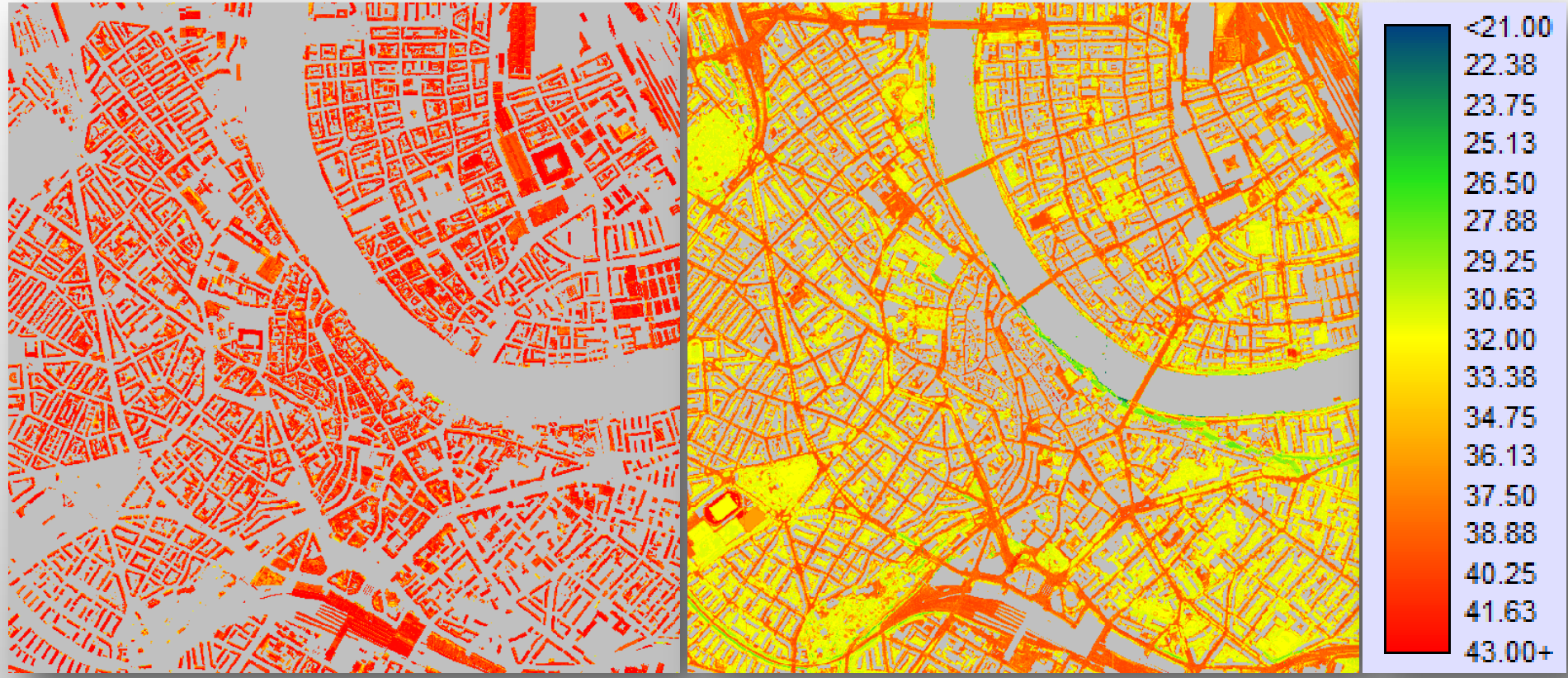
Simulated surface temperatures at Landsat resolution



When integrating 1-m-data to 60-m Landsat-ETM resolution a similar result as from satellite data can be obtained.
The analysis clear-ly shows that due to the coarse resolution satellite data are biased by roof temperatures.

Parlow, Vogt & Feigenwinter, Erde (2014)

Surface temperatures at roof and ground level



T_s roof level

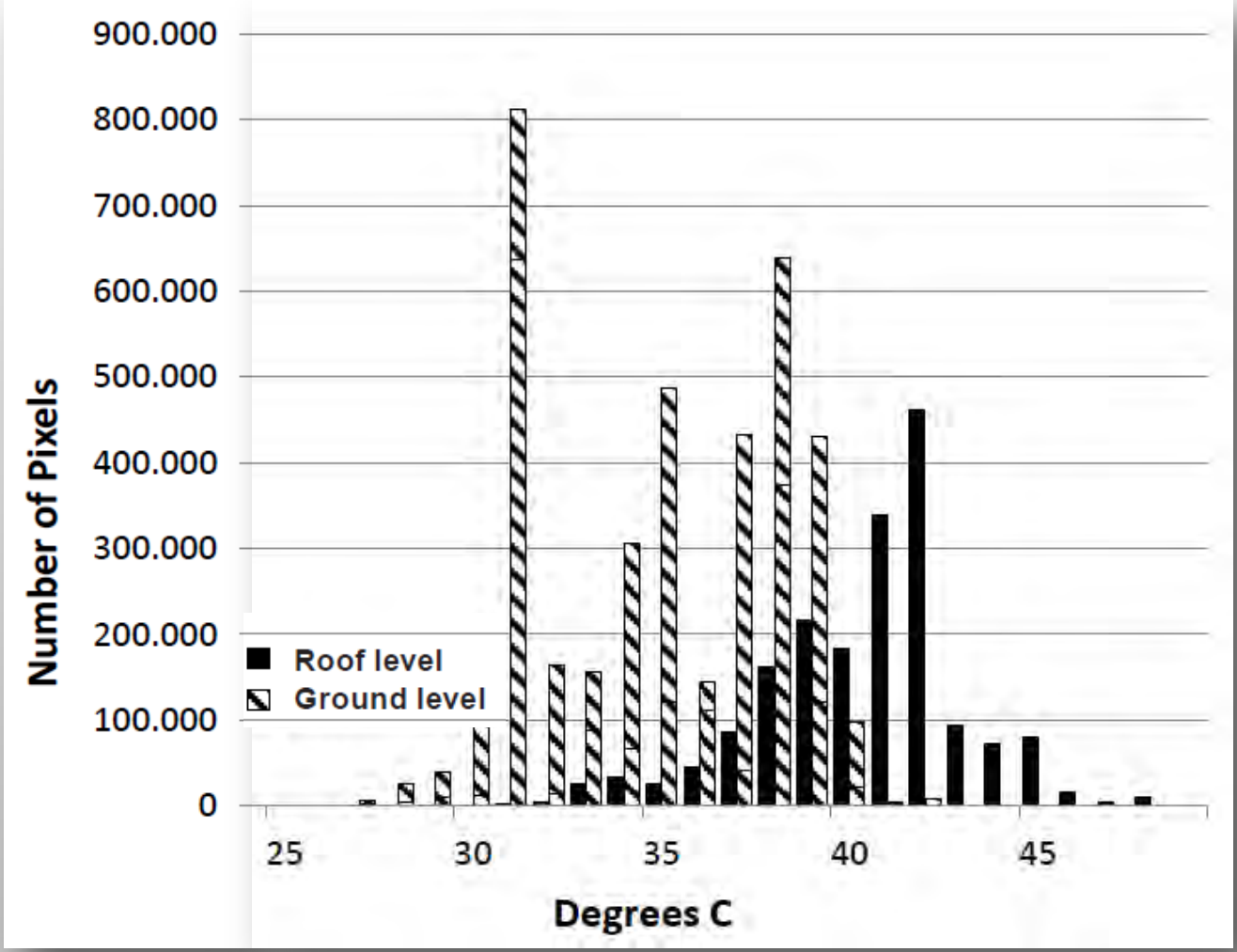
T_s ground level

The surface temperatures at roof level are higher than at ground level.

BUT: The air temperatures at ground level are higher than at roof level.

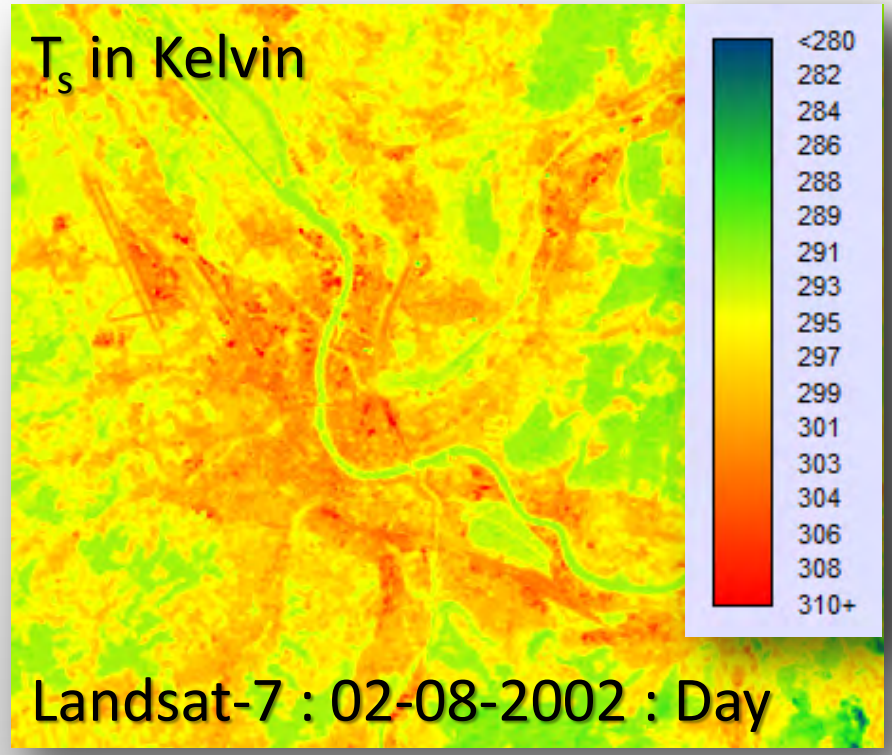
The SUHI is completely de-coupled from the air temperatures !!!!!

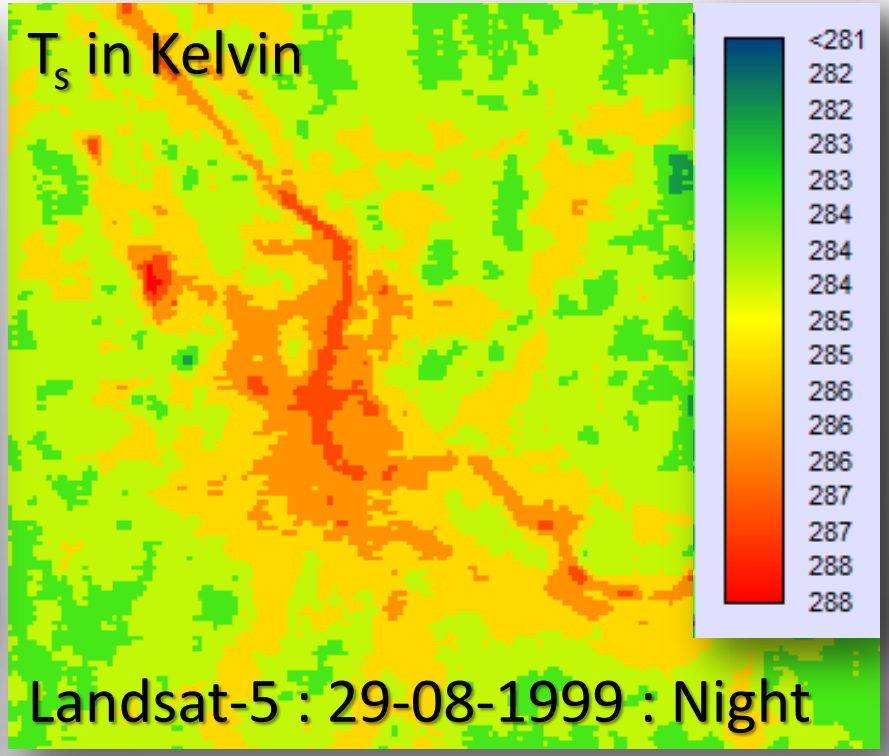
Surface temperatures at roof and ground level



The data range at roof level is much higher compared to ground level. The mean shift is about 5 – 6 Kelvin.

Conclusion: LST at day- & nighttime from Landsat-5/-7





At day the high T_s of urban areas does NOT indicate the UHI rather than an extreme storage heat flux of 30 – 50 % of day net radiation into the urban fabrics which cannot be used for sensible heat fluxes at that time of day.

At night Landsat shows the UHI !! Net radiation is very negative due to high T_s & is fully compensated by storage heat flux. Sensible heat flux is not needed for net radiation compensation -> higher air temperatures!!

Lessons learned :

- There are different types of «urban» heat islands existing:
- UHI (urban heat island) refers to the difference of air temperatures between an urban and a rural site and is mostly developed during night time
- The higher night urban air temperatures are due to a full compensation of negative net radiation by huge storage heat flux accumulated in the urban fabrics during day
- Depending on measurement height often an urban «cooling island» can be detected.
- When an UHI develops during daytime then it is most likely that the anthropogenic heat flux (AC or waste heat) plays an important role
- SUHI (surface urban heat island) refers to the surface temperature distributions and is developed during day AND night
- SUHI is strongly influenced by roof surface temperatures
- SUHI is mostly de-coupled from UHI and should not be mixed up

«An ideal site for urban people to survive the UHI»

Thank you for your attention !