The Eddy-Covariance Method – History, Status, and Prospects

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Department of Micrometeorology
The Eddy-Covariance Method

Obukhov (1946): “The absolute measurement of the friction velocity is of fundamental importance for the investigation of the surface layer and for the control of indirect methods.”

\[ \tau = -\rho \overline{u'w'} \]


The Eddy-Covariance Method

Wind vane with two hot wire anemometers (90° angle) for the measurement of the friction velocity (Obukhov, 1951) on the basis of Konstantinonov’s (1949) work.
The Eddy-Covariance Method

Evapotron: Dyer and Mahrer (1965)
Hot wire anemometer with cold wire psychrometer

Fluxatron: Dyer et al. (1967)
Propeller anemometer with cold wire thermometer
Sonic Anemometer-Thermometer


Vancouver 1968
(Miyake et al., 1971)

1: Japanese Kaijo-Denki PAT
2: Russian phase shift anemometer
3: hot/cold wire anemometer
My first Contacts with Sonic Anemometers (EKAM-1973)

Sonic anemometers of the Meteorological Main Observatory Potsdam (Kaijo-Denki PAT) and of the Shirshov-Institute Moscow

The young Prof. Panin controls the leveling
UV – Hygrometers

Lyman-alpha-hygrometer with variable path length (Foken, Buck et al., 1998)


## International Intercomparison Experiments

<table>
<thead>
<tr>
<th>Year</th>
<th>Place</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968</td>
<td>Vancouver, Canada</td>
<td>Miyake et al. (1971)</td>
</tr>
<tr>
<td>1970</td>
<td>Tsimlyansk, Russia</td>
<td>Tsvang et al. (1973)</td>
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<tr>
<td>1976</td>
<td>Conargo, Australia</td>
<td>Dyer et al. (1982)</td>
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<td>1981</td>
<td>Tsimlyansk, Russia</td>
<td>Tsvang et al. (1985)</td>
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Kaijo-Denki PAT with Lyman-alpha-hygrometer (left) and IR-hygrometer (right) at Tsimlyansk 1981 (Main Meteorological Observatory Potsdam)
The New Sonic Anemometer Type

Kaijo-Denki PAT (time difference principle, Mitsuta, 1966)

Kaijo-Denki DAT (travel time principle, Hanafusa et al., 1982)

Wind:

\[
\frac{1}{t_1} - \frac{1}{t_2} = \frac{2}{d} u_d
\]

Temperature:

\[
\frac{1}{t_1} + \frac{1}{t_2} = \frac{2}{d} c \sqrt{1 - \frac{u_n^2}{c^2}} \approx \frac{2}{d} c
\]
The Optimal Sonic Anemometer Type


Printed in U. S. A.

Workshop on Instrumental and Methodical Problems of Land Surface Flux Measurements

Thomas Foken\* and Steven Oncley\*

One year after an international workshop held in Grenoble in 1994, Campbell Sci. Inc. produced CSAT3

In memoriam
Dr. h.c. Bert Tanner

21st Symposium on Boundary Layers and Turbulence
9-13 June 2014, Leeds, United Kingdom
Concept of the Air Flow Through the Sensor

Low flow distortion for horizontal and vertical flow

\[ \frac{f_z}{u} = 0.05 \]

\[ \frac{f_z}{u} = 1.0 \]
Comparison Experiments

Concept:
- Flat and uniform terrain on a large scale
- Assumption of uniform turbulence statistics
- No flow distortion due to other instruments

© Mauder et al. (2007)

EBEX-2000 California
Recent Comparison Experiments

Concept:
- All instruments in the turbulent length scale
- Terrain influences ignored
- Flow distortion due to other instruments ignored

© Kochendorfer et al. (2012)
Problem of Sonic Anemometer Firmware

Comparison of Young 81000 with CSAT 3
- Significant changes between the prototype and the final device
- High scatter of the friction velocity (in comparison to other devices)
- Firmware changes unknown

<table>
<thead>
<tr>
<th></th>
<th>Variance of the vertical wind</th>
<th>Friction velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regression Coefficient</td>
<td>R²</td>
</tr>
<tr>
<td>ß-test 1999</td>
<td>0.77</td>
<td>0.98</td>
</tr>
<tr>
<td>EBEX-2000</td>
<td>1.06</td>
<td>0.99</td>
</tr>
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Problems in the CSAT 3 firmware for high wind velocities and low temperature (Burns et al., 2012)

METEK offers three different flow correction tools (open code)

Flow and crosswind correction of most of the anemometers are unknown!
Possible Self-Correlation

Self correlation due to
- Flow distortion
- Firmware
- Correction function

\[ u = f_1(\varphi, \vartheta) \cdot g_1(u_A, u_B, u_C) \quad \text{and} \quad w = f_2(\varphi, \vartheta) \cdot g_2(u_A, u_B, u_C) \]

Possible self correlation
- Function \( f \): flow distortion, angle of attack
- Function \( g \): coordinate transformation

\textbf{It is wrong:} The largest flux is the best because of the best energy balance closure

\textbf{It is necessary:} Each correction should be tested with random numbers for self correlation
# Correction Methods, Status quo

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<td>Density fluctuations</td>
<td>Webb et al. (1980)</td>
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<td>SND</td>
<td>Buoyancy flux into sensible heat flux</td>
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<td></td>
<td>High frequency lost</td>
<td>Moore (1986)</td>
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<tr>
<td>QA/QC</td>
<td>Data quality control</td>
<td>Foken &amp; Wichura (1996)</td>
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<tr>
<td>Planar fit</td>
<td>Tilt error in heterogeneous area</td>
<td>Wilsczak et al. (2001)</td>
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<tr>
<td>Footprint</td>
<td>Area of interest in a heterogeneous area</td>
<td>Göckede et al. (2004, 2006)</td>
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**Aubinet, Vesala, Papale (Eds.)**

**Leclerc & Foken**
## Correction Methods, Status quo

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### Additional Information

- **Aubinet, Vesala, Papale (Eds.)**

- **Leclerc & Foken**
  - 2014, XIX, 239 p.

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I have order forms available with 20% OFF
### Corrections with Reservations

<table>
<thead>
<tr>
<th>Correction</th>
<th>Reference</th>
<th>Remark</th>
</tr>
</thead>
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<tr>
<td>Fluctuations of the heat capacity</td>
<td>Brook (1978), Stull (1988)</td>
<td><strong>Do not use:</strong> Error in the calculation</td>
</tr>
<tr>
<td>Modified WPL-correction for energy balance closure</td>
<td>Liu, … Foken (2006)</td>
<td><strong>Do not use:</strong> Energy balance closure is no measuring error</td>
</tr>
<tr>
<td>Burba correction (WPL) for convective flux in LI-COR 7500 open path gas analyzer</td>
<td>Grelle &amp; Burba (2007) Burba et al. (2008)</td>
<td><strong>Be careful:</strong> Modification for polar night (Oechel et al., 2014), I am in discussion with G. Burba</td>
</tr>
<tr>
<td>Angle of attack correction</td>
<td>Van der Molen et al. (2004), Nakai et al. (2006), Nakai &amp; Shimoyama (2012)</td>
<td><strong>I disagree</strong></td>
</tr>
</tbody>
</table>
Correction of the angle of attack for each eddy (Nakai et al., 2006)
Questionable, because of low correlation between horizontal and vertical wind:
\[ r_{uw} = 0.15 \ldots 0.35 \] (Kaimal & Finnigan, 1994; Arya, 2001), but \[ r_{wT} > 0.5 \]
From 1D Point Measurements to 3D Generalized Eddy-Covariance Method

Rotation into stream lines for longer periods

What is the direction of the flux?

© Finnigan et al. (2003)
From 1D Point Measurements to 3D Generalized Eddy-Covariance Method

\[ \int_0^h \rho_d \frac{\partial \chi_s}{\partial t} dz + \rho_d w' \chi_s' \bigg|_h = \Sigma_s \]

Storage \hspace{1cm} EC-Flux \hspace{1cm} 1D-Flux

\[ \int_0^h \rho_d \frac{\partial \chi_s}{\partial t} dz + \rho_d w' \chi_s' \bigg|_h + \int_0^h \left[ \rho_d u \frac{\Delta \chi_{s,x}}{\Delta x} + \rho_d v \frac{\Delta \chi_{s,y}}{\Delta y} \right] dz + \int_0^h \left[ \rho_d w \frac{\partial \chi_s}{\partial z} \right] dz = \Sigma_s \]

Storage \hspace{1cm} EC-Flux \hspace{1cm} horizontal Advection \hspace{1cm} vert. Adv. \hspace{1cm} 3D-Flux

The eddy-covariance method is only one part of the flux equation!

© Aubinet et al. (2003), Finnigan et al. (2003), Foken et al. (2012)
Four Problems of the Eddy-Covariance Technique

- Energy balance closure
- Night-time fluxes
- Heterogeneous terrain
- Accuracy of the method
1. Energy Balance Closure: The Problem

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

\[ Q_s^* \geq Q_G + Q_H + Q_E \]

Typical residuals are:

\[ \frac{Q_G + Q_H + Q_E}{Q_s^*} \cdot 100\% = 70...100\% \]
1. Energy Balance Closure

The graph illustrates the energy balance closure for various components over a 24-hour period. The y-axis shows energy in W m$^{-2}$, while the x-axis represents UTC time (00:00 to 24:00 UTC). The energy components include:

- **Sensible heat flux**
- **Latent heat flux**
- **Net radiation**
- **Ground heat flux**
- **Residual**

The graph shows how these components contribute to the overall energy balance over the specified period.
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
Surface heterogeneity as a reason: Panin et al. (1998), Kanda et al. (2004), Mauder et al. (2007), Stoy et al. (2012)
Pieces of the puzzle emerge in the 2000s
Influence of the Heterogeneity of the Landscape on the Energy Balance 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. (2007), Stoy et al. (2012)
Schematic Overview of the Generation of Secondary Circulations and the Energy Balance Closure

© Foken (2008)
How to Correct the Energy Balance Closure?

- Correction according to the Bowen ratio © Twine et al. (2000)
- Correction according to the buoyancy flux © Charuchittipan et al. (2014)
2. Night-time Flux – Total Advection

© Aubinet et al. (2003)
2. Night-time Flux – Coherent Structures

© Siebicke and Foken, in preparation
2. Night-Time Fluxes – Gap Filling

Gap-filling with data quality (a) or u*-criterion (b)

© Ruppert et al. (2006)
2. Night-Time Fluxes – Gap Filling

Under non-turbulent conditions the fluxes have to be replaced by suitable parameterizations, e.g. Lloyd-Taylor-approach for respiration, which can often shift the final result in a dramatic way.

© Ruppert et al. (2006)
2. Night-Time Fluxes – Conditional Sampling

Basic idea by Desjardins (1972)

\[
\overline{w'c'} = \overline{w^+c} + \overline{w^-c} = \left(\overline{w^+} + \overline{w^-}\right) + \overline{w^+c'} + \overline{w^-c'}
\]

\[
\overline{w^+} + \overline{w^-} = \overline{w} = 0
\]

© Foken (2008)
3. Influence of an Heterogeneous Landscape with Canopy on Turbulent Fluxes

© Kanani and Raasch (personal communication, 2014)

© Belcher et al. (2012)
### 3. Influence of an Heterogeneous Landscape

Some Findings

<table>
<thead>
<tr>
<th>Finding</th>
<th>Reference (Experiment/Model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large fluxes at a forest edge</td>
<td>Klaassen et al. (2002)</td>
</tr>
<tr>
<td>Hübner (PhD, 2014)</td>
<td></td>
</tr>
<tr>
<td>At forest edge:</td>
<td></td>
</tr>
<tr>
<td>Daytime: ejections dominate</td>
<td>Eder et al. (2013)</td>
</tr>
<tr>
<td>Nightime: sweeps dominate</td>
<td></td>
</tr>
<tr>
<td>Representative fluxes at a distance of 10 $h_c$ from the forest edge</td>
<td>Belcher et al. (2012)</td>
</tr>
<tr>
<td>Kanani et al. (2014, submitted)</td>
<td></td>
</tr>
<tr>
<td>Large fluxes due to advection at the top of a hill</td>
<td>Belcher et al. (2008)</td>
</tr>
<tr>
<td>Zeri (PhD, 2008), Zeri et al. (2010)</td>
<td></td>
</tr>
</tbody>
</table>

Flux measuring sites should be selected in the near future with LES simulations and not only with footprint analysis.
4. Accuracy of Eddy-Covariance Measurements

- Classification of the anemometer type and the data quality (Foken and Oncley, 1995; Mauder et al., 2006)

<table>
<thead>
<tr>
<th>Sonic 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 Wm$^{-2}$</td>
<td>10% or 20 Wm$^{-2}$</td>
</tr>
<tr>
<td></td>
<td>4-6</td>
<td>10% or 20 Wm$^{-2}$</td>
<td>15% or 30 Wm$^{-2}$</td>
</tr>
<tr>
<td>Type B, e.g. USA-1</td>
<td>1-3</td>
<td>10% or 20 Wm$^{-2}$</td>
<td>15% or 30 Wm$^{-2}$</td>
</tr>
<tr>
<td></td>
<td>4-6</td>
<td>15% or 30 Wm$^{-2}$</td>
<td>20% or 40 Wm$^{-2}$</td>
</tr>
</tbody>
</table>

- Comparison of two towers in the neighbourhood (Hollinger and Richardson, 2005)
- Comparison with the annual cycle (Richardson et al., 2006)
- New statistical measures (Mauder et al., 2013)
The Present Day Problems of the Method

About 90 % of all eddy-covariance systems are purchased by non-specialists (ecology, biology, etc.)
Producers modifies the instruments and the firmware for this new group of custumers
The knowledge of the fathers of the eddy-covariance method is often forgotten and errors of the first days of the method are repeated
Users try to correct everything and do not accept the physical limitations of the methods (NEON, ICOS)
The book by LI-COR (Burba, 2013) is a good help for customers; in courses not only software and handling of instruments should be addressed but also basics for non-experts
Specialists in atmospheric turbulence and in modern modelling techniques (LES etc.) could help for a better understanding of the method – but this is missing or too complicated for many users.
Sensor Modifications Contrary to the Recommendations of the Workshop in 1994

Campbell IRGASON „Sexy for ecologist“

Campbell CSAT3/EC150 „a larger distance between both instruments would fulfill the old recommendations“
Two Papers with Different Outlooks

**Measuring Fluxes of Trace Gases and Energy between Ecosystems and the Atmosphere—the State and Future of the Eddy Covariance Method**

Global Change Biology, An Opinion

GCB 14-0470

Dennis Baldocchi

**Progress was made with new sensors for trace gases (tuneable laser)**

Large data sets are available for most of the ecosystems

In the future use of other methods as well as simpler ones, REA, surface renewable, …

The problems of the method itself are not discussed
Hills can change the flow in dramatic ways. It is difficult to interpret measurements from a single tower.

Nighttime canopy flows are likely to have a profound effect on scalar transport at FLUXNET sites.

The problems of the application of the method are discussed and modelling approaches are proposed.
The Eddy-Covariance Method in the Future

• The eddy covariance method is the only one method to measure fluxes in a direct way.
• The method is an important tool for controlling model parameterizations.
• Development of further progress should always be a task of researchers of atmospheric turbulence and not of applied users.
• Manufacturers should work together with researchers to make firmware transparent.
• The solution of the four mentioned problems is on a good path – but needs some more years.

• The method should only be applied for such sites and such conditions where the assumptions of the method are (nearly) fulfilled – for other cases a model approach should be applied.
References


Zeri, M.: Investigation of high nighttime CO₂-fluxes at the Wetzstein spruce forest site in Thuringia, Germany, PhD, University of Bayreuth, Bayreuth, 102 pp., 2007.