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

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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.”

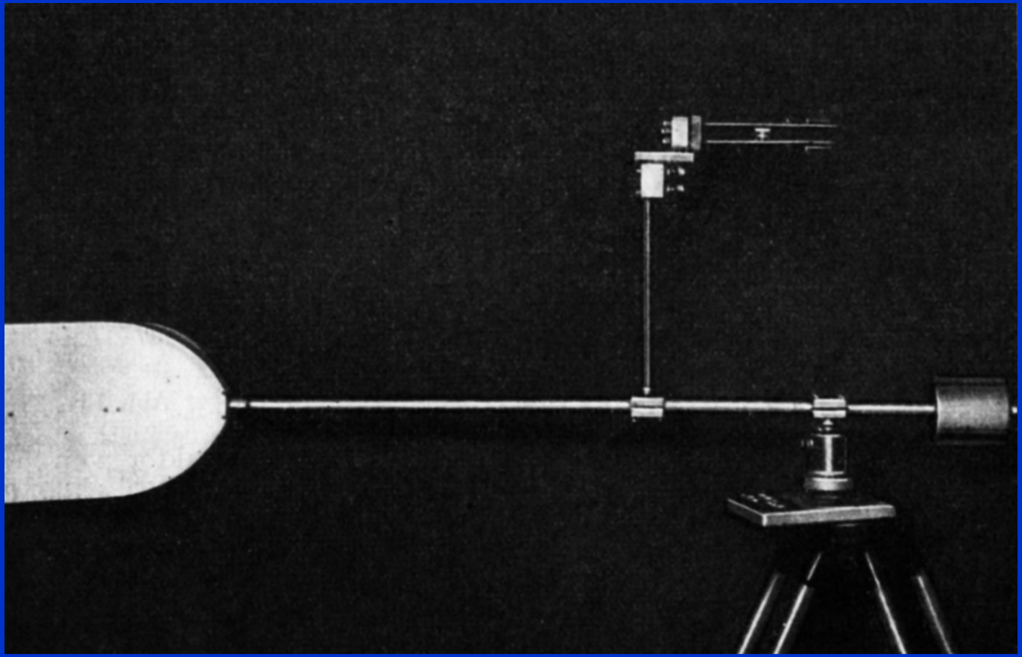
$$\tau = -\rho \ \overline{u'w'}$$

Montgomery, R. B., 1948: Vertical eddy flux of heat in the atmosphere. J. Meteorol 5: 265-274

Obukhov, A. M., 1951: Investigation of the micro-structure of the wind in the near-surface layer of the atmosphere (in Russian). Izv. AN SSSR, ser. geophys., vol. 3, p. 49ff

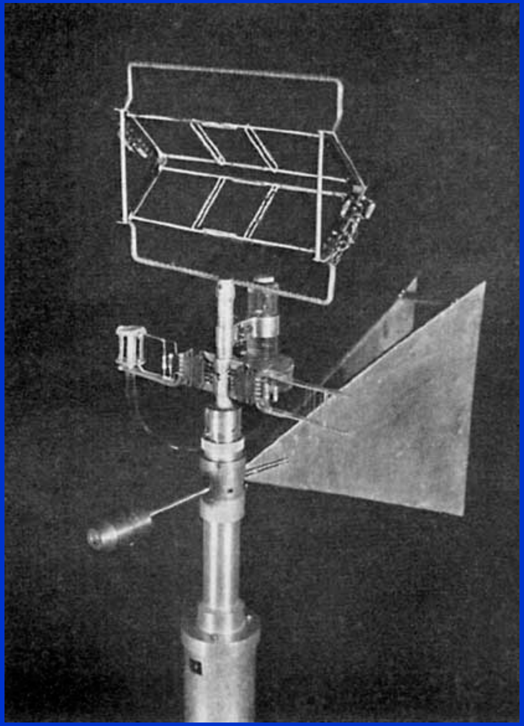
Swinbank, W.C., 1951: The measurement of vertical transfer of heat and water vapor by eddies in the lower atmosphere. J. Meteorol. 8: 135-145.

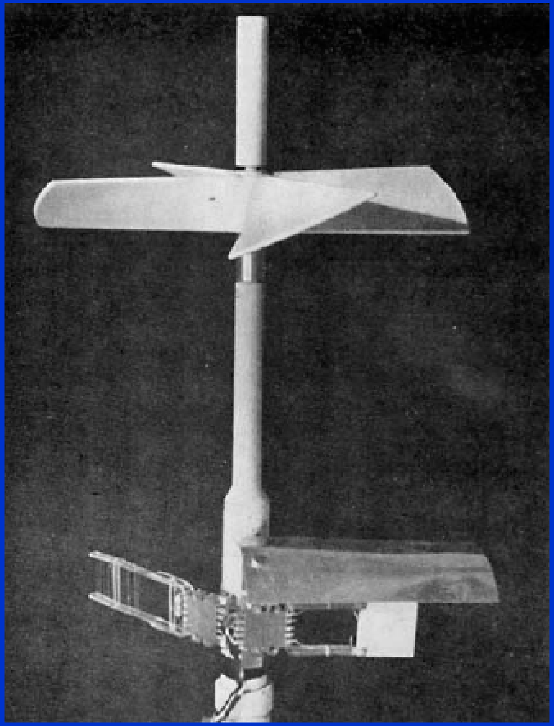
The Eddy-Covariance Method



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

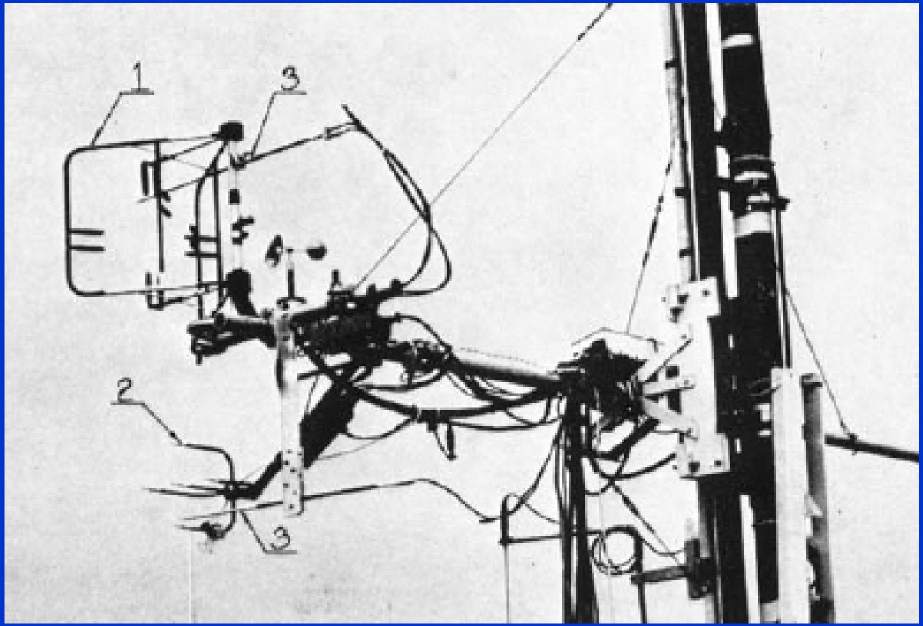




Evapotron: Dyer and Mahrer (1965)
Hot wire anemometer with cold wire psychrometer

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

Bovscheverov, V. M., and Voronov, V. P.: Akustitscheskii fljuger (Acoustic rotor), Izv. AN SSSR, ser. Geofiz., 6, 882-885, 1960.

Kaimal, J. C., and Businger, J. A.: A continuous wave sonic anemometer-thermometer, J. Climate Appl. Meteorol., 2, 156-164, 1963.

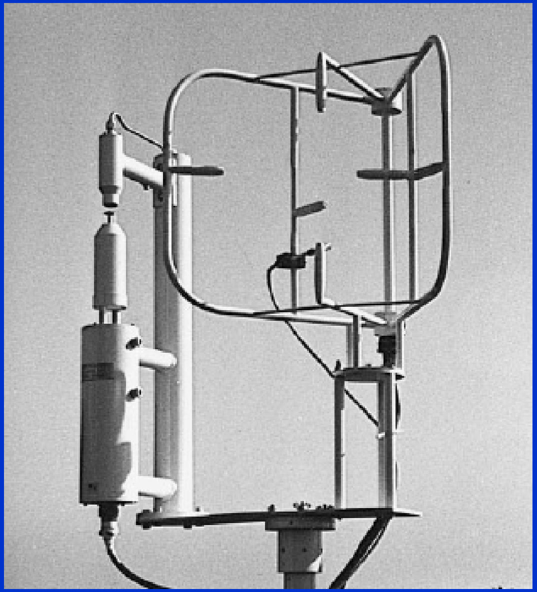
Mitsuta, Y.: Sonic anemometer-thermometer for general use, J. Meteor. Soc. Japan, Ser. II, 44, 12-24, 1966.

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)

Buck, A. L.: Development of an improved Lyman-alpha hygrometer, Atm. Technol., 2, 213-240, 1973.

Kretschmer, S. I., and Karpovitsch, J. V.: Maloinercionnyj ultrafioletovyj vlagometer (Sensitive ultraviolet hygrometer), Izv. AN SSSR, Fiz. Atm. i Okeana, 9, 642-645, 1973.

Martini, L., Stark, B., and Hunsalz, G.: Elektronisches Lyman-Alpha-Feuchtigkeitsmessgerät, Z. Meteorol., 23, 313-322, 1973.

International Intercomparison Experiments

Year	Place	Reference
1968	Vancouver, Canada	Miyake et al. (1971)
1970	Tsimlyansk Russia	Tsvang et al. (1973)
1976	Conargo, Australia	Dyer et al. (1982)
1981	Tsimlyansk Russia	Tsvang et al. (1985)

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)

$$t_{1,2} = \frac{\sqrt{c^2 - u_n^2} \pm u_d}{c^2 - u_n^2} d$$

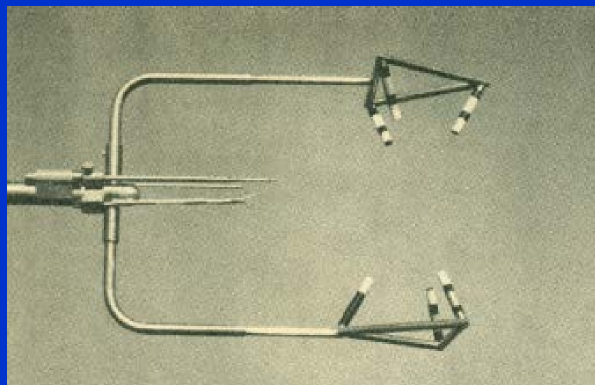
Wind:

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

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



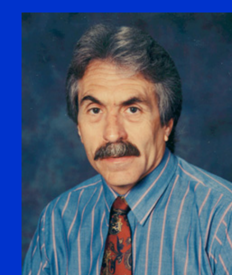
Zhang, S. F., Wyngaard, J. C., Businger, J. A., and Oncley, S. P.: Response characteristics of the U.W. sonic anemometer, J. Atm. Oceanic Techn., 2, 548-558, 1986.

[Reprinted from BULLETIN OF THE AMERICAN METEOROLOGICAL SOCIETY, Vol. 76, No. 7, July 1995]
Printed in U. S. A.

Workshop on Instrumental and Methodical Problems of Land Surface Flux Measurements

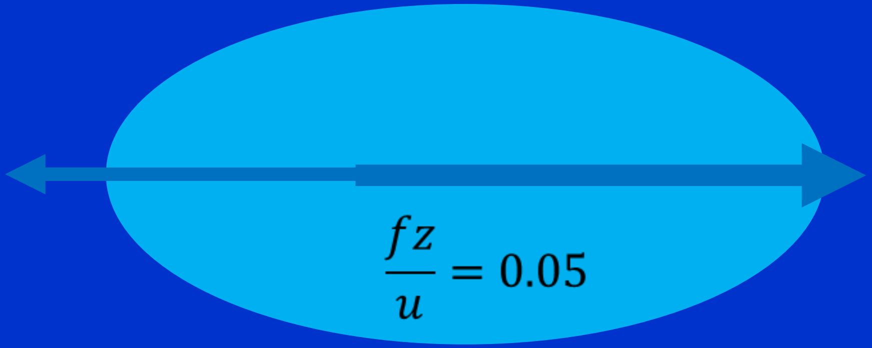
Thomas Foken* and Steven Oncley+

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

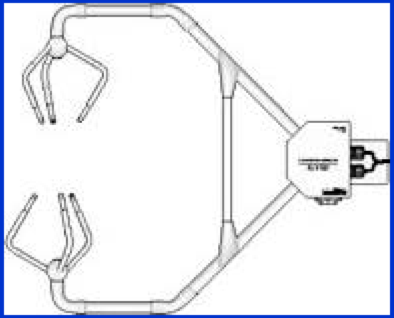


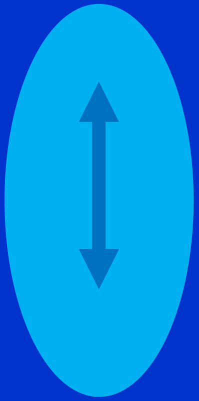
In memoriam
Dr. h.c. Bert Tanner

Concept of the Air Flow Through the Sensor



$$\frac{fz}{u} = 0.05$$





$$\frac{fz}{u} = 1.0$$

Low flow distortion for horizontal and vertical flow

Comparison Experiments

EBEX-2000
California

© Mauder et al. (2007)

Concept:

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

Recent Comparison Experiments

© Kochendorfer et al. (2012)

Concept:

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

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**

	Variance of the vertical wind		Friction velocity	
	Regression Coefficient	R^2	Regression Coefficient	R^2
ß-test 1999	0.77	0.98	0.86	0.82
EBEX-2000	1.06	0.99	0.99	0.88

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**

$$u = f_1(\varphi, \vartheta) \cdot g_1(u_A, u_B, u_C)$$

$$w = f_2(\varphi, \vartheta) \cdot g_2(u_A, u_B, u_C)$$

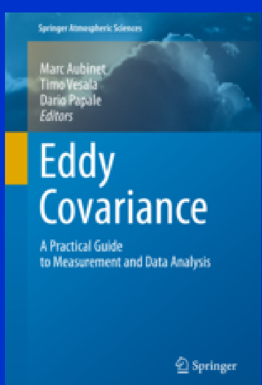
Possible self correlation
- **Function *f*: flow distortion, angle of attack**
- **Function *g*: coordinate transformation**

It is wrong: The largest flux is the best because of the best energy balance closure

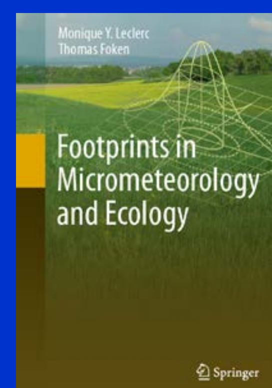
It is necessary: Each correction should be tested with random numbers for self correlation

Correction Methods, Status quo

Name	Reason	Reference
WPL	Density fluctuations	Webb et al. (1980)
SND	Buoyancy flux into sensible heat flux	Schotanus et al. (1983)
	High frequency lost	Moore (1986)
QA/QC	Data quality control	Foken & Wichura (1996)
Planar fit	Tilt error in heterogeneous area	Wilsczak et al. (2001)
Footprint	Area of interest in a heterogeneous area	Göckede et al. (2004, 2006)



Aubinet, **Vesala**, **Papale** (Eds.)
2012, XXII, 438 p.



Leclerc & Foken
2014, XIX, 239 p.

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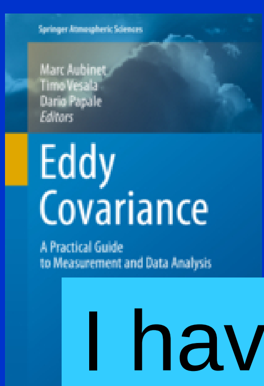

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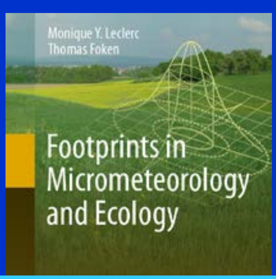


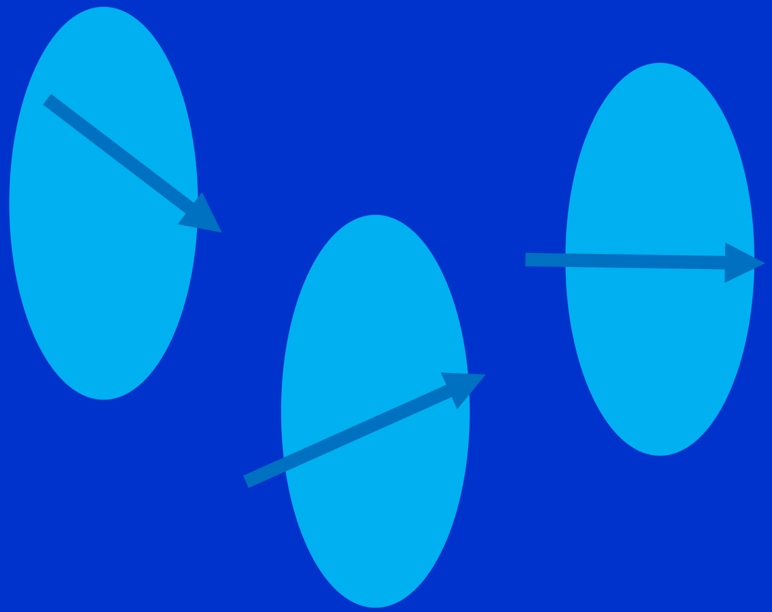
Leclerc & Foken
2014, XIX, 239 p.

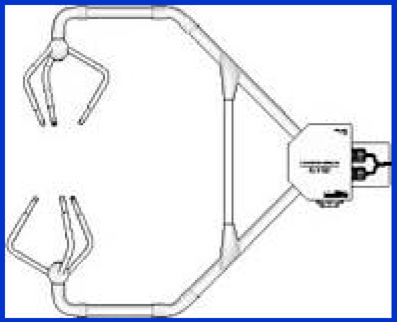
I have order forms available with 20 % OFF

Corrections with Reservations

Correction	Reference	Remark
Fluctuations of the heat capacity	Brook (1978), Stull (1988)	**Do not use:** Error in the calculation
Modified WPL-correction for energy balance closure	Liu, … Foken (2006)	**Do not use:** Energy balance closure is no measuring error
Burba correction (WPL) for convective flux in LI-COR 7500 open path gas analyzer	Grelle & Burba (2007) Burba et al. (2008)	**Be careful:** Modification for polar night (Oechel et al., 2014), I am in discussion with G. Burba
Angle of attack correction	Van der Molen et al. (2004), Nakai et al. (2006), Nakai & Shimoyama (2012)	**I disagree**

Angle of Attack Concept

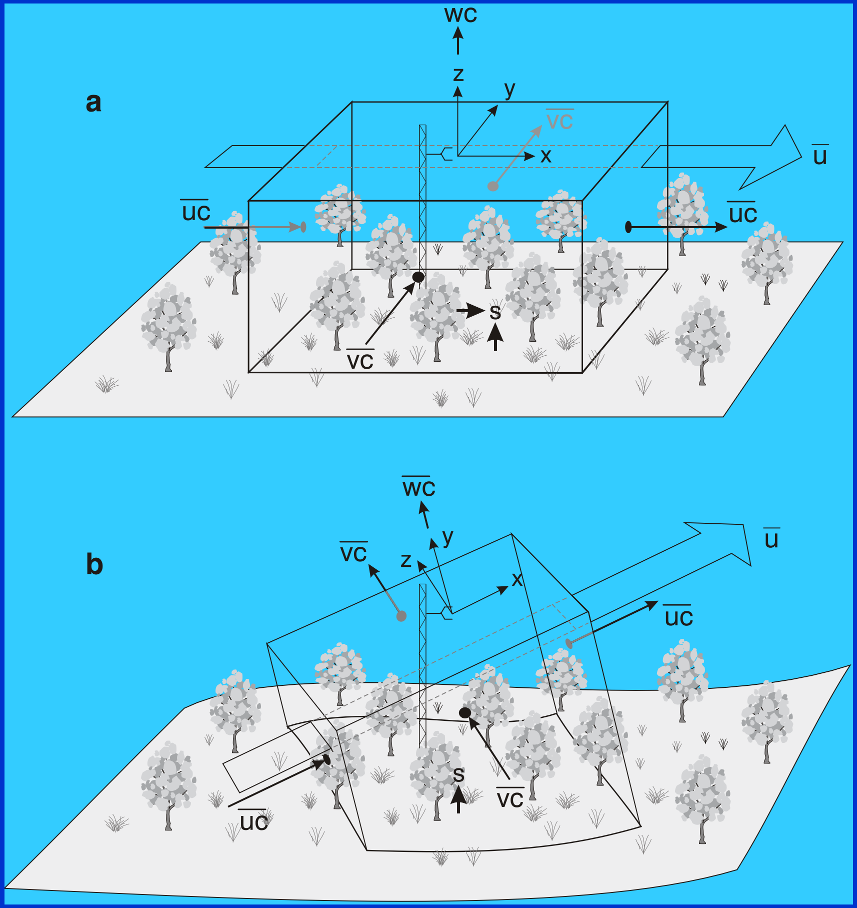




© Kochendorfer et al. (2012)

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 … 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?

From 1D Point Measurements to 3D Generalized Eddy-Covariance Method

$$\underbrace{\int_0^h \overline{\rho_d}\,\overline{\frac{\partial \chi_s}{\partial t}}\,dz}_{I} + \underbrace{\overline{\rho_d}\,\overline{w'\chi_s'}\Big|_h}_{IV} = \underbrace{\overline{\Sigma_s}}_{V}$$

Storage **EC-Flux** **1D-Flux**

$$\underbrace{\int_0^h \overline{\rho_d}\,\overline{\frac{\partial \chi_s}{\partial t}}\,dz}_{I} + \underbrace{\overline{\rho_d w'\chi_s'}\Big|_h}_{II} + \underbrace{\int_0^h \left[\overline{\rho_d u}\,\frac{\Delta\overline{\chi}_{s,x}}{\Delta x} + \overline{\rho_d v}\,\frac{\Delta\overline{\chi}_{s,y}}{\Delta y}\right]dz}_{III} + \underbrace{\int_0^h \left[\overline{\rho_d w}\,\overline{\frac{\partial \chi_s}{\partial z}}\right]dz}_{IV} = \underbrace{\overline{\Sigma_s}}_{V}$$

Storage **EC-Flux** **horizontal Advection** **vert. Adv.** **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

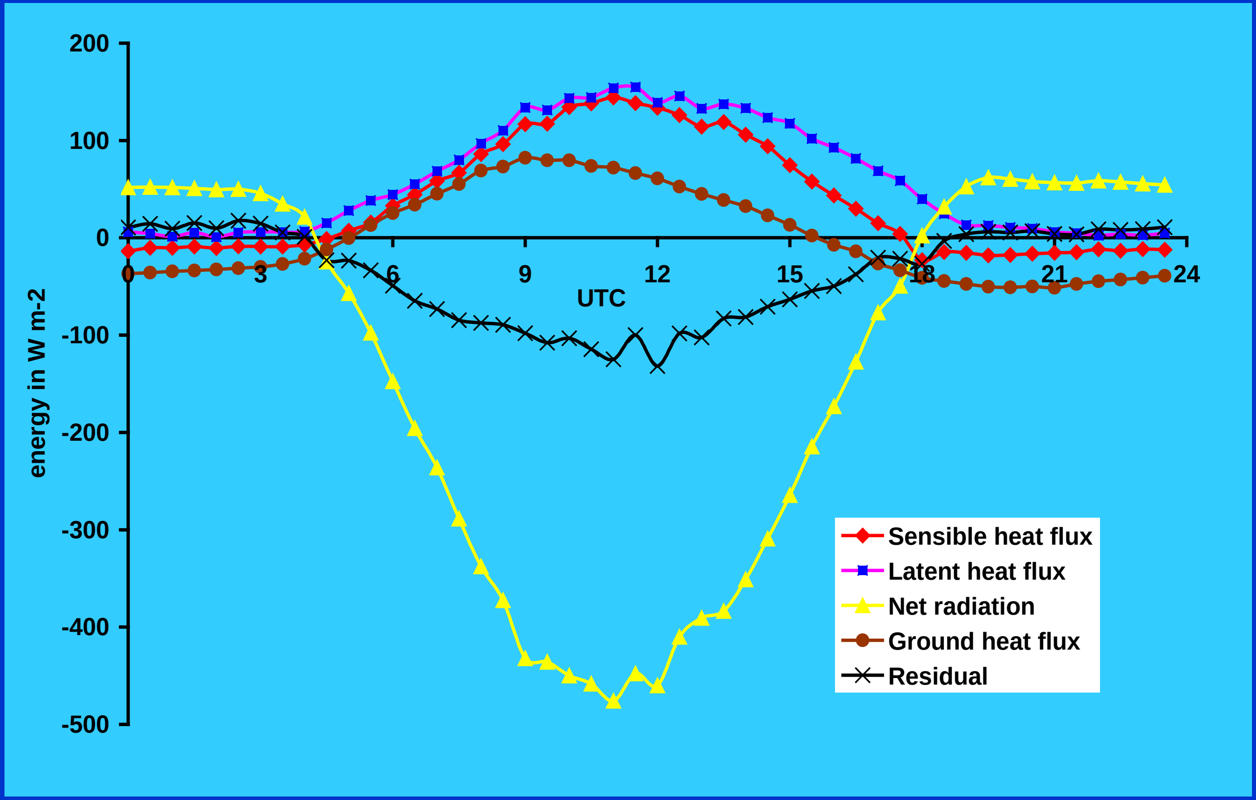
The net radiation is always larger than the sum of the turbulent fluxes (sensible and latent) and the ground heat flux:

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

Typical residuals are:

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

1. Energy Balance Closure



The 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

Several experiments in the 1990s and overview papers like: Foken (1998), Wilson *et al.* (2002), Culf *et al.* (2004), Foken (2008), Foken *et al.* (2012)

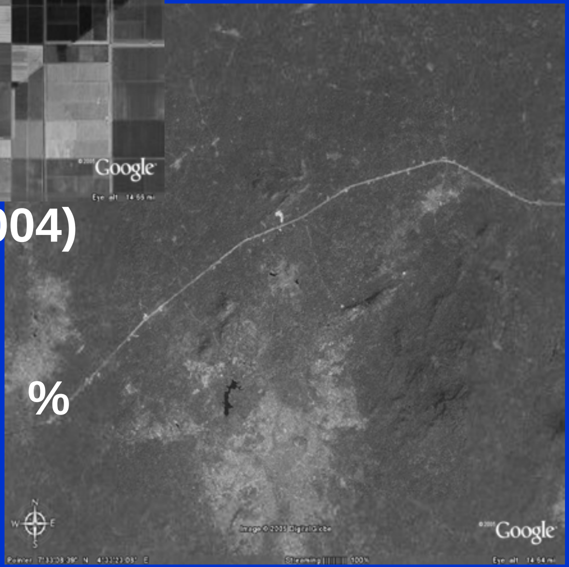
Surface heterogeneity as a reason: Panin *et al.* (1998), Kanda *et al.* (2004), Mauder *et al.* (2007), Stoy *et al.* (2012)

Pieces of the puzzle emerge in the 2000s

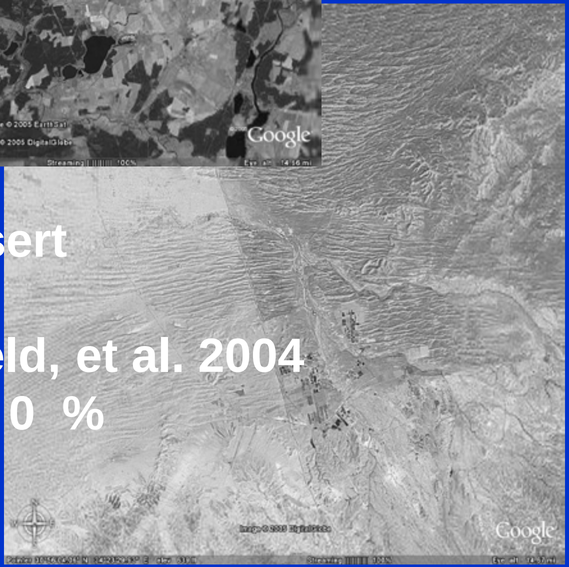
Influence of the Heterogeneity of the Landscape on the Energy Balance Closure

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

LITFASS-2003 Experiment
Germany
Residual: 25-35%



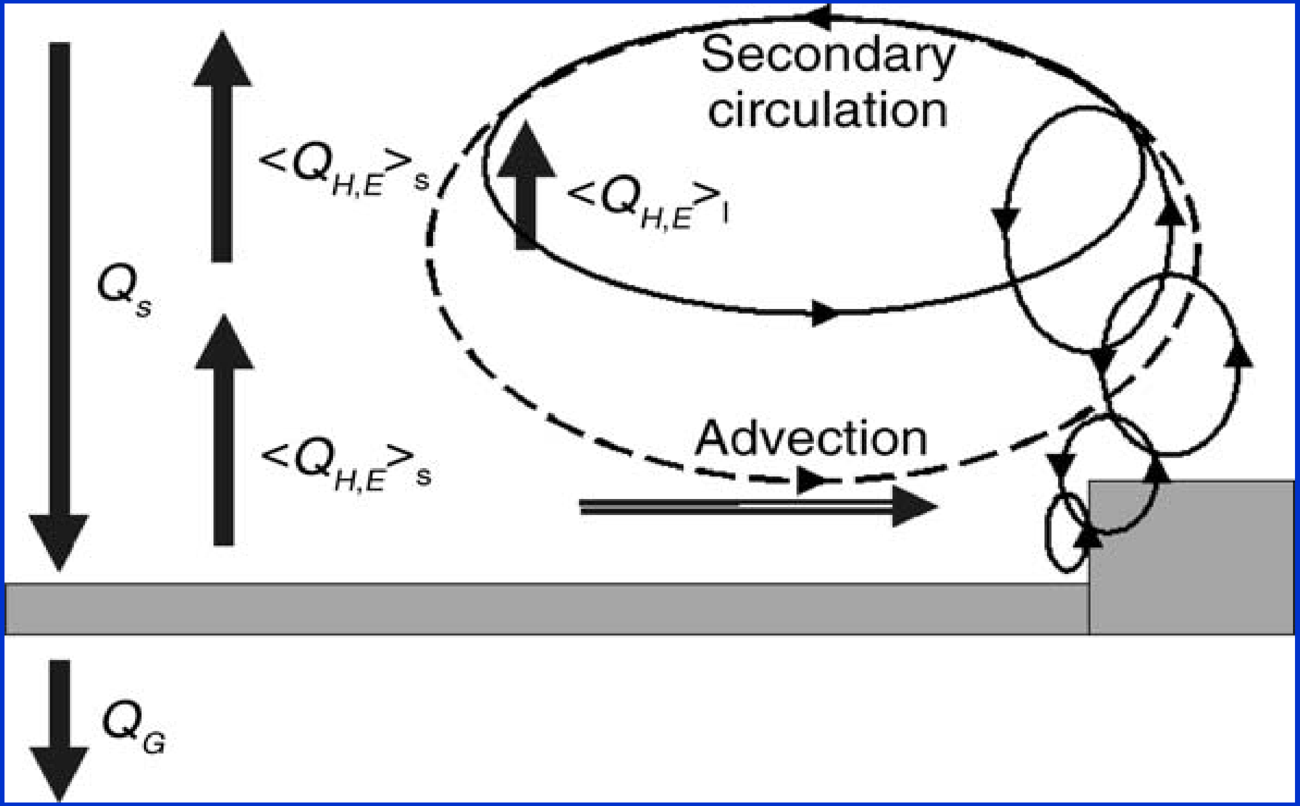
NIMEX-1 (2004) Experiment
Nigeria
Residual: 0 %



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

© Mauder *et al*. (2007), Stoy *et al.* (2012)

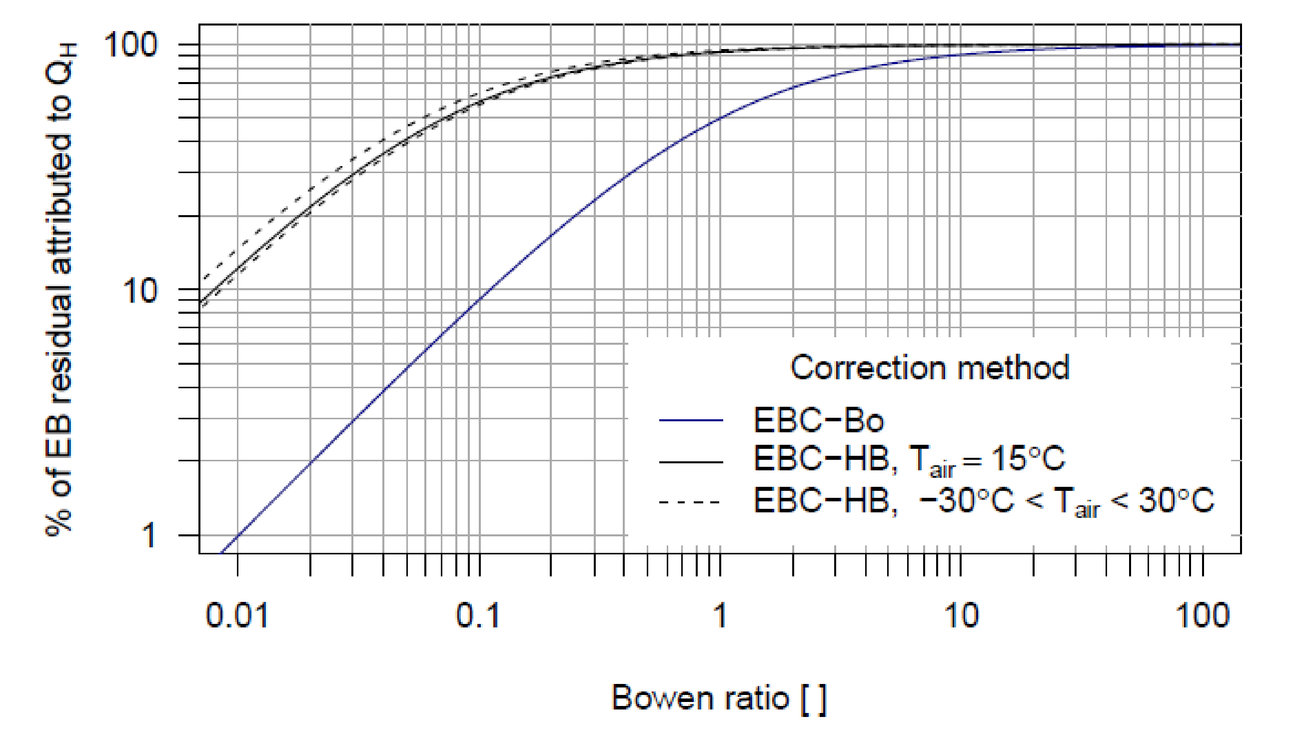
Schematic Overview of the Generation of Secondary Circulations and the Energy Balance Closure



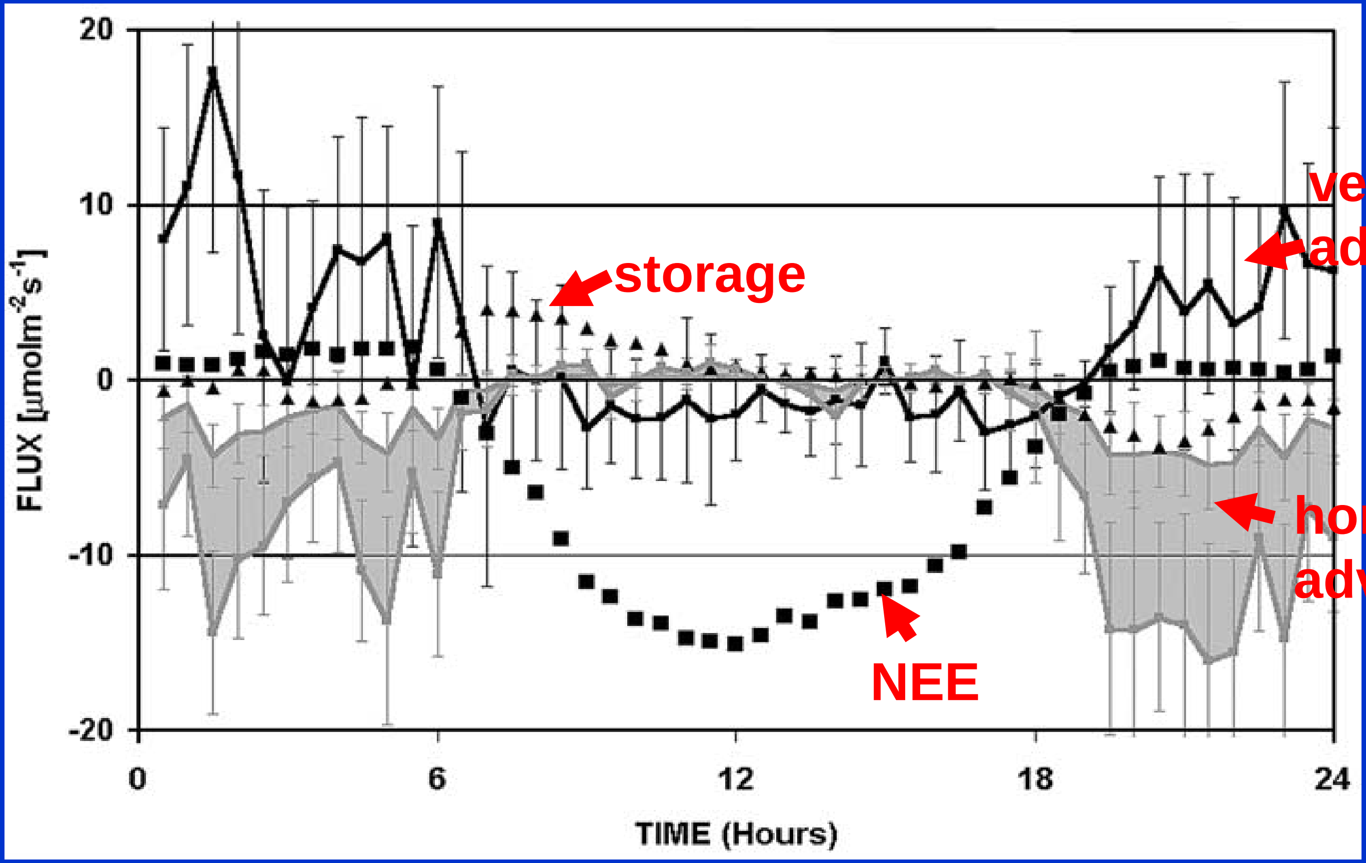
© Foken (2008)

How to Correct the Energy Balance Closure ?

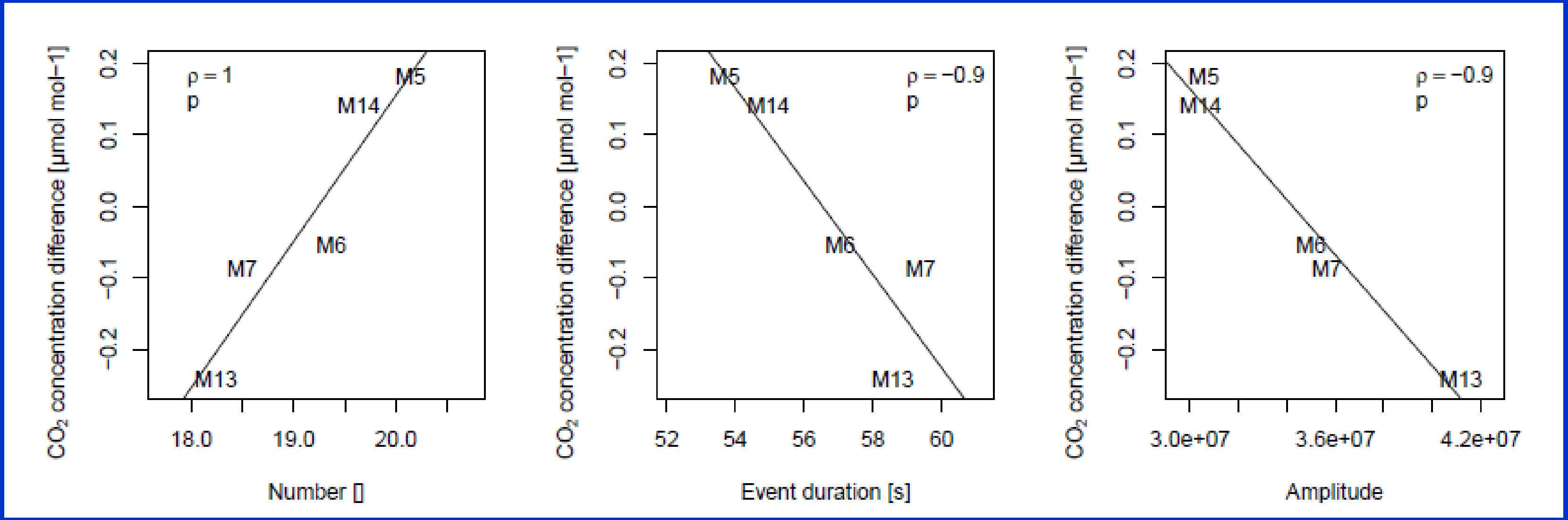
- **Correction according to the Bowen ratio** © Twine *et al.* (2000)
- **Correction according to the buoyancy flux** © Charuchittipan *et al.* (2014)

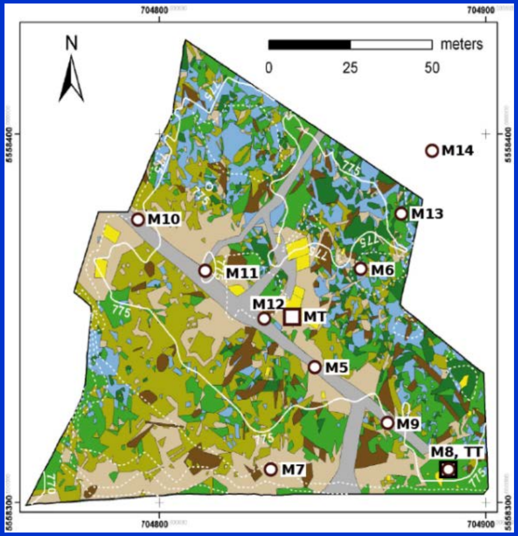


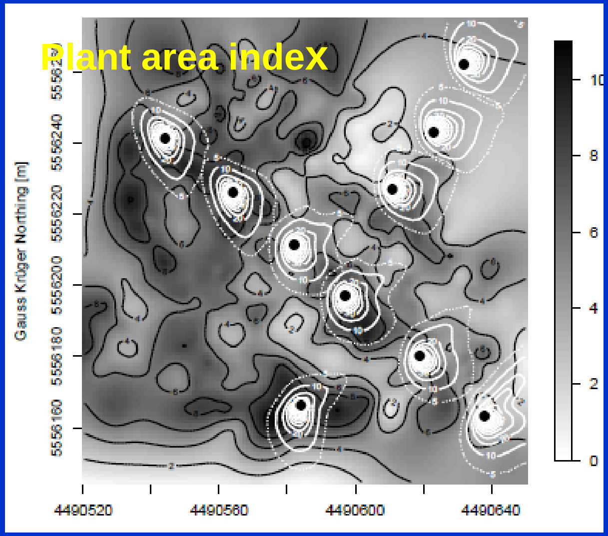
2. Night-time Flux – Total Advection

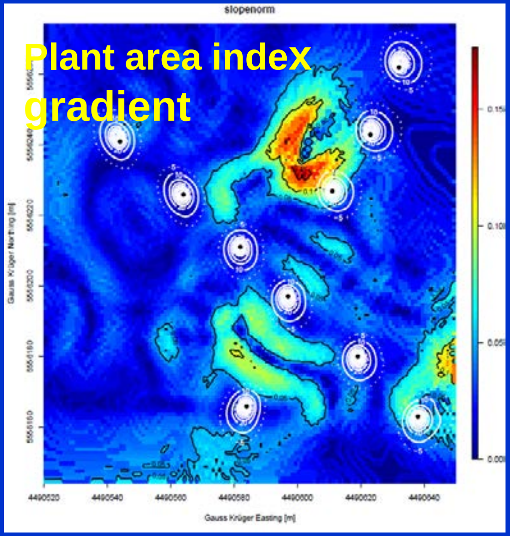


2. Night-time Flux – Coherent Structures









© Siebicke and Foken, in preparation

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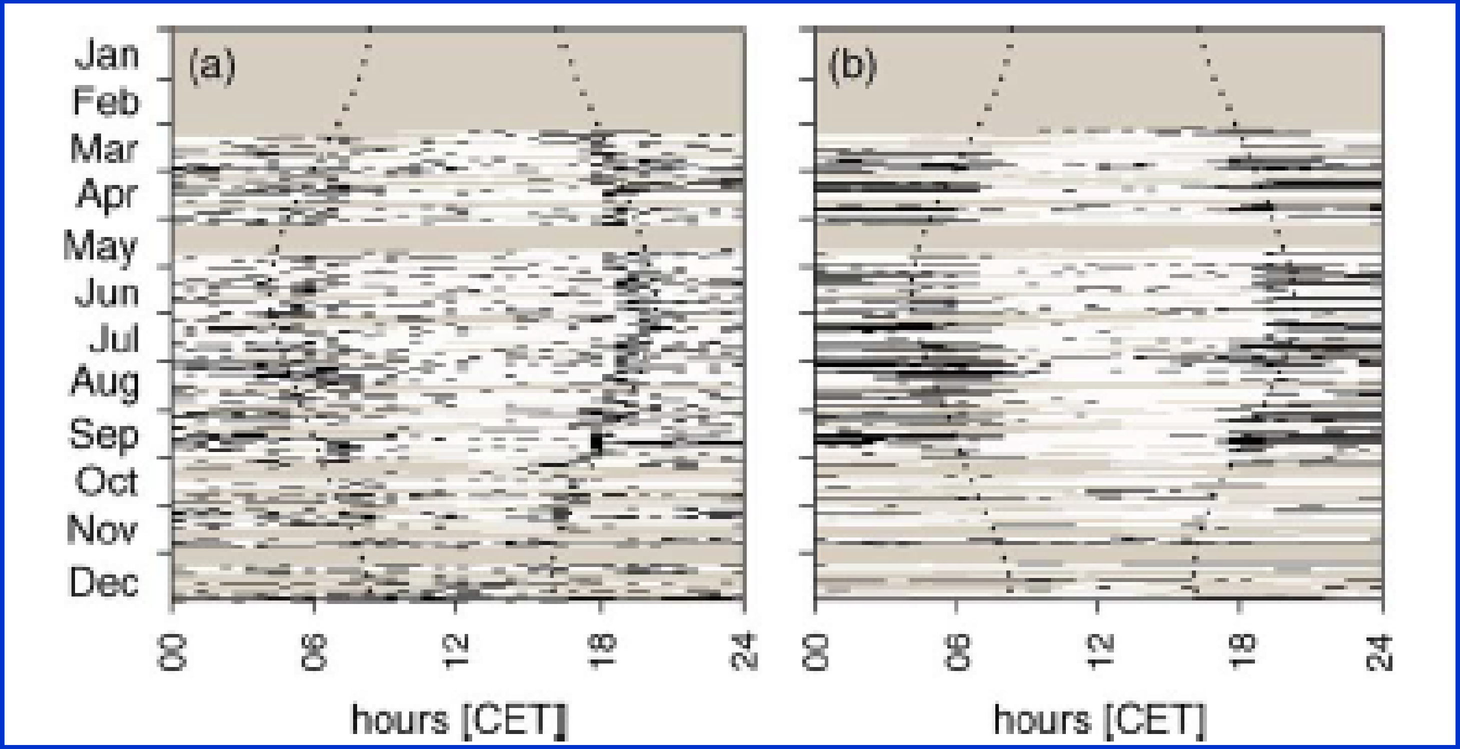
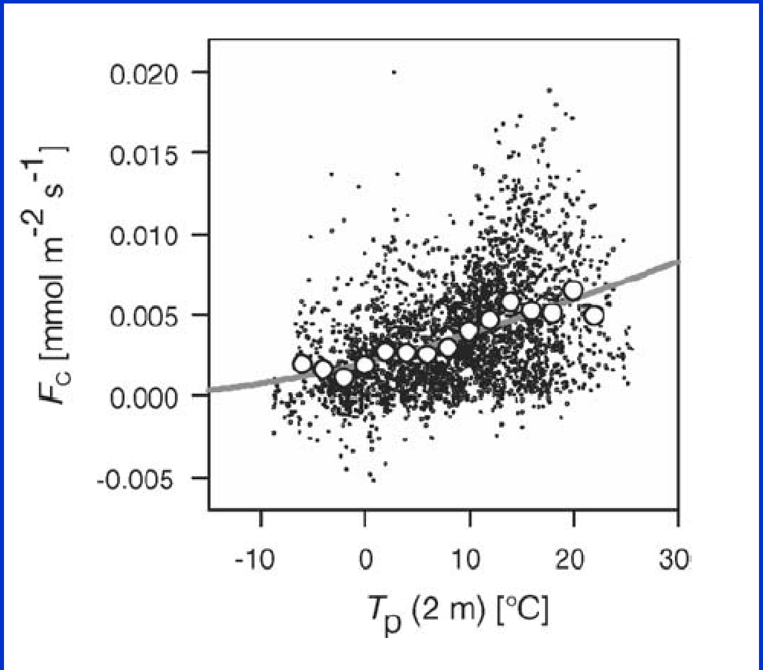
2. Night-Time Fluxes – Gap Filling



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

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

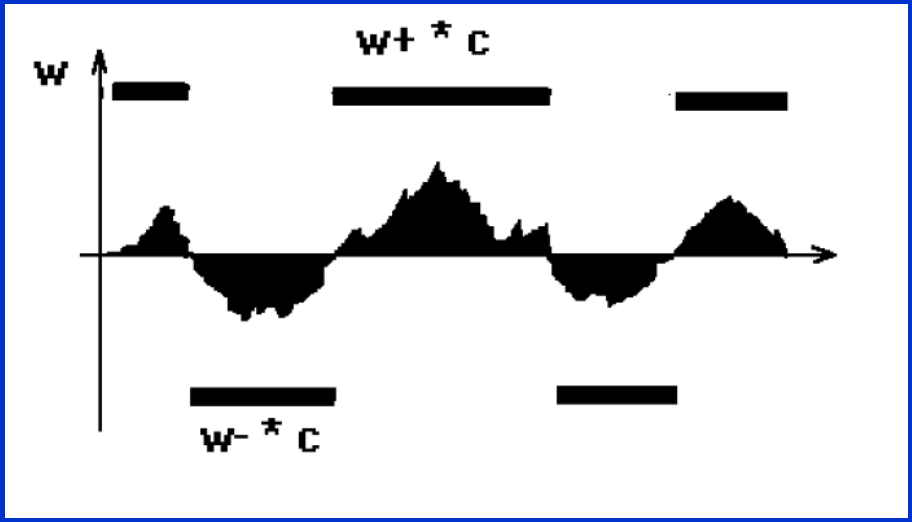


2. Night-Time Fluxes – Conditional Sampling

Basic idea by Desjardins (1972)

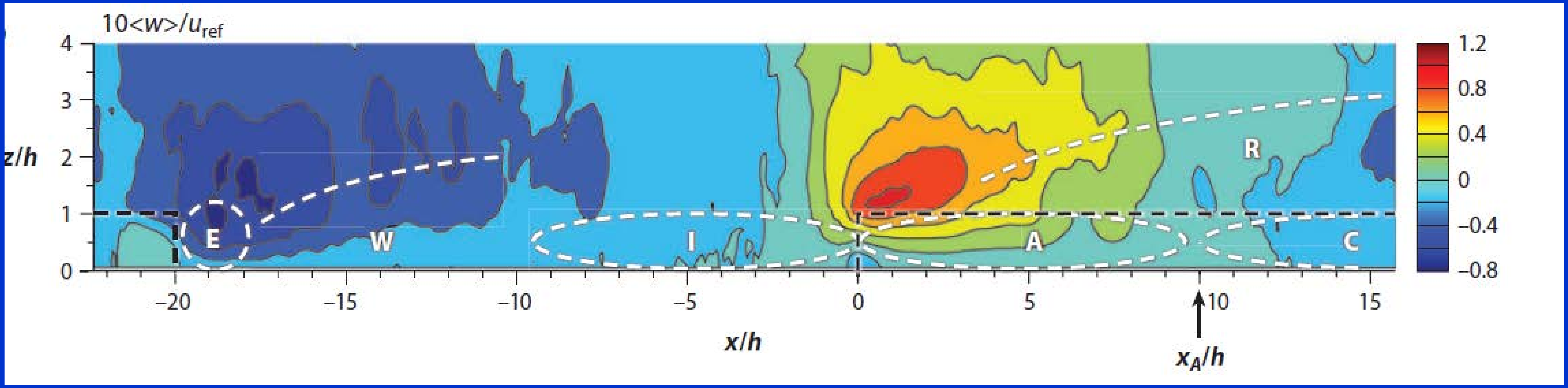
$$\overline{w'c'} = \overline{w^{+}c} + \overline{w^{-}c} = \left(\overline{w^{+}} + \overline{w^{-}}\right) + \overline{w^{+}c'} + \overline{w^{-}c'}$$

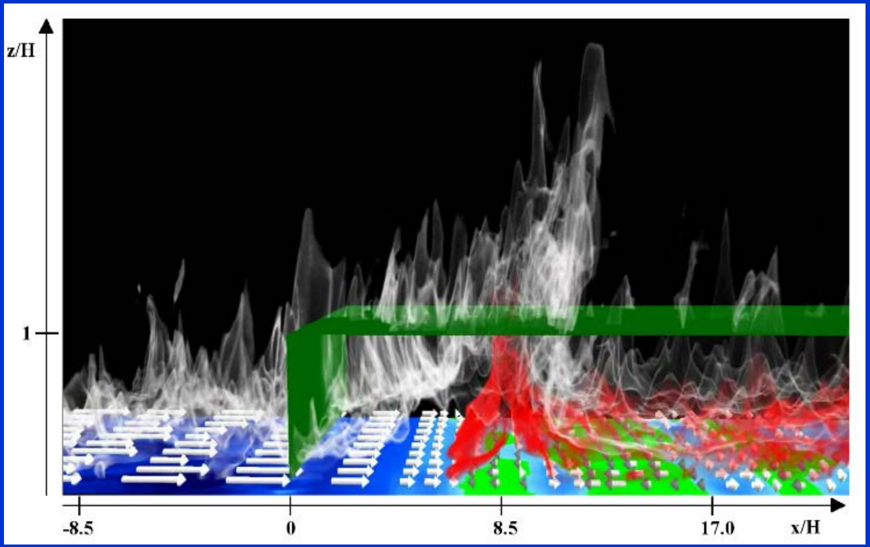
$$\overline{w^{+}} + \overline{w^{-}} = \overline{w} = 0$$



© Foken (2008)

3. Influence of an Heterogeneous Landscape with Canopy on Turbulent Fluxes





3. Influence of an Heterogeneous Landscape
Some Findings

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

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)

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

- 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

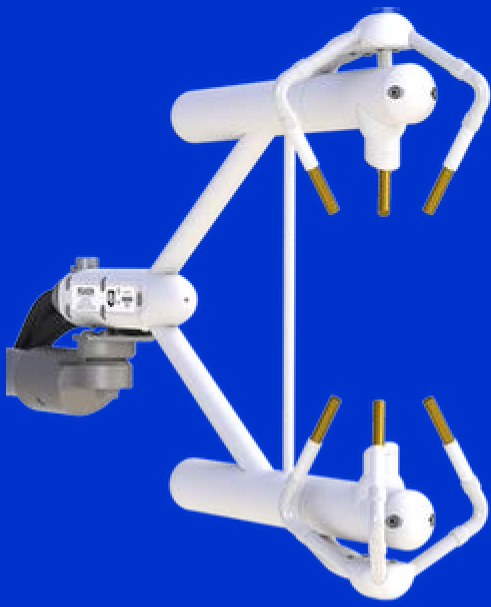
The knowledge of the fathers of the eddy-covariance method is often forgotten and errors of the first days of the method are repeated

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

20.05.2014

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

Two Papers with Different Outlooks

The Wind in the Willows: Flows in Forest Canopies in Complex Terrain

Stephen E. Belcher,[1] Ian N. Harman,[2] and John J. Finnigan[2]

Annu. Rev. Fluid Mech. 2012. 44:479–504

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

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