Capturing all relevant scales of biosphere-atmosphere exchange – the enigmatic energy balance closure problem

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The Energy Balance Closure Problem

Energy Balance

\[ R_n - G = \lambda E + H \]

- **H**: sensible heat flux
- **R_n**: net radiation
- **\lambda E**: latent heat flux
- **G**: soil heat flux

Worldwide in-situ measurements show:

**Underestimation** of turbulent exchange \((\lambda E + H)\) by 10-30%  
(e.g. Stoy and Mauder, 2011, analysis of 180 FLUXNET sites)
Energy Balance Closure – Landmarks

1985

- **Desjardins** *AFM* 36, 29-41: First description of the EBC problem

1995

- **Foken and Oncley** *BAMS* 76, 1191-1193: Raise awareness of the EBC problem and test various hypotheses

1998

- **Mahrt** *JTECH* 15, 416-429: Hypothesis: large-scale stationary circulations => spatial averaging

2004

- **Kanda** et al. *BLM* 110, 381-404.: First LES study of the EBC problem => spatial averaging
Agricultural and Forest Meteorology, 36 (1985) 29–41
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

CARBON DIOXIDE BUDGET OF MAIZE

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... underestimation of flux densities, which can be estimated using the energy balance approach, where net radiation minus soil heat flux density ($Q_n - Q_g$) should equal $Q_h + Q_e$. A sample of these flux densities recorded on a 10 minute basis, on calendar day 207 (1984), is presented in Fig. 3A. It can be seen that $Q_h + Q_e$ versus time are highly correlated with $Q_n - Q_g$. The extent of the underestimation of $Q_h + Q_e$ is taken into account in arriving at the corrected above-canopy CO$_2$ flux densities in Fig. 3B. It resulted in a mean increase in the CO$_2$ flux density of 15%. This approach ...
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Scale analysis of airborne measurements


Figure 1. Land cover classification of a Landsat thematic mapper (TM) image of the area around Candle Lake from 2 September 1994 [after Hall et al., 1997]. The flight track of the National Research Council (NRC) Twin Otter Candle Lake Run is indicated by a triple line.
Scale analysis of airborne measurements

Wavelet cross-scalograms

Flight BOREAS 1
1041 – 1116 CST
25 May 1994

Taylor-hypothesis:
2 km = 30 min x 1.1 m s⁻¹
Scale analysis of airborne measurements

![Graph showing cospectra and wavelength analysis](image)

- $Q_H$
- $Q_E$
- CO$_2$-Flux
- O$_3$-Flux

Wavelength (m)

- Turbulent
- Large-scale
Scale analysis of airborne measurements

20 flights analysed
⇒ 10 – 30%
large-scale flux contribution
⇒ Same magnitude as the imbalance of tower measurements below the flight track
Multi-tower set-up, 2008

27 June to 6 August 2008, Energy balance residual at central site

Research farm near Ottawa, Canada

Multi-tower set-up, 2008

27 June to 6 August 2008, mean vertical wind velocity

Temporal mean of the vertical velocity $w$ (m s$^{-1}$)

-0.06
-0.05
-0.04
-0.03
-0.02
-0.01
0.00

Time of day (EST)
0000   0400   0800   1200   1600   2000   0000

$=>$ Vertical advection
$=>$ Horizontal divergence
$=>$ Updraft at some distance
Multi-tower set-up, 2008, land use map

- Forage
- Corn
- Soy bean
- Wheat
- Mixed

1.2 km forage

1.2 km soy bean
Mean vertical wind velocity

27 June to 6 August 2008

Open canopy, \( h_c < 15 \text{ cm} \)

Closed canopy, \( h_c > 15 \text{ cm} \)
How can large-scale circulations cause a systematic lack of energy balance closure?

relatively cool and dry air

relatively warm and moist air
Conclusions

- Large-scale circulations superimposed on the general wind field are a dominant cause for the energy balance closure problem.

- Aircraft measurements show that the magnitude of large-scale transport is the same as the missing flux of tower measurements.

- From a multi-tower set-up, the updraft regions and downdraft regions of large-scale circulations could be identified.

- The development of innovative approaches for quantifying the complete biosphere-atmospheric exchange of a scalar is warranted.
Thank you for your attention!

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