Quantized Eddy Accumulation with Error Diffusion

A *New* Direct Micrometeorological Technique with Minimal Requirements

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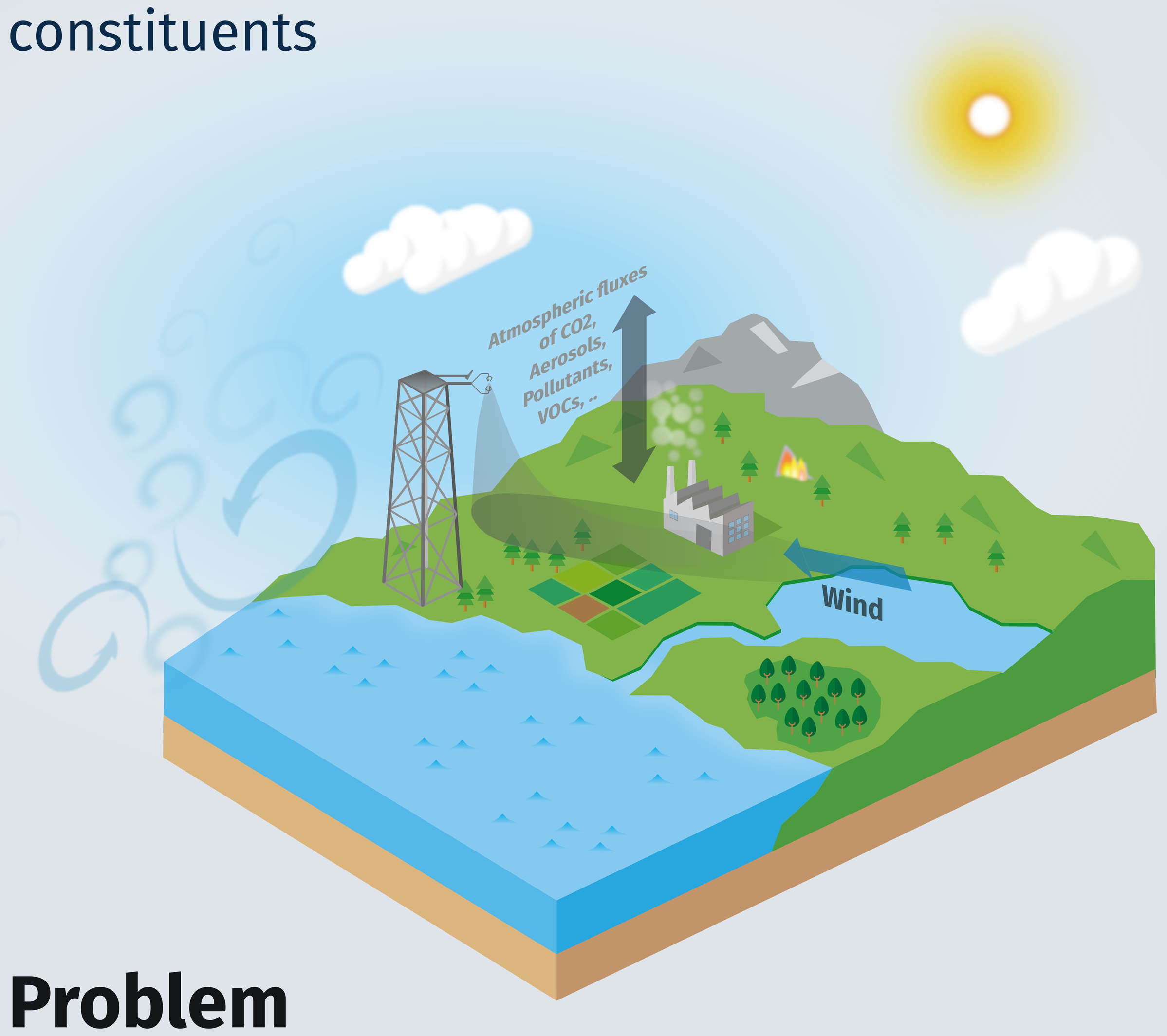
Background

Ecosystem-scale atmospheric fluxes are key to understanding terrestrial ecosystems' influence on atmospheric chemistry and global change

Eddy covariance, the gold standard in flux measurements, requires fast gas analyzers (typically > 10 Hz) to detect turbulent fluctuations relevant to transport, limiting its application to few atmospheric constituents



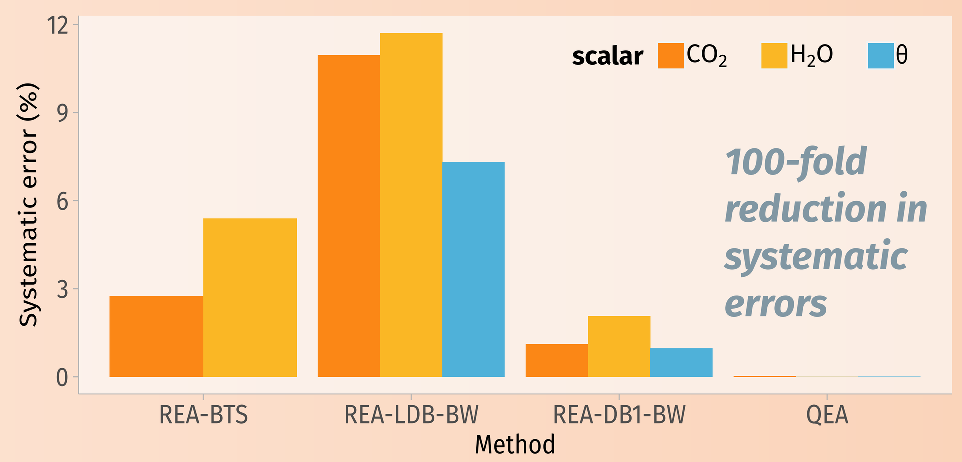
Problem

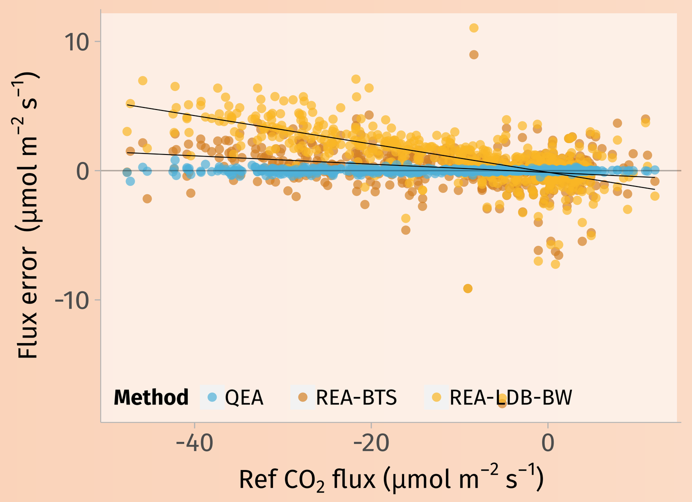
For a range of important atmospheric constituents, only slow-response analytical techniques are available such as stable isotopes, bio(aerosols), oxygen, and nitrogen compounds.

Current methods compatible with slow-response analyzers are either difficult to implement (such as true eddy accumulation) or have large biases due to dependence on estimated parameters (indirect)

A new method for slow-response analyzers

We developed **a new direct micrometeorological method** that combines the simple implementation requirements of relaxed eddy accumulation with the robustness and accuracy of eddy covariance



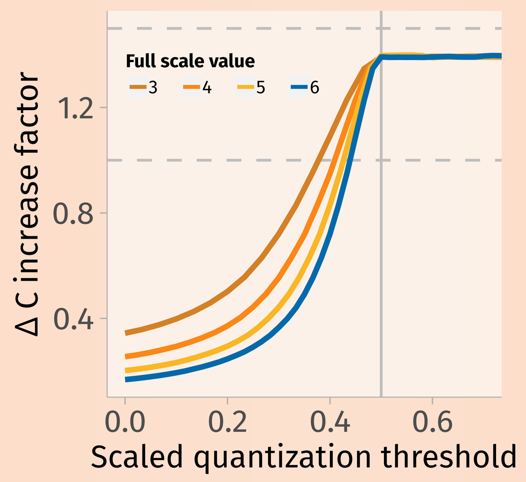


Simple implementation

Requires accumulating air into two reservoirs based on wind direction (updraft, downdraft) at a constant flow rate (no need for proportional flow rate control)

Direct and highly accurate

β is not needed. Errors less than 0.1% of the flux (over 100-fold smaller than REA) and random error less than 0.03 r_{wc}



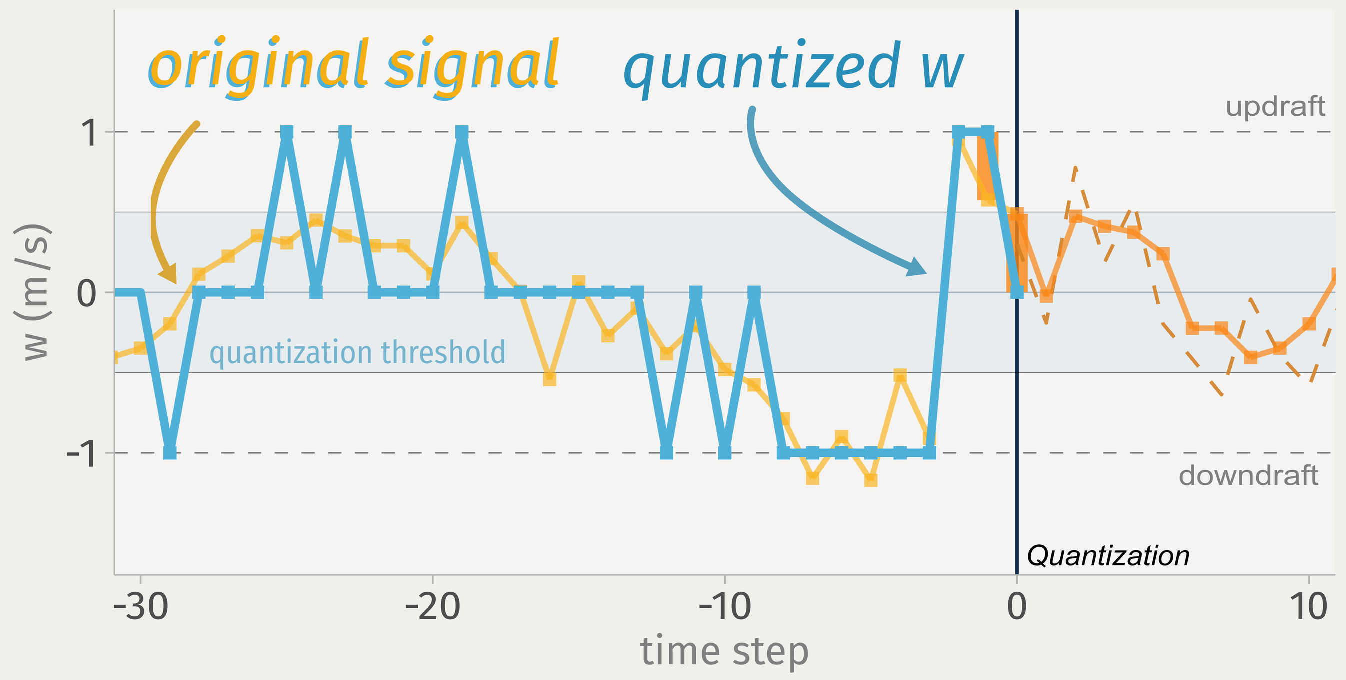
Enhance Signal-to-Noise

without compromising measurement accuracy, crucial for measuring small fluxes

Error diffusion allows to minimize biases in measured fluxes

What is error diffusion?

Error diffusion is a technique utilized in image and audio applications to enhance the perceptual quality of quantized signals.
Error from previous time step (or pixel in case of images) are diffused to current time step



1. **Modify** w with previous error $w_{mod} = w_n - err_{n-1}$
2. **Quantize** modified w $w_{qua} = Q(w_{mod})$
3. **Calculate** error $err = w_{qua} - w_{mod}$

Vertical wind velocity is quantized into three levels: up, down, and no-sampling. The quantization error (true - quantized) is used in a feedback loop to adjust the next measurement.

Theory

Relaxed eddy accumulation as a quantization process

- $flux = \overline{wc} = mean(w \times c)$ $\qquad \overline{wc} = \overline{c\,|w^{\uparrow}|}\,P_w^{\uparrow} - \overline{c\,|w^{\downarrow}|}\,P_w^{\downarrow}$
- Realize $w \times c$ by air accumulation $\qquad Flux = Acc_{\uparrow} - Acc_{\downarrow}$
- Accumulation of $\overline{c\,w^{\uparrow}}$ is very difficult
- "relaxation" by abolishing porportional control (Businger and Oncley 1990) $\qquad \overline{c\,w^{\uparrow}} \approx constant \cdot \bar{c}\,\bar{w}$
- Flux is expressed as

$$Flux = \beta\,\sigma_w\,\Delta C$$

- w can take only 3 values ($\overline{w^{\uparrow}}$, 0, $\overline{w^{\downarrow}}$)
- Rethinking conditional sampling as a quantization problem

$$\underbrace{\overline{cw}}_{\text{total flux}} = \underbrace{\overline{c\,w_q|I}}_{\text{quantized flux}} + \underbrace{\overline{c\,\varepsilon_q}}_{\text{quantization error}}$$

- This implies: REA is the flux of quantized w
- β linked to quantization errors

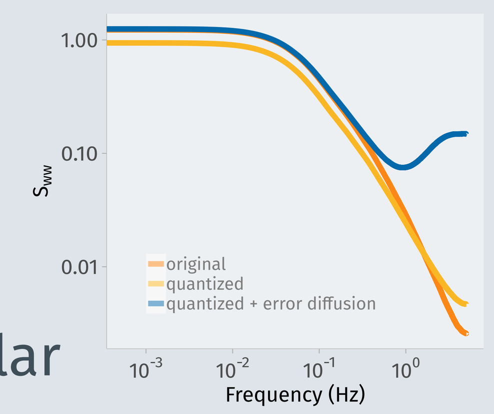
We can use error diffusion to randomize the error term

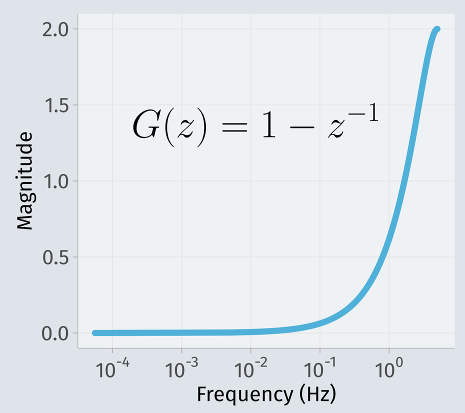
- Adjusted quantized wind measurement incorporating error diffusion:

$$w_q[n] = Q\left(w[n] - \varepsilon_q[n-1]\right)$$

The unreasonable effectiveness of error diffusion

Errors from spurious covariance between quantization error and scalar concentration are less than expected from two random samples, as error diffusion acts as a high-pass filter and shapes the noise





Learn more, test with your own data!

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Figure 1. adapted from Browne et al (2019)