2.8 EDDY SAMPLING METHODS, A COMPARISON USING SIMULATION RESULTS

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1. INTRODUCTION

Different Eddy Sampling methods derived from the Eddy Covariance (EC) method are used to measure trace gas fluxes in the boundary layer when fast chemical sensors are not available (Table 1a). Sampling in Relaxed Eddy Accumulation (REA), Hyperbolic Relaxed Eddy Accumulation (HREA) and Disjunct Eddy Covariance (DEC) was simulated using high resolution datasets. These simulations allowed to quantify sources of error in REA, HREA and DEC methods originating from underlying assumptions and depending on the meteorological conditions (Table 1b).

2. THEORY

Methods based on Relaxed Sampling are indirect methods for flux measurements, because they rely on a parameterization in which the so called b-factor is determined from a second scalar quantity (proxy scalar) which shows similarity in its atmospheric transport and can be measured with high temporal resolution, e.g. temperature or water vapor. Flux-variance similarity is assumed when using the variance of the vertical wind velocity σ_w in the parameterization (Businger and Oncley, 1990) (Table 1b, row 3 and 4). F_s is the turbulent flux of a scalar s determined by Eddy Covariance ($\overline{w's'}$).

$$F_s \approx b \cdot \sigma_w \cdot \Delta s \tag{1.1}$$

Application of a wind deadband D, in which no samples are taken, increases the concentration difference Δs in the accumulation reservoirs and thereby the certainty of the flux measurement.

$$\left| \frac{w'}{\sigma_w} \right| \le D \tag{1.2}$$

In HREA the deadband is applied not only to samples with small fluctuations of the vertical wind velocity w' but extended to samples with small deviations from the mean concentration, which further increases the concentration difference Δs (Bowling et al., 1999).

$$\left| \frac{w' \cdot s'}{\sigma_w \cdot \sigma_s} \right| \le H \tag{1.3}$$

The hyperbolic deadband must be determined online from a proxy scalar measured with high temporal resolution, which again assumes scalar similarity ($s \approx s_{proxy}$) (Table 1b, row 5).

A deadband reduces the number of samples used for flux calculation (Table 1b, row 2 and 6). It can reduce the sensitivity to uncertain definition of the mean vertical wind velocity $\overline{w}$ from preceding wind data needed for segregating samples in the up and down reservoir (Table 1b, row 1) (Businger and Oncley, 1990; Pattey et al., 1993).

Disjunct sampling is the basis for direct methods for flux measurements (Disjunct Eddy Covariance, DEC, Disjunct Eddy Accumulation, DEA) as it does not require parameterizations or assumptions of flux-variance or scalar similarity. Disjunct samples are taken very fast (grab sampling for 0.1 s) and represent a single 10 Hz sample ($w's'$). Samples are separated by disjunct intervals of several seconds, which violates the requirement of the sampling theorem to sample the highest energy containing frequency (Nyquist frequency) at least twice (Table 1b, row 7). The number of samples used for flux calculation decreases significantly in comparison to continuos sampling (Table 1a and 1b, row 6). The time during disjunct intervals is used to accumulate a volume proportional to w' (DEA) or to analyze gas samples in-situ with a moderately fast sensor (DEC) (Lenschow et al., 1994; Rinne et al., 2000; Rinne et al., 2001). DEC allows to directly measrue fluxes of reactive gases that cannot be accumulated.

3. DATA

High resolution turbulence data (20 Hz) from the EBEX-2000 Experiment, San Joaquin valley, CA, USA (Oncley et al., 2002) was selected according to quality criteria (Foken and Wichura, 1996) for the simulation of Eddy Sampling methods in order to minimize errors from instationarity and inhomogeneity. Selected data from 9 to 16 h local time on August 20th, 2000 assured significant absolute buoyancy, humidity and CO_2 fluxes. A planar fit rotation (Wilczak et al., 2001) was applied to the wind data to minimize errors from changing flow field orientation.

4. SIMULATIONS

REA and HREA simulations applied different wind deadband sizes (*D*) and hyperbolic deadband sizes (*H*) and used buoyancy flux or humidity flux to derive b-factors for CO_2 flux calculations.

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For DEC simulations up to 50 realizations were performed for one integration interval of 30 min. by starting disjunct sampling with different offsets. The large number of results allowed thorough statistical analysis of the bias and the scatter of results.

Relative flux errors in reference to the EC flux were used in the evaluation in order to excluded errors similarly inherent to EC and derived Eddy Sampling methods. The Variation coefficient equals a normalized standard deviation. It was used to quantify the systematic deviation and random scatter of results around the EC flux.

5. RESULTS

Simulation results presented in this abstract assume ideal conditions for accumulation methods (REA, HREA, DEA), as a definition of $\overline{w}$ from planar fit rotation (Wilczak et al., 2001) was used instead of estimating $\overline{w}$ from preceding data. The letter is a necessary online procedure in field experiments when measuring gas fluxes with accumulation methods (Table 1b, row 1). Expected additional error could be analyzed by changing the simulation procedures to fully include the corresponding uncertainty.

5.1. Relaxed Sampling

Fixed *b*-factors (*b* = 0.56, deadband correction according to Pattey et al., 1993) produce larger uncertainty in flux results of ideal REA simulations than *b*-factors derived from proxy scalars (Figure 1). Errors from scalar similarity were small when summarizing REA results for a whole day. However, slightly reduced similarity during certain periods was detected in REA flux errors (water vapor and CO_2 before noon, sonic temperature and CO_2 after noon) (periodic small negative effect, Table 1b, line 4).

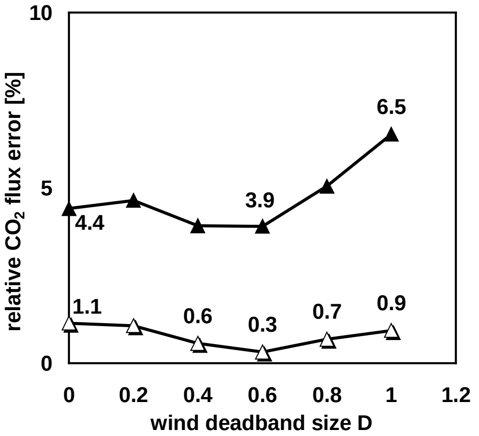

Figure 1. Variation coefficients from REA simulations using fixed *b*-factors (filled triangles) and *b*-factors calculated from humidity flux (empty triangles) expressed as relative CO_2 flux error.

The introduction of a wind deadband ($D \le 0.6$) in REA simulations decreases the error caused by non-perfect scalar similarity and the uncertainty in the definition of $\overline{w}$ which is present even when previously rotating coordinates (positive effect, Table 1b, row 1). Relative flux errors start to increase in relaxed sampling methods, when increasing wind or hyperbolic deadband sizes $D, H > 0.8$ and thereby decreasing sample numbers (negative effect, Table 1, row 6). Errors due to missing flux information from samples within the deadband and from missing validity of the flux variance similarity remained undetected in the simulation results (Table 1b, row 2 and 3).

Minimum relative CO_2 flux errors occur in ideal simulations of REA using a wind deadband of $D = 0.6$ and *b*-factors calculated from humidity fluxes (variation coefficient = 0.3 %).

5.2. Hyperbolic Relaxed Eddy Accumulation

HREA flux measurement simulations show relative flux errors up to 26 % underestimation during certain periods due to poor scalar similarity. The errors observed increase with the size of the hyperbolic deadband *H* (Figure 2) (periodic strong negative effect, Table 1b, line 5).

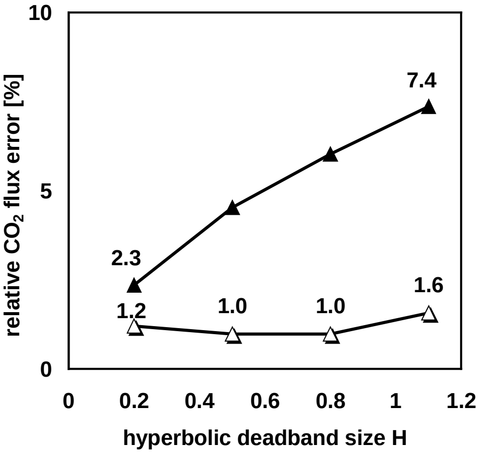

Figure 2. Variation coefficients from HREA simulations using *b*-factors calculated from buoyancy flux (filled triangles). Empty triangles represent simulation results when excluding periods of poor scalar similarity (15–16 h).

Minimum relative CO_2 flux errors in HREA were found only when excluding periods of poor scalar similarity, using *b*-factors calculated from buoyancy fluxes and applying hyperbolic deadbands of $H = 0.5$ or $H = 0.8$ (variation coefficient = 1.0 %)

5.3. Disjunct Sampling

No systematic error from violation of the sampling theorem was detected in simulations of DEC (bias < ± 1%) (Table 1b, row 7). Simulation results from multiple realizations were normally distributed. Remaining random error was quantified by the variation coefficient and found to depend mainly on the number of samples taken, which is defined by the disjunct interval applied (Figure 3 and Table 1b, row 6). DEC simulation results for buoyancy flux, humidity flux and CO_2 flux showed only small differences. When assuming ideal information on $\overline{w}$, no additional error is present in DEA simulation results.

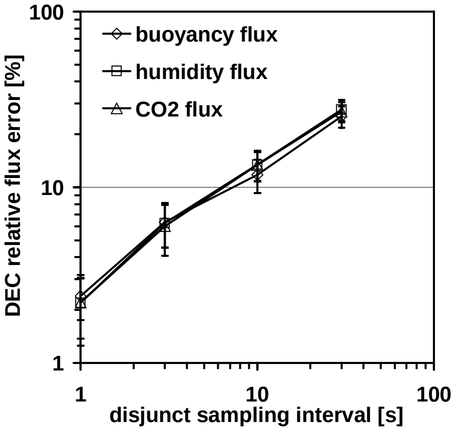

Figure 3. Average variation coefficients from DEC simulation results as a measure for the random error. Error bars are standard deviations used to indicate the scatter of variation coefficients from different integration intervals from 9 to 16 h.

6. DISCUSSION

Using an ideal definition of the mean vertical wind velocity $\overline{w}$, simulations showed generally smaller errors for REA methods than for the disjunct sampling methods investigated (1 s, 3 s, 10 s, 30 s). In the simulations presented, REA has slightly smaller relative flux errors when using optimum deadband sizes than HREA during periods of good scalar similarity.

While the use of a fixed b-factor in REA is not able to adjust to the diurnal variation of the b-factor, the use of a proxy scalar to parameterize the b-factor was able to reduce errors in REA simulations. The minimum error in REA methods coincides with an optimum in concentration difference at wind deadband sizes about $D \approx 0.6$ (Oncley et al., 1993), which means that also sources of error related to the hardware and sensor resolution will be minimal at this deadband size.

The use of HREA might be required for reaching concentration differences above the detection limit of a sensor. Then, it must be applied with great care regarding the underlying assumption of scalar similarity under changing meteorological conditions to avoid systematic errors. An analysis of the advantage of HREA over REA for measuring certain species fluxes will need a definition of the error due to measuring very close to the limit of detection. Simulation results for the concentration difference can be used to estimate errors related to sensor accuracy. Further investigation should aim at finding ways to avoid large errors from periods of poor scalar similarity, e.g. by online evaluating bivariate joint frequency distributions to derive values for the mean vertical wind velocity $\overline{w}$ and for the definition of the deadband thresholds used to segregate samples.

In DEC, flux contributions from high frequency turbulence are accounted for as fast grab sampling (0.1 s) of the time series keeps the information on high frequency variability (aliasing effect) (Horst, 2000). Thus, violation of the sampling theorem causes no systematic errors, like loss of flux, as long as samples are taken fast enough. A general validity of these findings is suggested by missing systematic error for all disjunct sampling intervals analyzed and the similarity of results for different fluxes.

7. CONCLUSIONS

The risk of periodic errors from poor scalar similarity is much smaller in REA than in HREA. Therefore we conclude, that generally measuring fluxes with the REA method applying a wind deadband is less problematic than the application of hyperbolic deadbands.

The absence of systematic errors and presence of random errors makes methods based on disjunct sampling more appropriate to measure long term budgets than for specifying absolute fluxes during individual short time periods. The DEC method allows to measure fluxes of reactive trace gases that cannot be measured by accumulation techniques due to their instability. Simulation results presented in this study can be used to estimate uncertainty of DEC measurements.

A complete assessment of the most appropriate method to measure turbulent fluxes of certain scalar quantities like trace gases should additionally include errors that have to be expected from the hardware of a Eddy Sampling system and the restrictions given by the sensor to be used. Minimal systematic errors and the identification and quantification of random errors of such flux measurements are essential for their correct interpretation. Thus, the findings of this study can be used to improve the quality of flux measurements and thereby contribute to better understanding of exchange processes in the boundary layer.

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Table 1 a) Eddy Sampling methods and b) their methodological sources of error

a) **Eddy Sampling methods** derived from Eddy Covariance	**EC**	**EA**[1]	**REA**[1]	**REA**	**HREA**	**DEC**	**DEA**
	Eddy Covariance	Eddy Accumulation	Relaxed Eddy Accumulation (no deadband)	Relaxed Eddy Accumulation (wind deadband)	Hyperbolic Relaxed Eddy Accumulation	Disjunct Eddy Covariance	Disjunct Eddy Accumulation
	direct method	direct method	indirect method	indirect method	indirect method	direct method	direct method
Eddy Sampling	continuous	continuous	continuous	continuous	continuous	disjunct	disjunct
		proportional[2]	relaxed[3]	relaxed[3]	relaxed[3]		proportional[2]
	in situ measurement of scalar at 10 Hz rate			wind deadband size e.g. $D = 0.6 \geq \left\vert \frac{w'}{\sigma_w} \right\vert$	hyperbolic deadband size e.g. $H = 0.8 \geq \left\vert \frac{w's'}{\sigma_w \sigma_s} \right\vert$	in situ measurement of scalar e.g. every 10s	e.g. every 10 s
No. of Samples taken during 30 min. integration interval	18000	18000	18000	e.g. 10000	e.g. 6000	e.g. 180	e.g. 180

b) **Methodological sources of error** investigated by simulation in this study [4]								
1	uncertainty of $\overline{w}$ when estimating online from preceding data		**-**	**-**	**± (D)**	**± (H)**		**-**
2	deadband error: assuming neglectable net flux contribution within the deadband				**- (D)**	**- (H)**		
3	validity of flux-variance similarity when using σ_w as wind proportionality factor for flux calculation			**- (σ_w)**	**- (σ_w)**	**- (σ_w)**		
4	Scalar similarity of the proxy scalar used for parameterization of factor b			**- (s-proxy)**	**- (s-proxy)**	**- (s-proxy)**		
5	Scalar similarity of the proxy scalar used for online determination of the hyperbolic deadband H					**- (s-proxy)**		
6	number of samples used for flux calculation (amount of information)				**- (D)**	**- (H)**	**-- (DS int.)**	**-- (DS int.)**
7	violation of sampling theorem						**o (DS int.)**	**o (DS int.)**

- = negative and **+** = positive influence on correctness of flux measurement, **o** = no systematic effect on flux results, **±** applying a deadband can reduce uncertainty

dependence on **(D)** =wind deadband, **(H)** =hyperbolic deadband, $\overline{w}$ = time mean of vertical wind velocity, **(s-proxy)** =scalar quantity used as proxy, **(σ_w)** =standard deviation of vertical wind velocity, **(σ_s)** = standard deviation of scalar quantity used as proxy, **(DS int.)** =disjunct sampling interval

[1] no realization for technical reasons, [2] sampling proportional to fluctuation of vertical wind velocity w' (conditional sampling), [3] sampling with constant gas flow, flux proportionality by parameterized factor b and the standard deviation σ_w of vertical wind velocity w, [4] Methodological sources of error similarly inherent to EC and all derived methods were minimized by data selection.