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)
• 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:

\[ \frac{Q_G + Q_H + Q_E}{Q_s^*} \cdot 100\% = 70\ldots 100\% \]
The measurements

There is no balance layer!
Measurements cover an energy budget of a volume

The errors and scales

<table>
<thead>
<tr>
<th></th>
<th>Error in %</th>
<th>Energy in W m(^{-2})</th>
<th>Horizontal scale in m</th>
<th>Height in m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latent heat flux</td>
<td>5-20</td>
<td>20-50</td>
<td>100</td>
<td>2-10</td>
</tr>
<tr>
<td>Sensible heat flux</td>
<td>5-20</td>
<td>10-30</td>
<td>100</td>
<td>2-10</td>
</tr>
<tr>
<td>Net radiation</td>
<td>5-20</td>
<td>20-100</td>
<td>10</td>
<td>1-2</td>
</tr>
<tr>
<td>Ground heat flux without storage</td>
<td>20-50</td>
<td>20-50</td>
<td>0.1</td>
<td>-0.02 – -0.1</td>
</tr>
<tr>
<td>Storage term</td>
<td>20-50</td>
<td>20-50</td>
<td>0.1 – 1</td>
<td>-0.02 – -0.1</td>
</tr>
</tbody>
</table>

Including a storage term (+ advection):

\[ Q_s^* \geq Q_G + Q_H + Q_E \pm \Delta Q \]
### The findings (low vegetation)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reference</th>
<th>Residual</th>
<th>Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Müncheberg 1983 and 1984</td>
<td>Koitzsch et al. (1988)</td>
<td>14</td>
<td>Winter wheat</td>
</tr>
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<td>Tsvang et al. (1991)</td>
<td>23</td>
<td>Different agricultural fields</td>
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<td>FIFE-89</td>
<td>Kanamasu et al. (1992)</td>
<td>10</td>
<td>Step</td>
</tr>
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<td>TARTEX-90</td>
<td>Foken et al. (1993)</td>
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<td>Barley and bare soil</td>
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<td>Foken et al. (1997)</td>
<td>20</td>
<td>High grass</td>
</tr>
<tr>
<td>LINEX-97/1</td>
<td>Foken (1998)</td>
<td>32</td>
<td>Short grass</td>
</tr>
<tr>
<td>LINEX-98</td>
<td>Beyrich et al. (2002)</td>
<td>37</td>
<td>Bare soil</td>
</tr>
</tbody>
</table>

© Foken (2003), [Angew. Meteorologie, Springer]
The findings (low vegetation)

Different interpretation of this data set:

**Panin et al. (1998):**

\[ Q_s - Q_G = k(Q_H + Q_E) \]

\( k \): Factor of heterogeneity

**Foken (1998):**

Residuum depends on the degree of soil exposure

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The findings (tall vegetation)

<table>
<thead>
<tr>
<th>Station</th>
<th>Closure</th>
<th>Footprint</th>
</tr>
</thead>
<tbody>
<tr>
<td>BE1</td>
<td>92 %</td>
<td>Class 1</td>
</tr>
<tr>
<td>GE2</td>
<td>92 %</td>
<td>Class 1</td>
</tr>
<tr>
<td>FR2</td>
<td>89 %</td>
<td>Class 2</td>
</tr>
<tr>
<td>FR1</td>
<td>71 &amp;</td>
<td>Class 2</td>
</tr>
<tr>
<td>GE1</td>
<td>≈75 %</td>
<td>Class 2</td>
</tr>
</tbody>
</table>

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

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:

<table>
<thead>
<tr>
<th>anemometer</th>
<th>quality class</th>
<th>sensible heat flux</th>
<th>latent heat flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A, e.g. CSAT3</td>
<td>1-3</td>
<td>5% or 10 W m⁻²</td>
<td>10% or 20 W m⁻²</td>
</tr>
<tr>
<td></td>
<td>4-6</td>
<td>10% or 20 W m⁻²</td>
<td>15% or 30 W m⁻²</td>
</tr>
<tr>
<td>Type B, e.g. R3</td>
<td>1-3</td>
<td>10% or 20 W m⁻²</td>
<td>15% or 30 W m⁻²</td>
</tr>
<tr>
<td></td>
<td>4-6</td>
<td>15% or 30 W m⁻²</td>
<td>20% or 40 W m⁻²</td>
</tr>
</tbody>
</table>

© Mauder et al. (2006), [Boundary-Layer Meteorol., revised]
Measurement errors

Data quality can be checked.

But: Energy balance closure is not a quality control!

© Foken & Wichura (1996)
Foken et al. (2004)
Corrections have no significant influence on the closure problem.
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.
# Measurement errors

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sensor</th>
<th>Accuracy 1990 in W m⁻²</th>
<th>Accuracy 1995 in W m⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global radiation</td>
<td>Pyranometer</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>Aktinometer, Sun photometer</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Diffuse radiation</td>
<td>Shaded Pyranometer</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Downwelling longwave radiation</td>
<td>Pyrgeometer</td>
<td>30</td>
<td>10</td>
</tr>
</tbody>
</table>

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

**Typical accuracy of net radiometers (EBEX-2000)**

<table>
<thead>
<tr>
<th>Type</th>
<th>Sensor</th>
<th>Accuracy in %</th>
<th>Accuracy in W m(^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short wave</td>
<td>Eppley PSP</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kipp&amp;Zonen CM11, CM 21</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Long wave</td>
<td>Eppley PIR</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Net radiation</td>
<td>Kipp&amp;Zonen CNR1</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>REBS Q*7</td>
<td></td>
<td>(20)</td>
</tr>
<tr>
<td></td>
<td>Schulze-Däke</td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

© Kohsiek et al. (2006), [Boundary-Layer Meteorol., submitted]
ii Energy storage

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

EBEX-2000: cotton

\[ Q_{G(5cm)} + Q_{\text{storage}} \]

\[ Q_{G(5cm)} \]

\[ Q_{\text{air}} \]

\[ Q_{\text{canopy}} \]

Photosynthesis:

3.8 Wm\(^{-2}\), Max. 12 Wm\(^{-2}\)

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[Boundary-Layer Meteorol., submitted]
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]
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 Meteorol., 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)
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]
For EBEX-2000 horizontal advection was found to be an important factor.

Residual
Horizontal advection
Photosynthesis
Canopy storage
iii Ogive test

Case 1

Case 2

Case 3

\[ og_{w,x}(f_0) = \int_0^\infty Co_{w,x}(f) \, df \]

© Oncley et al. (1990)
### iii Ogive test

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Og_{uw}$</td>
<td>85 (96 %)</td>
<td>3 (3 %)</td>
<td>1 (1 %)</td>
</tr>
<tr>
<td>$Og_{wT}$</td>
<td>77 (87 %)</td>
<td>4 (4 %)</td>
<td>8 (9 %)</td>
</tr>
<tr>
<td>$Og_{wa}$</td>
<td>68 (76 %)</td>
<td>13 (15 %)</td>
<td>8 (9 %)</td>
</tr>
<tr>
<td>$Og_{wc}$</td>
<td>75 (84 %)</td>
<td>7 (8 %)</td>
<td>7 (8 %)</td>
</tr>
</tbody>
</table>

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

© Foken et al. (2006), see poster
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 Experiment
Israel
Residual: 0 %
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

© 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

![Graph showing fluxes from an LES simulation and comparison with other methods.]

- **LES**: time-spatial covariance of 240 virtual towers, 40 m
- **LES**: 240 covariances averaged, 40 m
- **XLAS scintillometer**: approx. 50 m
- **EC**: composite agriculture sites, approx. 2 m
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

Scalar similarity is not fulfilled - mainly for low frequencies

\[ r'_{c, c_{\text{proxy}}} = \frac{\sigma_c \sigma'_{c_{\text{proxy}}}}{\sigma_{c_{\text{proxy}}}^2} \]

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

\[ \rho_{\text{CO}_2} - T (\Diamond, \text{solid line}) \]
\[ \rho_{\text{CO}_2} - \rho_{\text{H}_2\text{O}} (+, \text{dashed line}) \]

© 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).
Acknowledgements

- The EBEX-2000 group, in particular S.P. Oncley, A. C. Delany, W. Kohsiek, R. Vogt, H. Liu, C. Bernhofer and others
- My Russian, Estonian and Nigerian colleagues, in particular L. R. Tsvang, V. P. Kukharetz, G. N. Panin, J. Ross (†), O. O. Jegede and others
- My Master and Ph.D. students, in particular M. Mauder, C. Liebethal, C. Thomas, J. Ruppert, F. Wimmer, J. Schröter, D. Kracher and others
- My technicians and all other colleagues
References available on:

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

- Publications
- Lectures, Posters
References:


Beyrich, F. et al., 2006. Area-averaged surface fluxes over the heterogeneous LITFASS area from eddy-covariance measurements. Boundary-Layer Meteorology, accepted.

Beyrich, F. et al., 2002. Experimental determination of turbulent fluxes over the heterogeneous LITFASS area: Selected results from the LITFASS-98 experiment. Theoretical and Applied Climatology, 73: 19-34.


Göckede, M., Mauder, M., Markkanen, T. and Foken, T., 2006b. Summary of the results of the footprint based QA/QC study for turbulent fluxes at forest sites, CarboEurope-IP, Bayreuth, pp. 29.


