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Limitations of two energy balance closure parameterizations

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Motivation: the energy balance closure problem

The **eddy-covariance technique** tends to underestimate the fluxes of sensible (Q_H) and latent heat (Q_E) by 10-30%. Consequently, the turbulent heat fluxes are not in balance with the net radiation ($-Q_S^*$) and the ground heat flux (Q_G), which is known as the **energy balance closure problem**. The energy balance ratio (R),

$$R = \frac{Q_H + Q_E}{-Q_S^* - Q_G},$$

is usually smaller than 1.

Since the eddy-covariance method is widely used to determine fluxes of energy and trace gases on an ecosystem scale, a robust **parameterization of the missing turbulent energy** is necessary. Here, we tested two approaches that can be found in the literature: ***Huang et al. (2008)*** and ***Panin and Bernhofer (2009)***.

Data I: aircraft measurements (Canada)

Flight details (Fig. 1):

- BOREAS,1994: 16 flights
- BERMS, 2002: 4 flights
- height: ~ 30 m a.g.l.
- length: ~ 110 km

Energy balance closure from airborne data:

1. Calculate cross-scalograms (wavelet transform) of w and T / w and q
2. Determine flux contribution of scales < 2 km
3. $R = \frac{(Q_H + Q_E)_{scales<2km}}{(Q_H + Q_E)_{all\ scales}}$

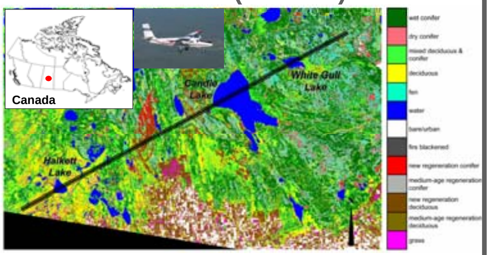

FIG 1 Location of the 20 flights conducted by the Twin Otter Research aircraft during BOREAS and BERMS and land use in the investigation area (*Hall et al. 1997*)

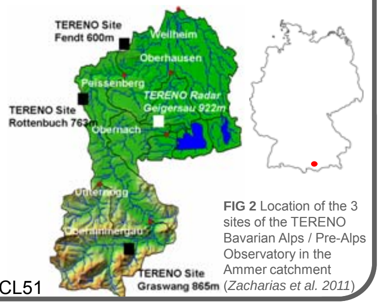

FIG 2 Location of the 3 sites of the TERENO Bavarian Alps / Pre-Alps Observatory in the Ammer catchment (*Zacharias et al. 2011*)

Data II: tower measurements (TERENO, Bavarian Alps / pre-Alps Observatory)

Graswang
47° 34‘ 16“ N
11° 01‘ 59“ E
865 m a.s.l.
R = 0.73

Equipment (i.a.):
CSAT-3, LI-7500, CL51

Rottenbuch
47° 43‘ 48“ N
10° 58‘ 10“ E
763 m a.s.l.
R = 0.60

Equipment (i.a.):
CSAT-3, LI-7200, CL51

Fendt
47° 50‘ 12“ N
11° 03‘ 37“ E
600 m a.s.l.
R = 0.77

Equipment (i.a.):
CSAT-3, LI-7500, CL51

Parameterization by *Huang et al. (2008)*

Description:

- **large-eddy simulation** of the **homogeneous** convective boundary layer
- considers **atmospheric conditions**
- energy imbalance (I) due to the presence of **turbulent organized structures**
- parameterization of the energy imbalance **for every 30-min period**

$$I = \frac{Q_H + Q_E}{-Q_S^* - Q_G} - 1 \qquad I \sim f_1\left(\frac{u_*}{w_*}\right) \times f_2\left(\frac{z}{z_i}\right)$$

u_*: friction velocity, w_*:Deardorff velocity, z: measurement height; z_i: boundary-layer depth

Results:

- only daytime data were analyzed ($-Q_S^*$ > 30 W m^{-2})
- dependence of energy imbalance on u_* / w_*: function f_1 could **not** be confirmed; no correlation with u_* / w_* was found (Fig. 3)
- dependence of energy imbalance on z / z_i: also **no** correlation (data not shown)
- but: **weak dependence of imbalance on u_*** at 2 of 3 TERENO sites (Fig. 4)

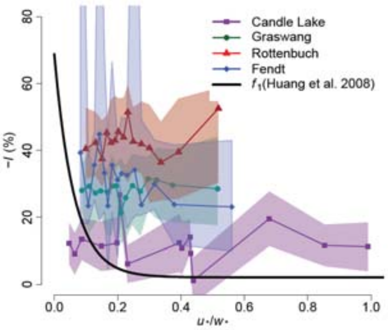

FIG 3 Energy imbalances (*–I*) for 16 aircraft flights above Candle Lake during BOREAS and for the TERENO sites Graswang, Rottenbuch and Fendt vs. the ratio of friction velocity (u_*) to Deardorff velocity (w_*); shaded areas indicate interquartile ranges and, for Candle Lake, the random error of the airborne measurements (*Eder et al. 2014, modified*)

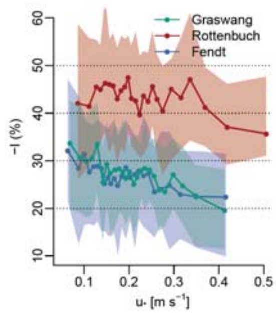

FIG 4 Energy imbalance (*–I*) vs. friction velocity (u_*) for Graswang, Rottenbuch and Fendt; shaded areas indicate interquartile ranges

Discussion / Conclusions:

The parameterization is **not applicable** to our surface-layer data.

- neglects any influence of surface heterogeneities
- w_* is not an appropriate scaling parameter for the surface layer
- the large-eddy simulation model used by *Huang et al. (2008)* has an insufficient grid resolution close to the surface

Parameterization by *Panin and Bernhofer (2008)*

Description:

- empirical parameterization, based on **eddy-covariance measurements**
- considers **properties of the landscape** (surface roughness heterogeneities)
- energy imbalance due to secondary circulations **generated by heterogeneities**
- parameterization of the **mean** energy balance correction factor (k_f) for a site

$$k_f = \frac{-Q_S^* - Q_G}{Q_H + Q_E} \qquad k_f \sim \frac{z_{0eff}}{L_{eff}}$$

z_{0eff}: effective surface roughness, L_{eff}: horizontal scale of the heterogeneities

Results:

- Determination of heterogeneity index (z_{0eff}/L_{eff}): surface roughness maps (Fig. 5), L_{eff}: Fourier transform along selected transects
- **k_f factor of TERENO sites is larger** (i.e. energy balance closure is poorer) than expected (Fig. 6)
- the data from Candle Lake match well with the data of *Panin and Bernhofer (2008)*

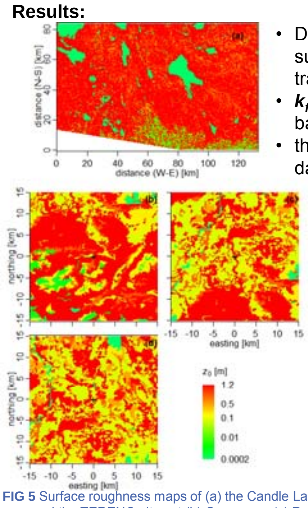

FIG 5 Surface roughness maps of (a) the Candle Lake area and the TERENO sites at (b) Graswang, (c) Rottenbuch and (d) Fendt; in (b)-(d), black crosses mark the approximate location of the EC systems (*Eder et al. 2014*)

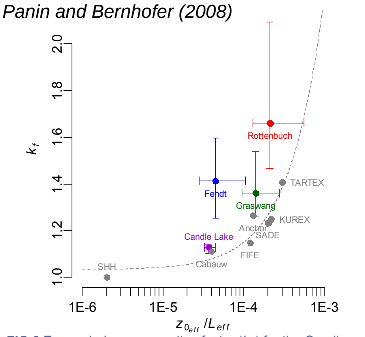

FIG 6 Energy balance correction factor (k_f) for the Candle Lake area and the EC systems at Graswang, Rottenbuch and Fendt vs. heterogeneity index (z_{0eff}/L_{eff}); data from *Panin and Bernhofer (2008)* are displayed in grey (*Eder et al. 2014*)

Discussion / Conclusions:

A **rough qualitative estimate** of the energy imbalance is possible.

- neglects any surface heterogeneity other than surface roughness, e.g. surface temperature, surface moisture, topography
- L_{eff} is the crucial parameter, but there should be an ‘optimum scale’ of heterogeneites (e.g. 4-9 times z_i, cf. *Patton et al. 2005*)

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