The energy balance closure problem: An overview

Some new results – or a final discussion

Content

- Introduction
- The energy balance closure problem
- Investigations toward solving the problem
- The possible solution of the problem
- Consequences

The history

- First detection of an unclosed energy balance during experiments like FIFE and KUREX at the end of the 1980s
- Problem addressed during an EGS workshop 1994 at Grenoble/France (Foken & Oncley, 1975)
- Several experiments in the 1990s and overview papers like: Laubach & Teichmann (1996), Foken (1998), Wilson et al. (2002), Culf et al. (2004)
- Pieces of the puzzle emerge in the 2000s

The problem

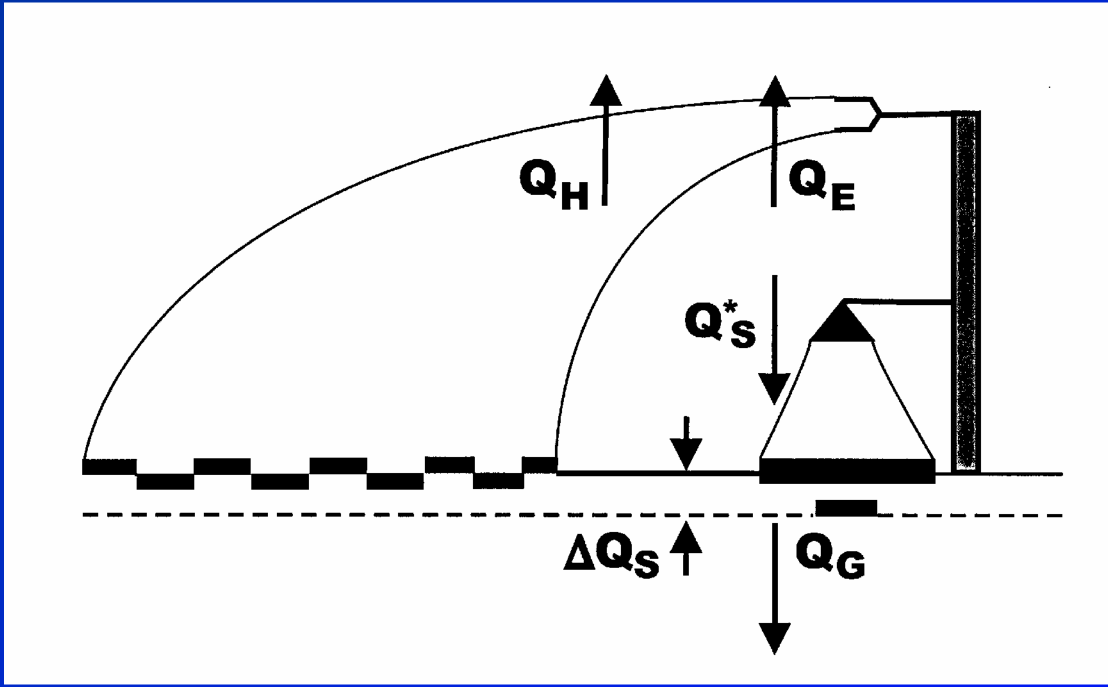
- The net radiation is always larger than the sum of the turbulent (sensible and latent) and ground heat flux

$$Q_s^* \geq Q_G + Q_H + Q_E$$

- Typical energy balance closure:

$$\frac{Q_G + Q_H + Q_E}{Q_s^*} \cdot 100\% = 70...100\%$$

The measurements



There is no balance layer !

Measurements cover an energy budget of a volume

The errors and scales

	Error in %	Energy in W m^{-2}	Horizontal scale in m	Height in m
Latent heat flux	5-20	20-50	100	2-10
Sensible heat flux	5-20	10-30	100	2-10
Net radiation	5-20	20-100	10	1-2
Ground heat flux without storage	20-50	20-50	0.1	-0.02 – -0.1
Storage term	20-50	20-50	0,1 – 1	-0.02 – -0.1

© Foken (1998)

Including a storage term (+ advection):

$$Q_s^* \geq Q_G + Q_H + Q_E \pm \Delta Q$$

The findings (low vegetation)

Experiment	Reference	Residual	Surface
Müncheberg 1983 and 1984	Koitzsch et al. (1988)	14	Winter wheat
KUREX-88	Tsvang et al. (1991)	23	Different agricultural fields
FIFE-89	Kanamasu et al. (1992)	10	Step
TARTEX-90	Foken et al. (1993)	33	Barley and bare soil
KUREX-91	Panin et al. (1998)	33	Different agricultural fields
LINEX-96/2	Foken et al. (1997)	20	High grass
LINEX-97/1	Foken (1998)	32	Short grass
LINEX-98	Beyrich et al. (2002)	37	Bare soil

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© Foken (2003) [Angew. Meteorologi Springer]

Different interpretation of this data set:

Panin et al. (1998):

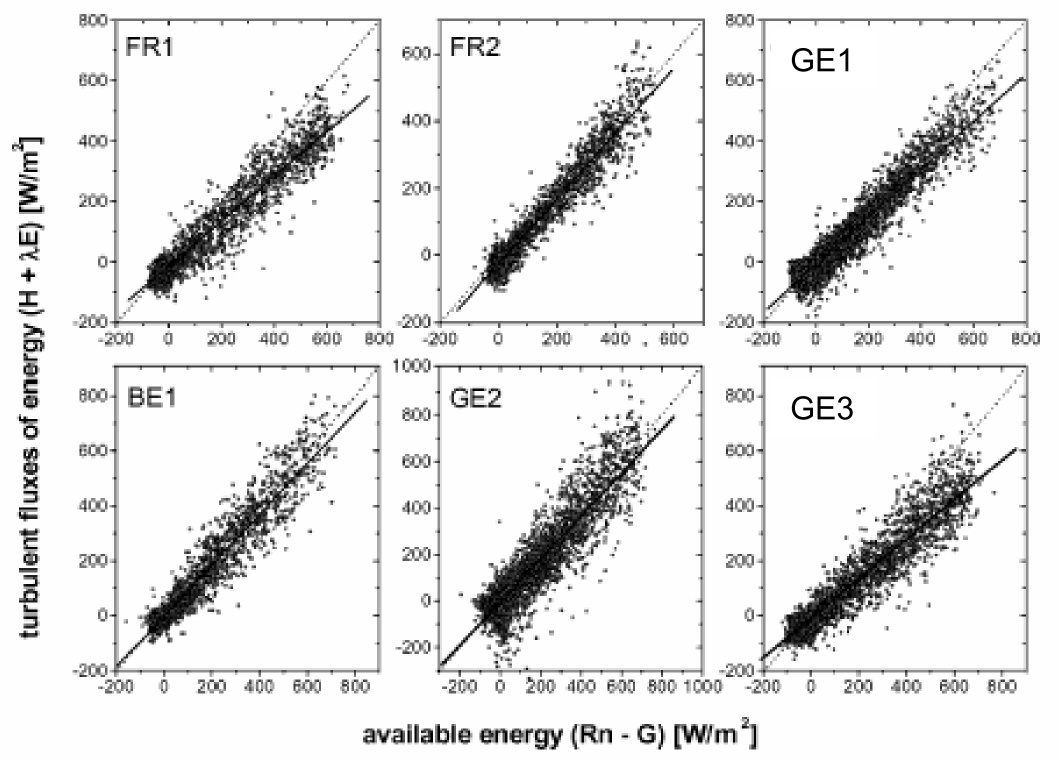
$$Q_s * - Q_G = k\left(Q_H + Q_E\right)$$

k: Factor of heterogeneity

Foken (1998):

Residuum depends on the degree of soil exposure

The findings (tall vegetation)



Station	Closure	Footprint
BE1	92 %	Class 1
GE2	92 %	Class 1
FR2	89 %	Class 2
FR1	71 &	Class 2
GE1	≈75 %	Class 2

Class 1: > 90 % of the data are within the footprint threshold (80 % of the target area)
Class 2: > 60 % to 90 %

© Aubinet et al. (2000) [Adv. Ecol. Res. 30: 113-175.]
Göckede et al. (2004, 2006)
Foken et al. (2006)

The main reasons for energy balance un-closure

i. Measurement errors, especially those relating to the eddy-covariance technique

ii. Different balance layers and scales of diverse measuring methods, as well as the energy storage

iii. Advection and fluxes due to longer wave lengths

i Measurement errors

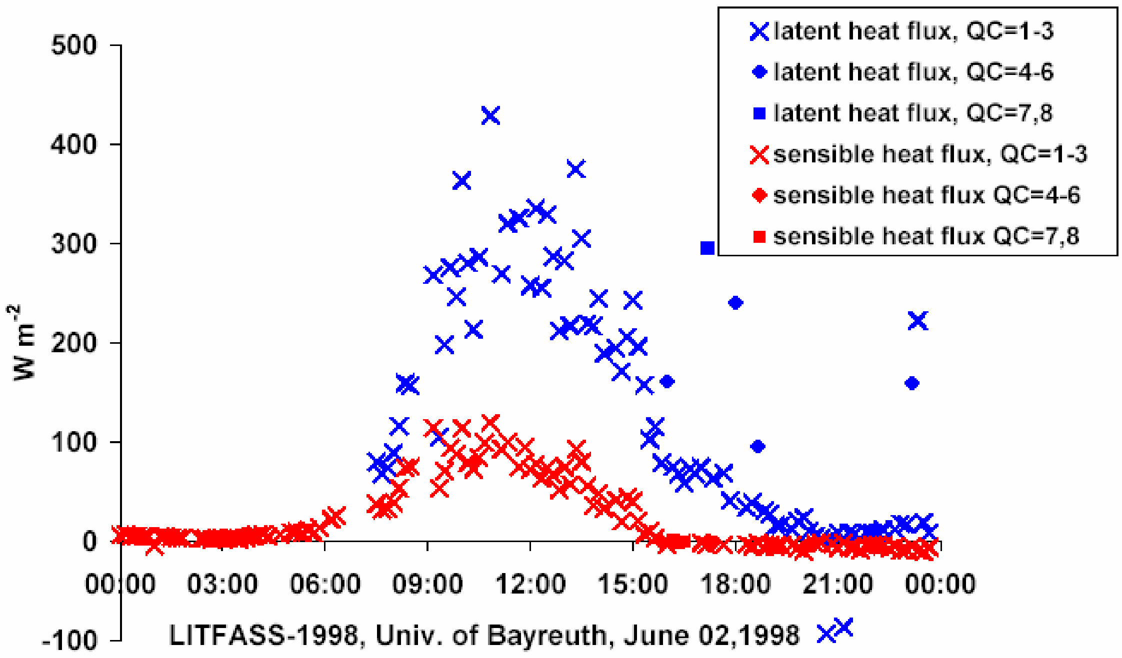
Eddy-covariance technique is well-established (new sensors in the last ten years) and data quality can be checked.

From intercomparison experiments during EBEX-2000 and LITFASS-2003 follows:

anemometer	quality class	sensible heat flux	latent heat flux
Type A, e.g. CSAT3	1-3	5% or 10 W m^{-2}	10% or 20 W m^{-2}
	4-6	10% or 20 W m^{-2}	15% or 30 W m^{-2}
Type B, e.g. R3	1-3	10% or 20 W m^{-2}	15% or 30 W m^{-2}
	4-6	15% or 30 W m^{-2}	20% or 40 W m^{-2}

© Mauder et al. (2006), [Boundary-Layer Meteorol., revise

i Measurement errors



Data quality can be checked.

But: Energy balance closure is not a quality control!

© Foken & Wichura (1996)
Foken et al. (2004)

i Measurement errors

Raw data

Spike detection

Maximum of covariances

Coordinate transformation

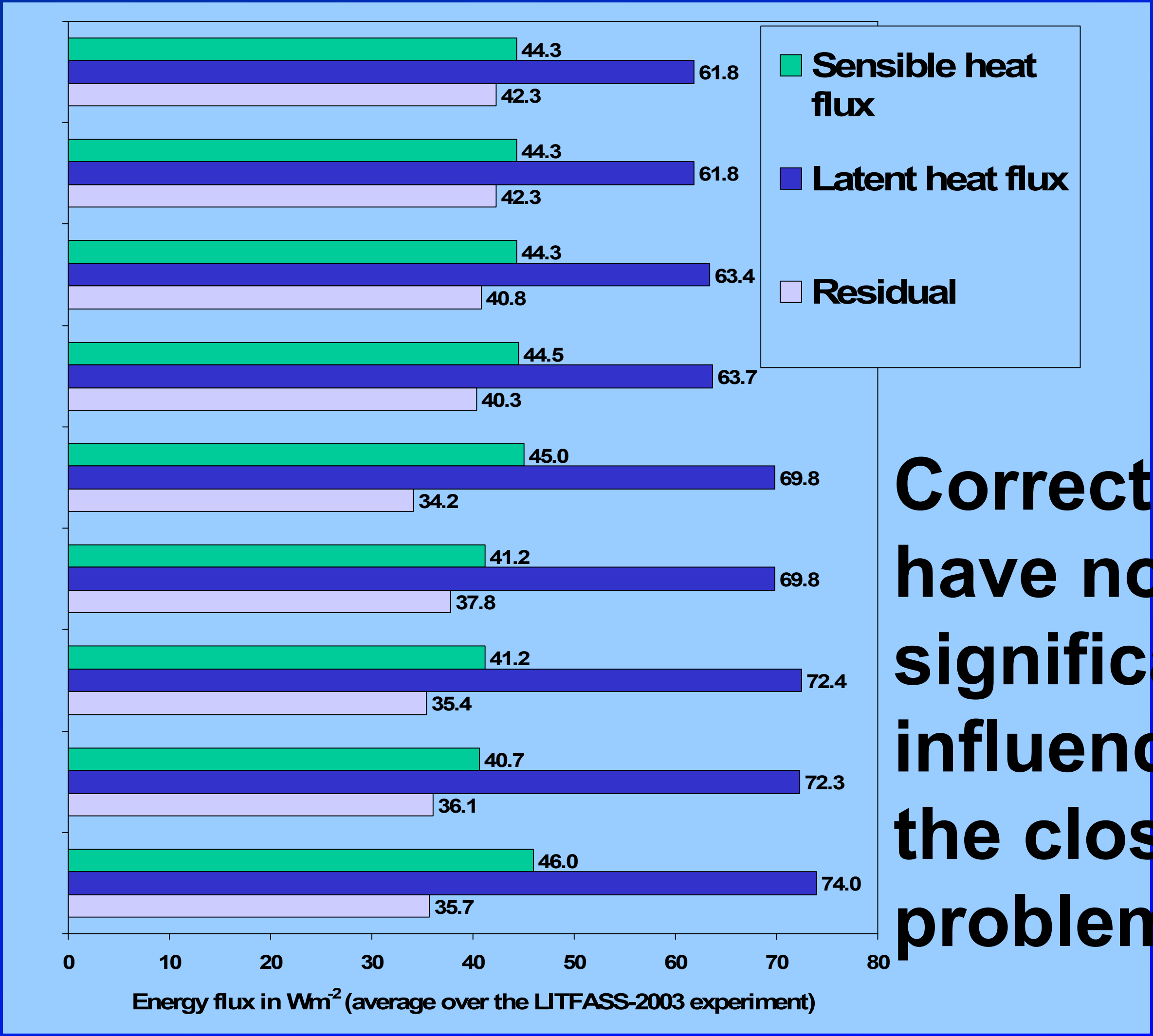
Spectral corretion

Buoyancy to sensible flux

WPL correction

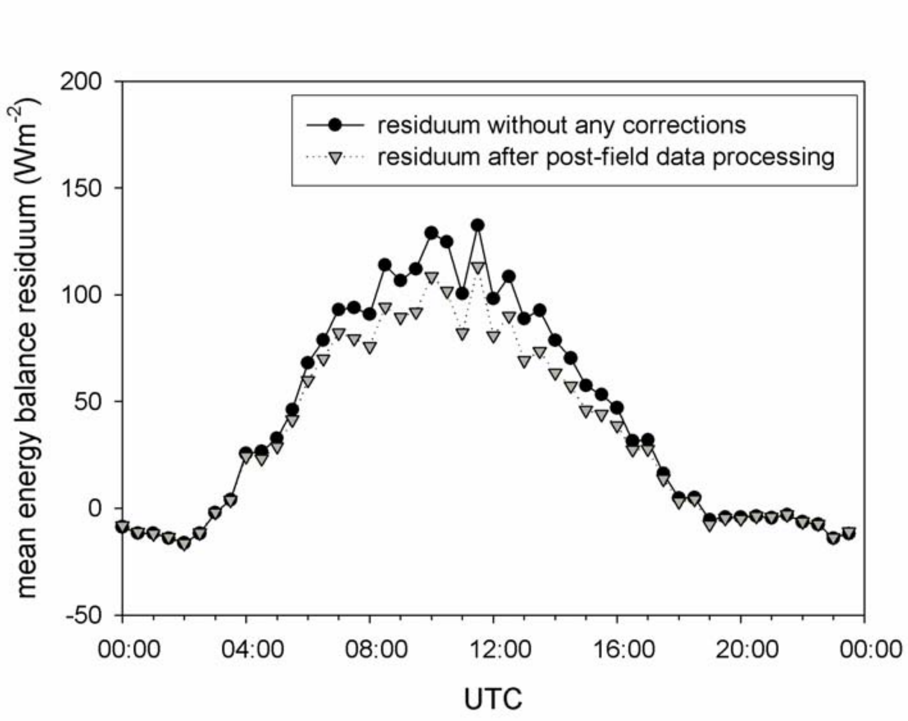
Iteration of all corrections

Quality check



Corrections have no significant influence on the closure problem.

i Measurement errors



The transformation of the buoyancy flux into the sensible heat flux and the transformation of the latent heat flux (CO_2 flux) due to density fluctuations can impact the flux to some degree but doesn't significantly influence the closure problem

LITFASS-2003 Experiment, maize, 6 weeks average
© Mauder & Foken (2006), [Meteorol. Z., submitted]

i Measurement errors

The accuracy of radiation measurements has increased significantly in the last 15 years

Parameter	Sensor	Accuracy 1990 in W m^{-2}	Accuracy 1995 in W m^{-2}
Global radiation	Pyranometer	15	5
Solar radiation	Aktinometer, Sun photometer	3	2
Diffuse radiation	Shaded Pyranometer	10	5
Downwelling longwave radiation	Pyrgeometer	30	10

© Ohmura et al. (1998); WMO classification of pyranometers (Brook & Richardson, 2001)

i Measurement errors

Typical accuracy of net radiometers (EBEX-2000)

Type	Sensor	Accuracy in %	Accuracy in $W\ m^{-2}$
Short wave	Eppley PSP	2	
	Kipp&Zonen CM11, CM 21	1	
Long wave	Eppley PIR		5
Net radiation	Kipp&Zonen CNR1		20
	REBS Q*7		(20)
	Schulze-Däke		10

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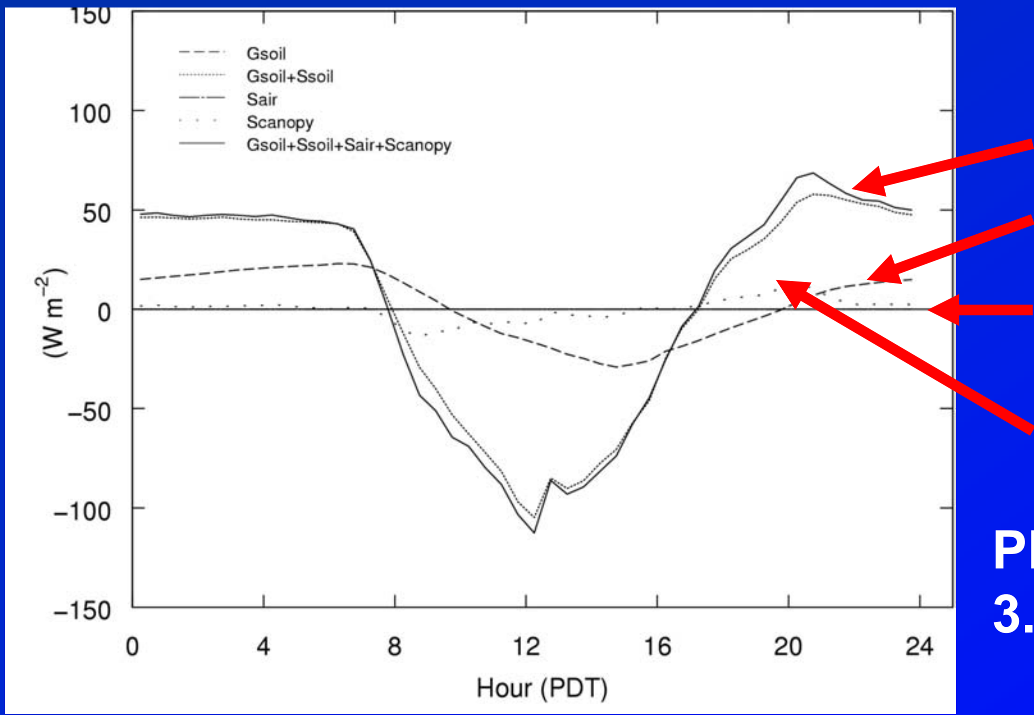
ii Energy storage

The energy storage in the air and the plants are very small

EBEX-2000: cotton

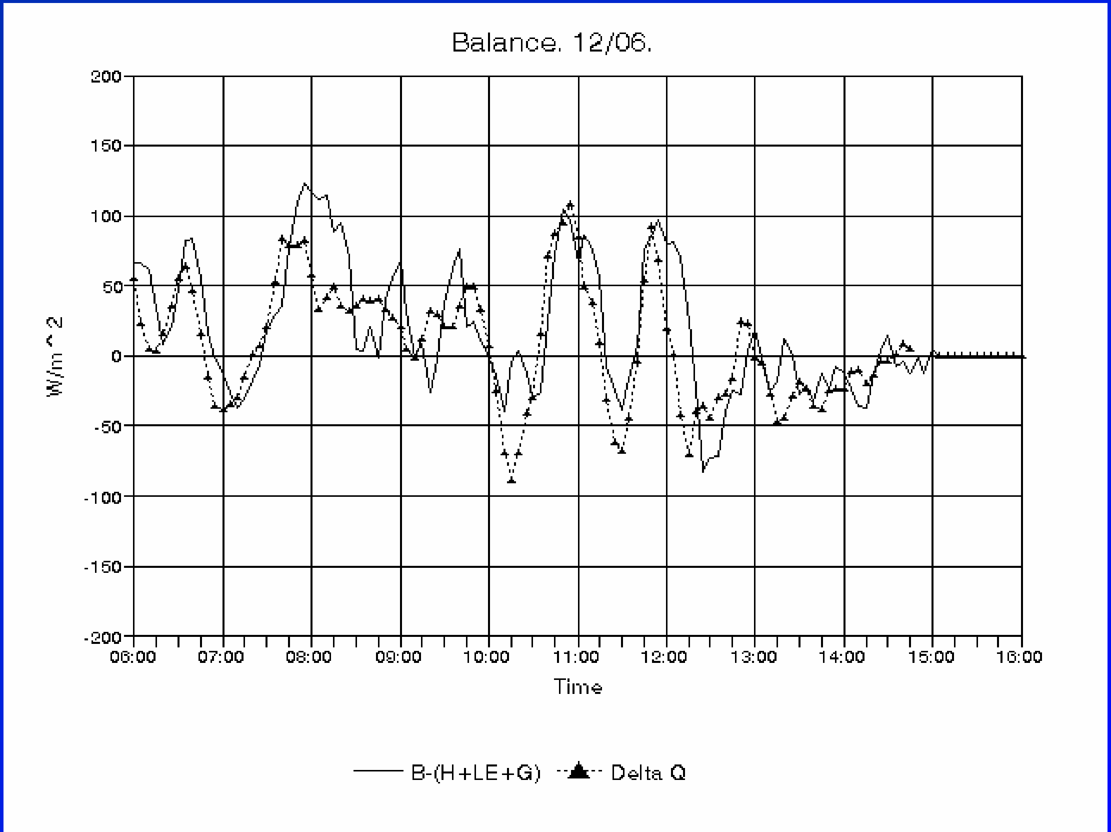


Photosynthesis:
3.8 Wm^{-2}, Max. 12 Wm^{-2}

© Oncley et al. (2006)
[Boundary-Layer Meteorol., submitte

ii Energy storage

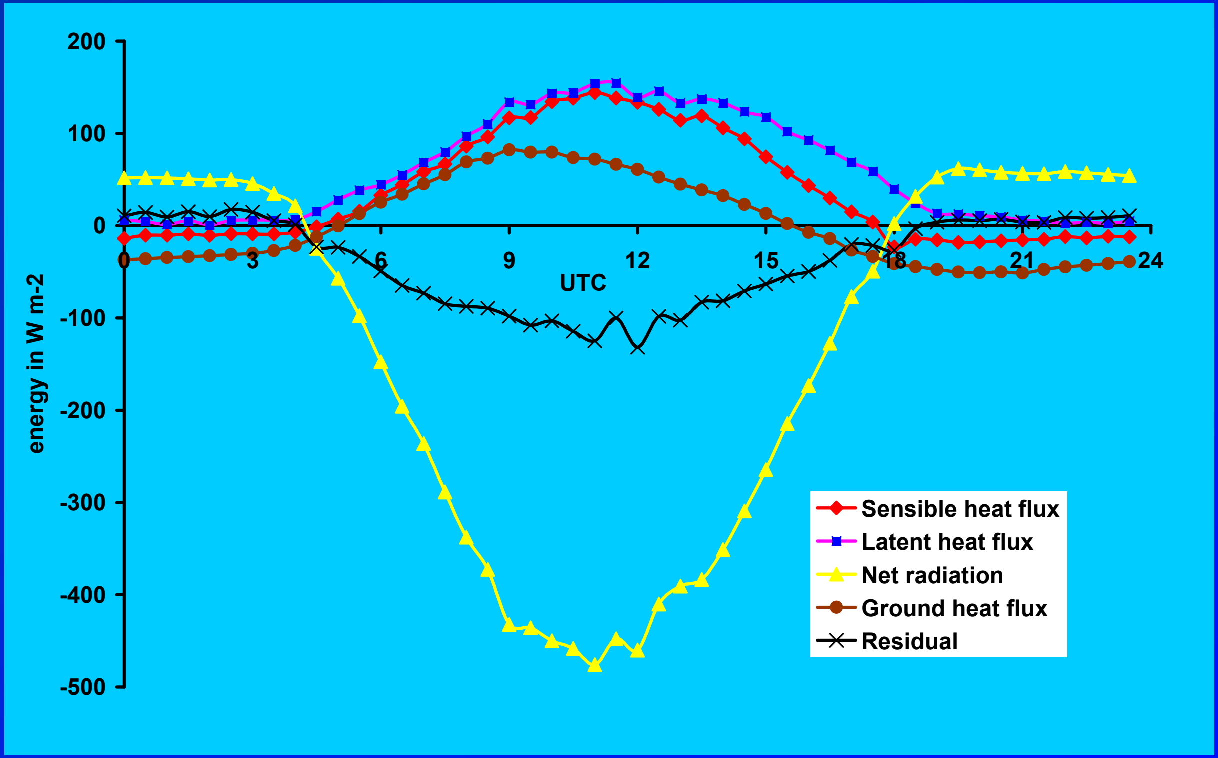
The only relevant storage term is the heat storage in the soil with some relation to the closure problem



© Kukharez et al. (1998, 2000) [German Meteorological Service]

ii Energy storage

With an accurate determination of the ground heat flux at the surface the energy balance can be closed for non-turbulent cases at night.

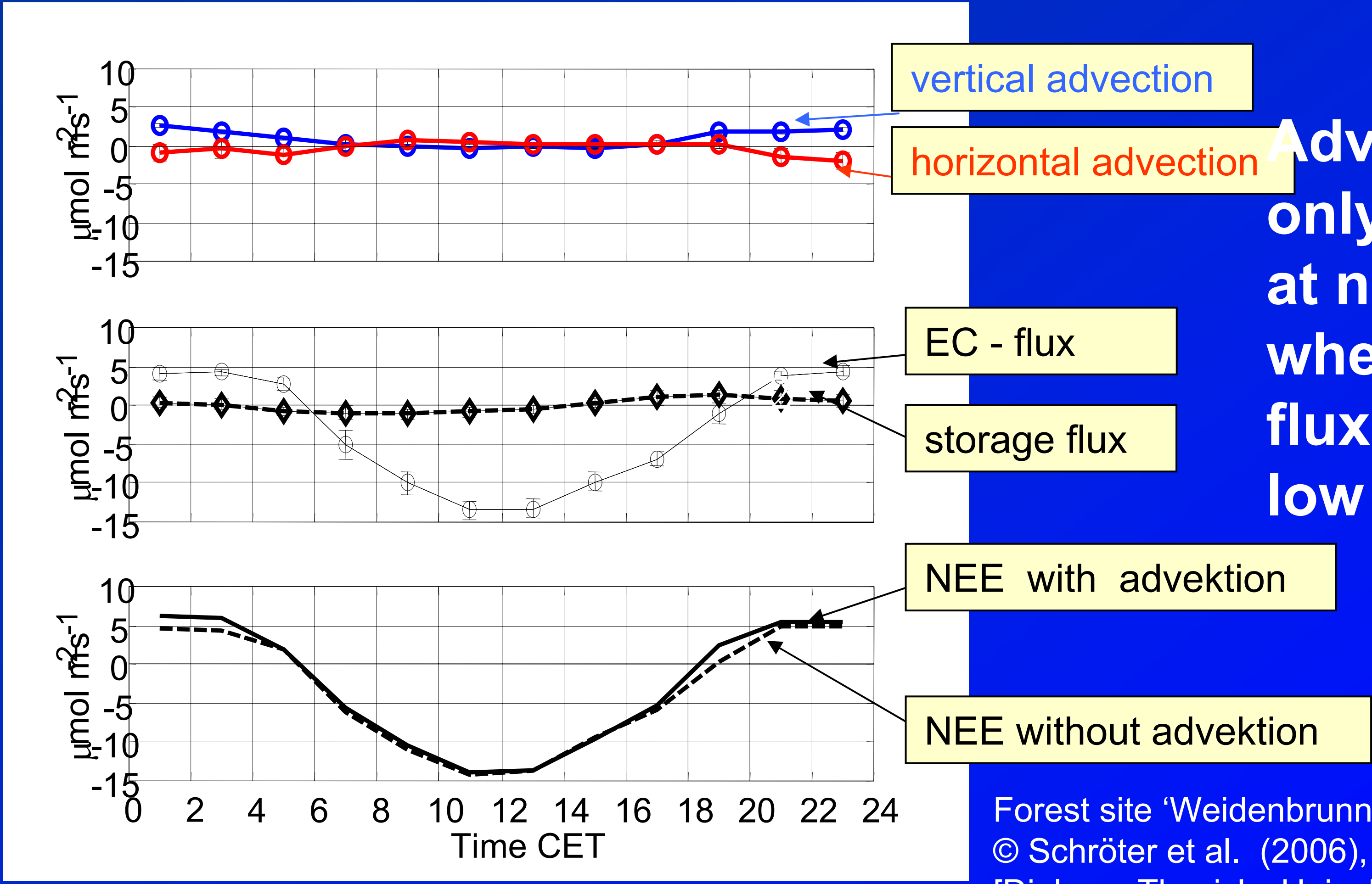


© LITFASS-2003, maize
Liebethal et al. (2005, 2006)
[Agric. Forest Metreorol., submitted]

iii Longer wavelengths

- The heterogeneity of the fields (Panin et al., 1998, see above)
- Advection (Aubinet et al., 2003, Lee, 1998)
- Coherent structures contribute appr. 20 % to the flux but are measured with EC (Thomas & Foken, 2006)
- Ogive functions can correct parts of longer wavelength (up to 2 hours) but cannot close the energy balance (Foken et al., 2006)
- Long-term integration (Finnigan et al., 2003)
- Turbulent Organized Structures (Kanda et al., 2004)

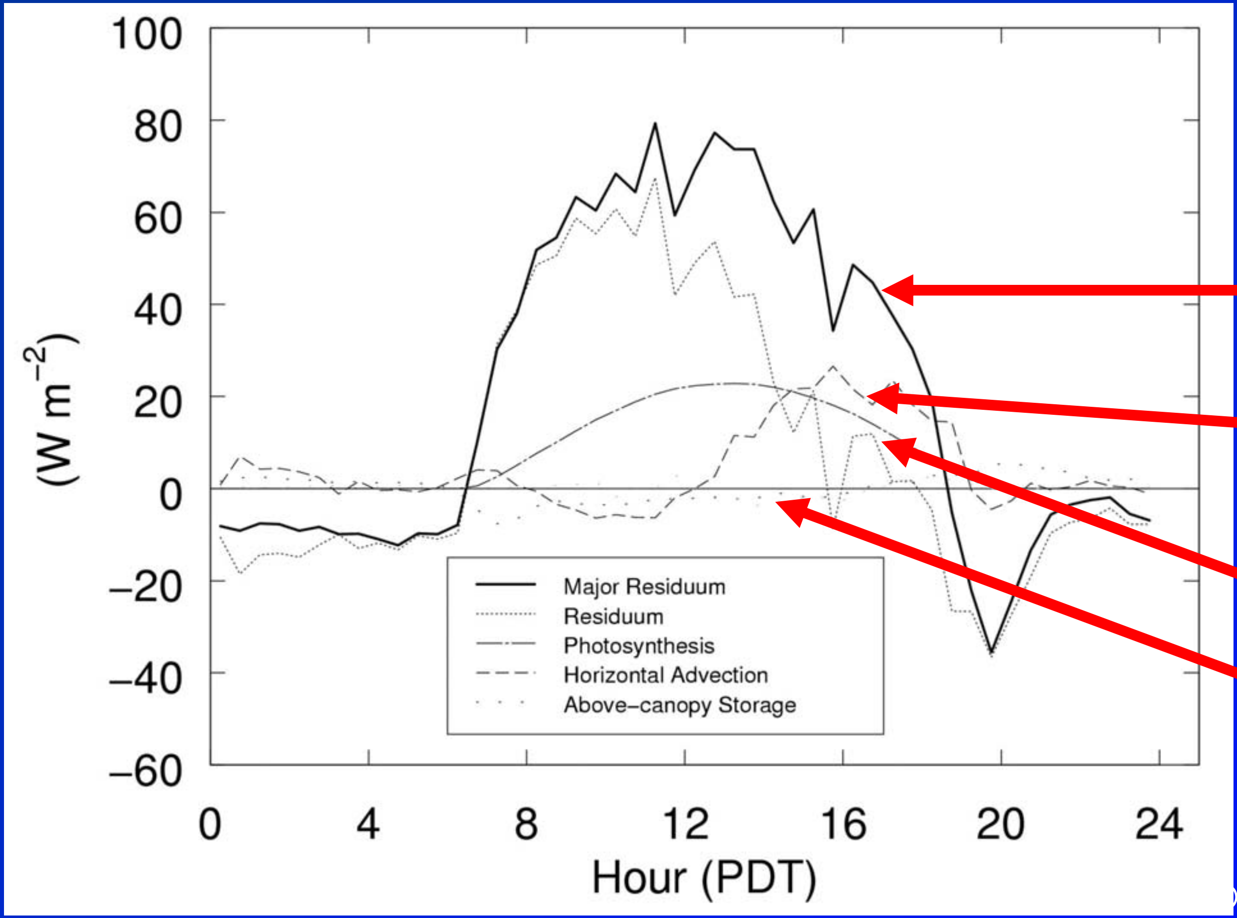
iii Energy advection



Advection is only relevant at night, when energy fluxes are low

Forest site 'Weidenbrunnen' Germany
© Schröter et al. (2006), see Poster
[Diploma Thesis's, Univ. Bayreuth, 2005]

iii Energy advection



For EBEX-2000 horizontal advection was found to be an important factor

Residual

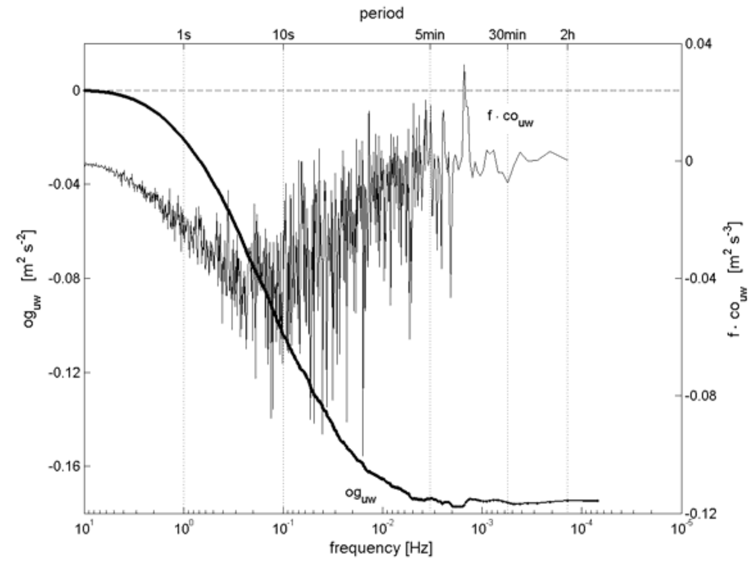
Horizontal advection

Photosynthesis

Canopy storage

Oncley et al. (2006) [Boundary-Layer Meteorol., submitt

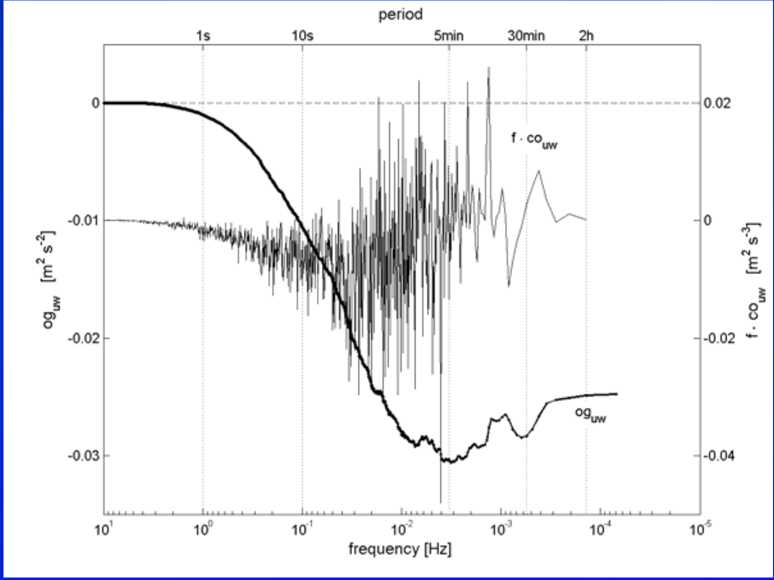
iii Ogive test

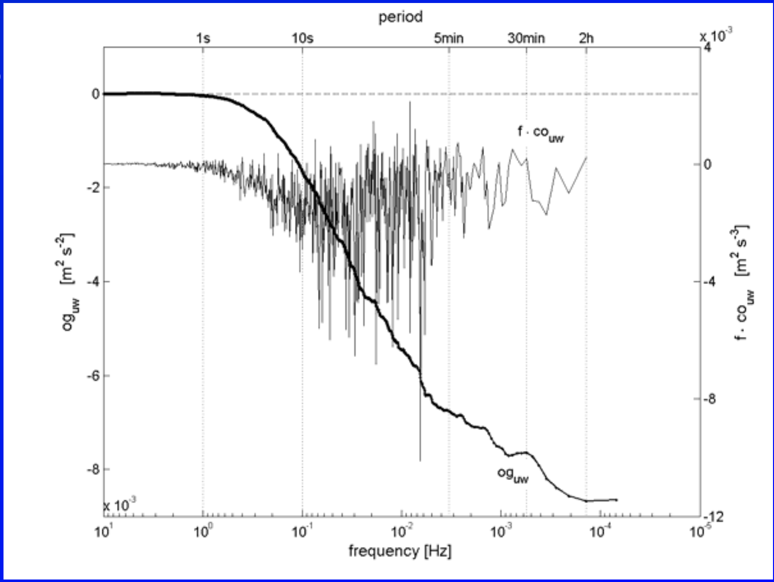


Case 1

Case 2

Case 3





$$og_{w,x}(f_0) = \int_{\infty}^{f_0} Co_{w,x}(f)\, df$$

© Oncley et al. (1990)
Foken et al. (2006) [Atm. Chem. Phys., submitted]

iii Ogive test

	Case 1	Case 2	Case 3
Ogive og_{uw}	85 (96 %)	3 (3 %)	1 (1 %)
Ogive og_{wT}	77 (87 %)	4 (4 %)	8 (9 %)
Ogive og_{wa}	68 (76 %)	13 (15 %)	8 (9 %)
Ogive og_{wc}	75 (84 %)	7 (8 %)	7 (8 %)

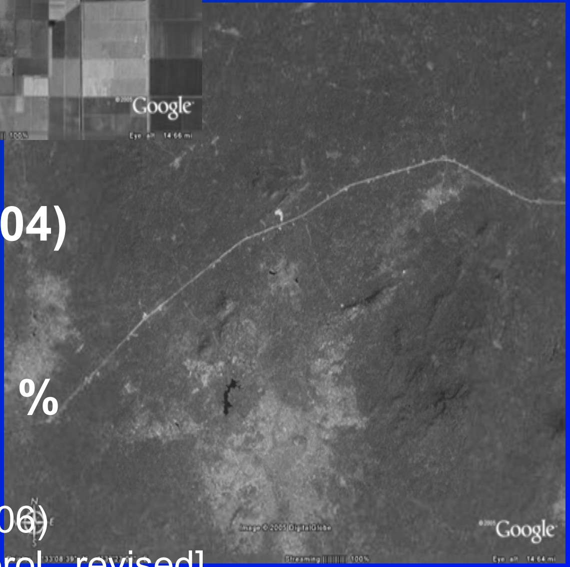
Forest site, similar results for agricultural site and African bush land.

Conclusions for the energy balance problem as a composite of all relevant results

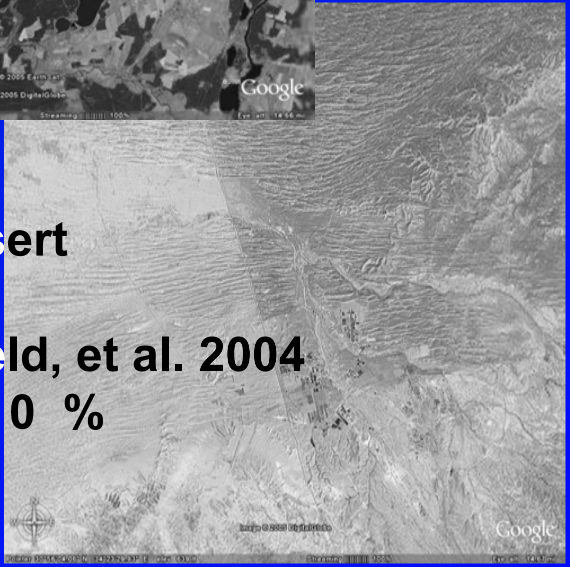
Finding 1: The influence of landscape on the closure

EBEX-2000
Experiment
U.S.A., CA
Residual: 10-15 %

LITFASS-2003
Experiment
Germany
Residual: 25-35 %



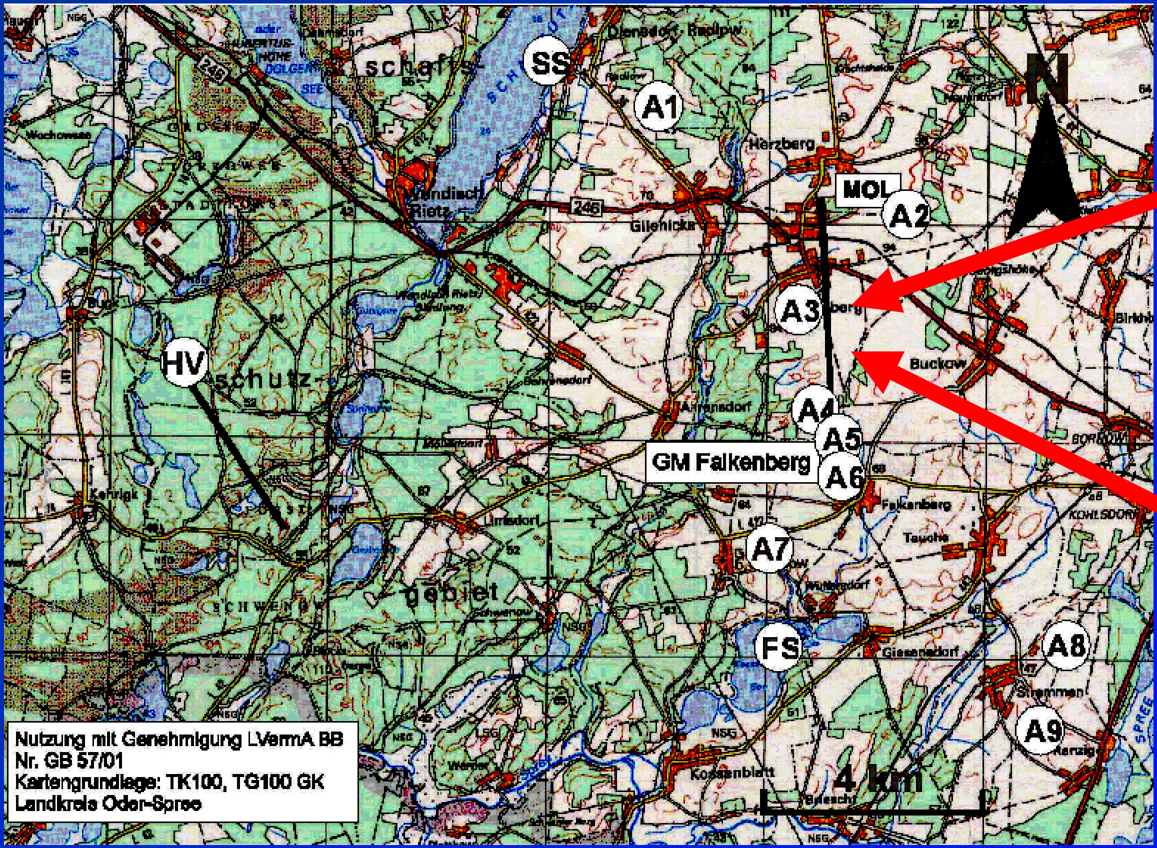
NIMEX-1 (2004)
Experiment
Nigeria
Residual: 0 %



Negev desert
Israel
Heusinkveld, et al. 2004
Residual: 0 %

© Mauder et al. (2006)
[Theor. Appl. Meteorol., revised]

Special findings for the LITFASS-2003 experiment

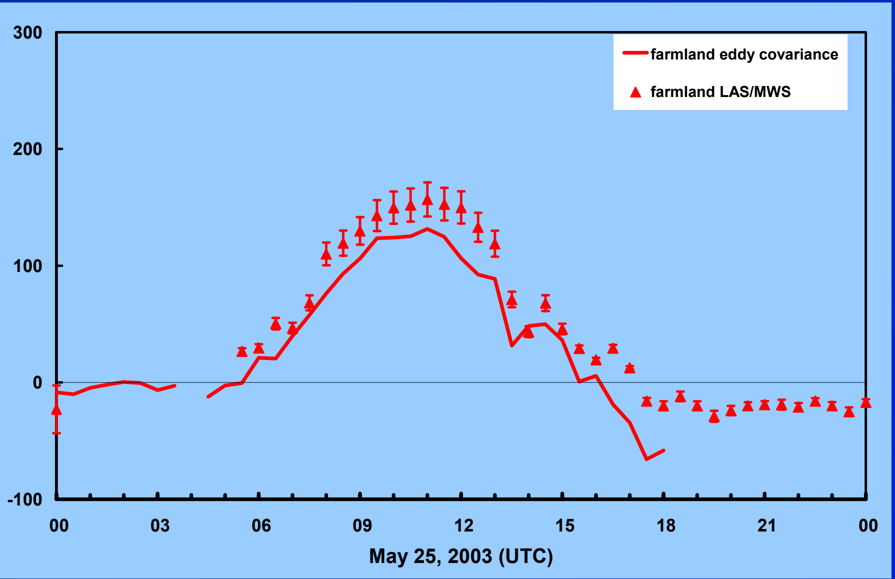


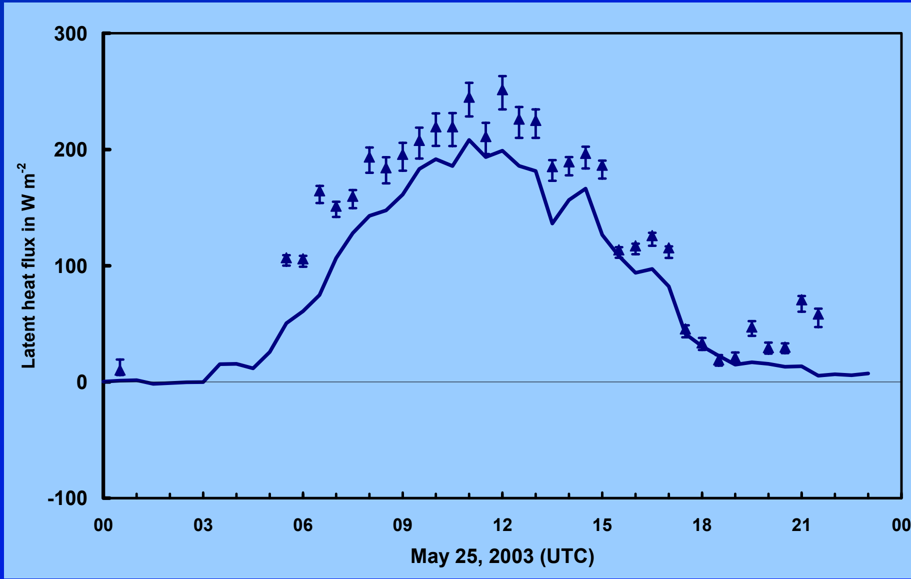
Large Aperture Scintillometer Path (approx. 5 km)

Line of 7 eddy-flux towers on agricultural fields

© Beyrich et al. (2006)
[Boundary-Layer Meteorol., accepted]

Finding 2: Area-integrated fluxes are larger than surface fluxes

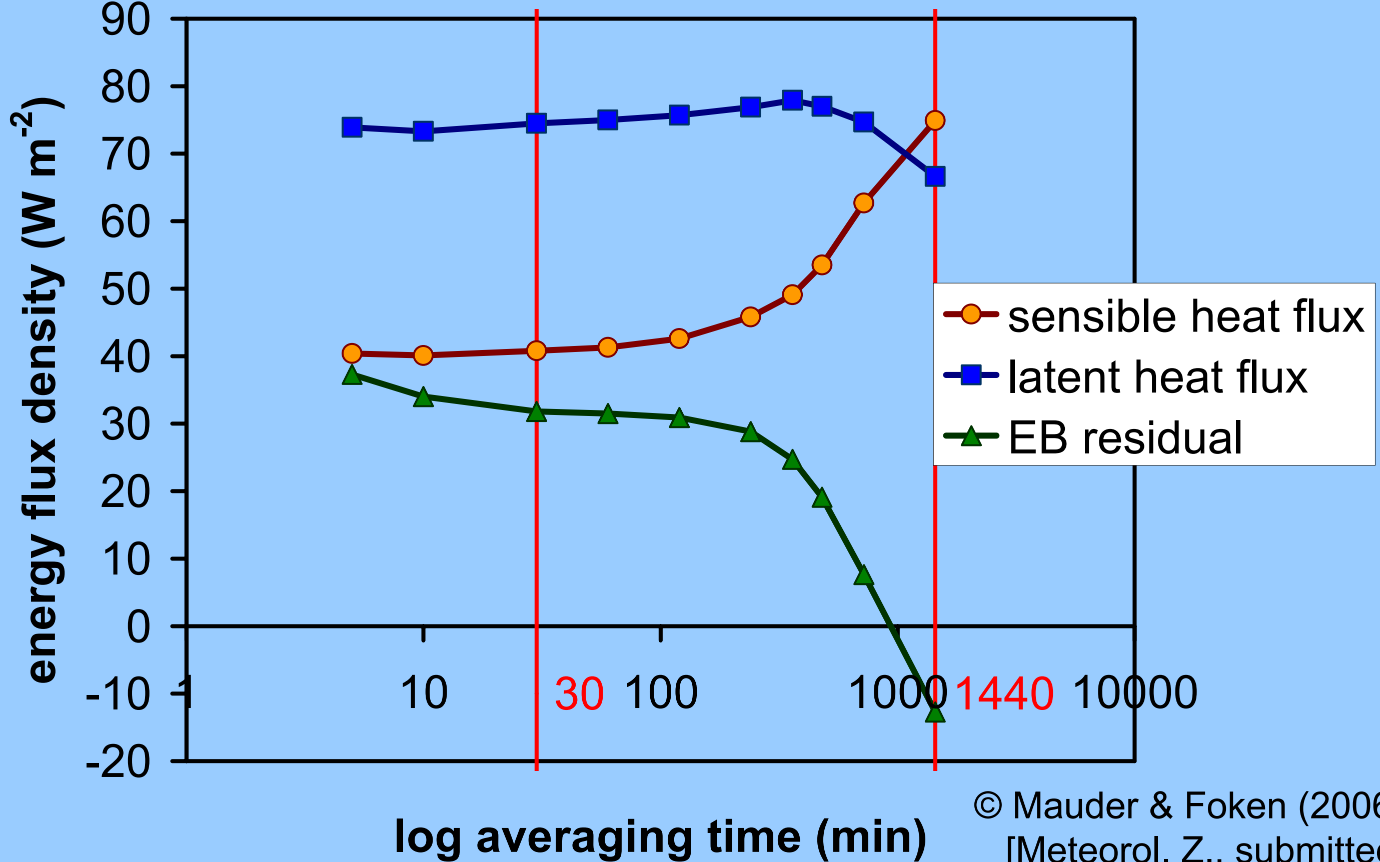




Fluxes measured with a Large Aperture Scintillometer over a horizontal path are larger than an area-average of turbulent fluxes measured with flux towers.

© Beyrich et al. (2006), [Boundary-Layer Meteorol., accepted]

Finding 3: Long time integrated fluxes reduce the residual

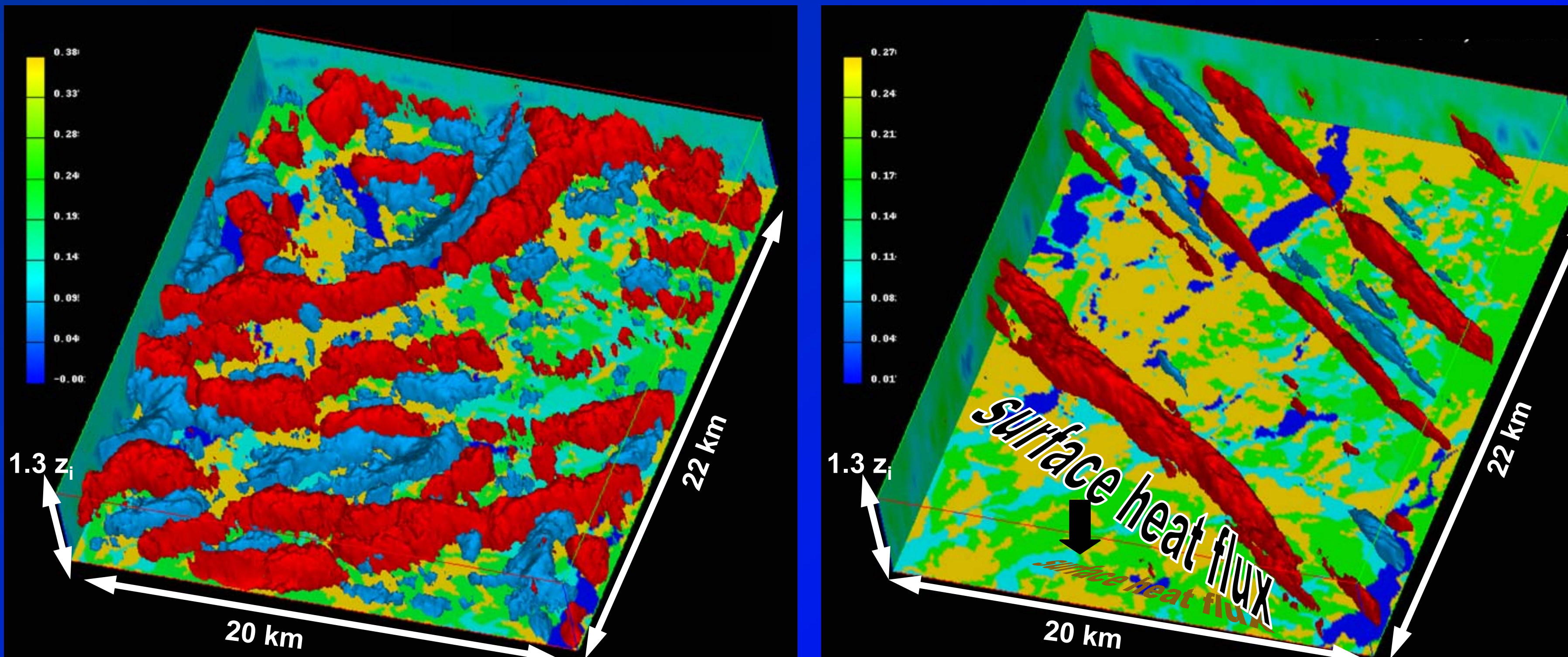


© Mauder & Foken (2006)
[Meteorol. Z., submitted]
see also Finnigan et al. (2003)

Finding 4: Organized Turbulent Structures have a contribution to the energy balance

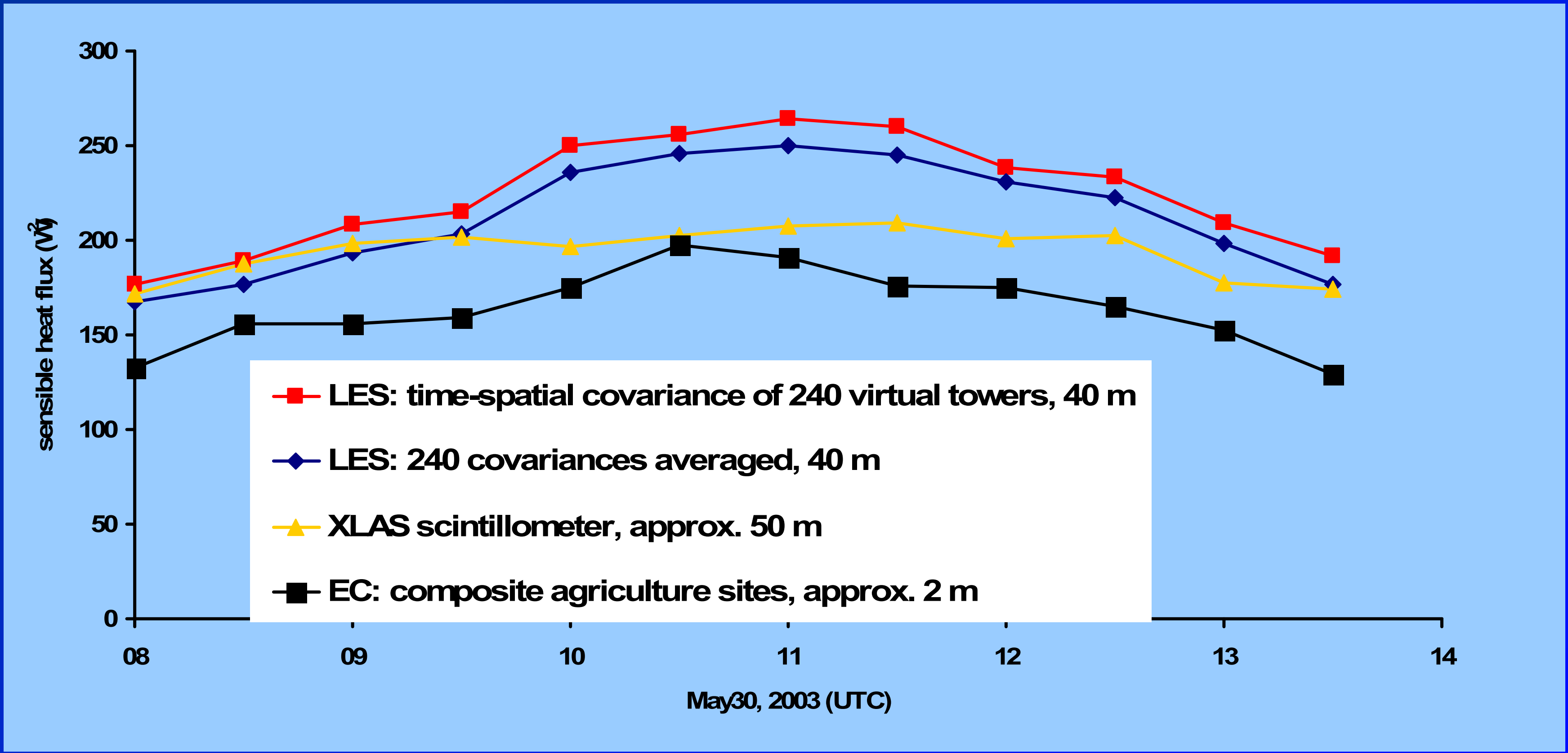
2003/05/30, 12 UTC

2003/06/13, 12 UTC



© Kanda et al. (2004), but data from the LITFASS-2003 experiment (Raasch & Uhlenbrock, personal communication)

Finding 5: Fluxes from an LES simulation fulfil the energy balance closure



Comparison of the results

Modelling outcomes

- Heterogeneous surfaces generate additional fluxes - mosaic meso-models.
- LES models can close the energy balance with Turbulent Organized Structures (TOS).

Experimental findings

- Forest edges generate additional fluxes
- Scintillometer measurements nearly close the energy balance
- Aircraft measurements close the energy balance
- Long integration times of surface measurements close the energy balance
- Tower measurements are closed more thoroughly (80-90 %) than surface measurements (60-80 %)

Conclusions:

The energy balance problem is a scale problem!

The energy balance can only be closed on a landscape scale.

On the plot scale, the volume for budget measurements is too flat.

Conclusions

Landscape scale (5-50 km)

- The energy balance is closed!
- This can be controlled by: LES and subgrid modelling, scintillometer and aircraft measurements, integration of surface measurements over 24 h

Plot scale (0,1 – 2 km)

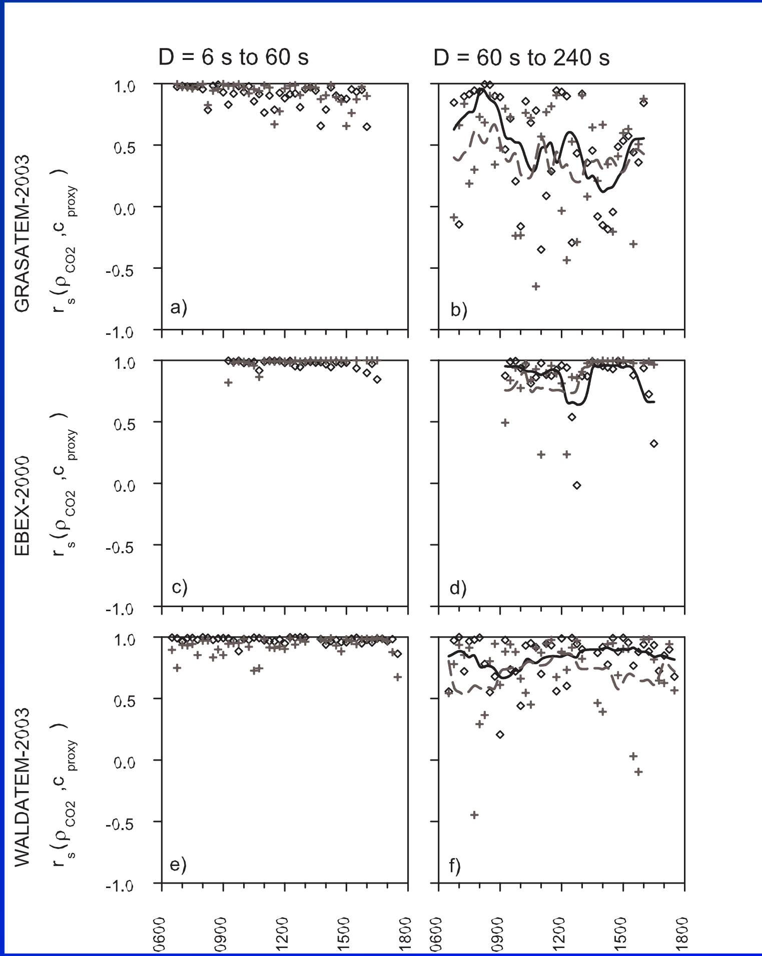
- The energy balance is not closed!

  - except for measurements in a homogeneous landscape
- But: EC measurements are accurate for the plot, process studies are possible, MO-theory is valid Bowen-ration method fails
- Probably no scalar similarity

How to solve the problem ?

- First guess: Increase all turbulent fluxes (including trace gas fluxes) according to the residual of the energy balance closure (assumption: scalar similarity)
- Increase the sensible and the latent heat flux according to the Bowen ratio (assumption: scalar similarity and similar accuracy of both fluxes)
- Control the scalar similarity

Excursion into scalar similarity



$$r_{c,c_{proxy}} = \frac{\overline{c' c'_{proxy}}}{\sigma_c \sigma_{c_{proxy}}}$$

See: Gao (1995)
Katul & Hsieh. (1999)
Pearson jr. et al. (1998)

Scalar similarity is not fulfilled - mainly for low frequencies

ρ_{CO2} - T (◊, solid line)
ρ_{CO2} - ρ_{H2O} (+, dashed line)

© Ruppert et al. (2006)
[Boundary-Layer Meteorol., accepted]

Is this relevant for modelers ?

- Models close the energy balance by definition.
- Models calibrated with the surface temperature overestimate the fluxes.
- Models calibrated with the turbulent fluxes extremely overestimate the ground heat flux.

Necessary research

- Investigation of scalar similarity under different conditions.
- Repetition of the experiments of the LITFASS type with Large aperture and microwave scintillometers, aircraft, surface layer measurements and LES modelling.
- LES modelling of Organized Turbulent Structures (TOS).

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http://www.bayceer.uni-bayreuth.de/mm/

- Publications
- Lectures, Posters

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