Micrometeorological Methods Used to Measure Greenhouse Gas Fluxes: The Challenges Associated with Them, at the Local to Global Scales

Dennis Baldocchi and Matteo Detto
University of California, Berkeley

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Methods To Assess Terrestrial Carbon Budgets at Landscape to Continental Scales, and Across Multiple Time Scales

- GCM Inversion Modeling
- Remote Sensing/ MODIS
- Eddy Flux Measurements/ FLUXNET
- Forest/Biomass Inventories
- Physiological Measurements/ Manipulation Expts.
- Biogeochemical/ Ecosystem Dynamics Modeling
From point to globe via integration with remote sensing (and gridded meteorology)

century

decade

year

month

week

day

hour

Forest/soil inventories

Landsurface remote sensing

Eddy covariance towers

tall tower observatories

remote sensing of CO₂

Spatial scale [km]

local
plot/site

0.1

1

10

100

1000

Countries

10,000

EU

global

Markus Reichstein, MPI
Challenges in Measuring Greenhouse Gas Fluxes

• Measuring/Interpreting greenhouse gas flux in a quasi-continuous manner for days, years and decades
• Measuring/Interpreting fluxes over patchy sources (e.g. CH$_4$, N$_2$O)
• Measuring/Interpreting fluxes of temporally intermittent sources (CH$_4$, N$_2$O, O$_3$, C$_5$H$_8$, HNO$_3$, SO$_2$, NO$_x$)
• Measuring/Interpreting fluxes over complex terrain
• Measuring fluxes of greenhouse gases in remote areas without ac line power
• Developing New Sensors for Routine Application of Eddy Covariance, or Micrometeorological Theory, for trace gas Flux measurements and their isotopes (CH$_4$, N$_2$O, $^{13}$CO$_2$, C$^{18}$O$_2$)
Eddy Covariance

- Direct Measure of the Trace Gas Flux Density between the atmosphere and biosphere, mole m\(^{-2}\) s\(^{-1}\)
- *In situ*
- Quasi-continuous
- Integrative of a Broad Area, 100s m\(^2\)
- Introduces No artifacts, like chambers
Eddy Covariance,
Flux Density: mol m\(^{-2}\) s\(^{-1}\) or J m\(^{-2}\) s\(^{-1}\)

\[
F = \rho_a ws \sim \rho_a \cdot w's'
\]

\[
s = \left(\frac{\rho_c}{\rho_a}\right)
\]
Eddy Covariance Tower
Sonic Anemometer, CO2/H2O IRGA,
inlet for CH4 Tunable diode laser spectrometer &
Meteorological Sensors
24 Hour Time Series of 10 Hz Data, Vertical Velocity (w) and Methane (CH₄) Concentration

Sherman Island, CA: data of Detto and Baldocchi
Non-Dispersive Infrared Spectrometer, CO₂ and H₂O

Open-path, 12.5 cm
Low Power, 10 W
Low noise, CO₂: 0.16 ppm; H₂O: 0.0047 ppth
Low drift, stable calibration
Low temperature sensitivity: 0.02%/degree C
Measuring Methane with Off-Axis Infrared Laser Spectrometer

Closed path
Moderate Cell Volume, 400 cc
Long path length, kilometers
High power Use:
Sensor, 80 W
Pump, 1000 W; 30-50 lpm
Low noise: 1 ppb at 1 Hz
Stable Calibration

Los Gatos Research
Piccaro, Cavity Ring-Down Infrared Laser Spectrometer

Closed path
Smaller Cell Volume, 35 cc
Long path length, 20 km
Less Power Use: < 300 W, sensor and pump
Moderate Noise: 3 ppb at 10 Hz
Stable Calibration
LI-7700 Methane Sensor, variant of frequency modulation spectroscopy

Open path, 0.5 m
Short optical path length, 30 m
Low Power Use: 8 W, no pump
Moderate Noise: 5 ppb at 10 Hz
Stable Calibration
Power Spectrum defines the Frequencies to be Sampled

Power Spectrum

\[ w' w' = \int_{0}^{\infty} S_{ww}(\omega)d\omega \]

Co-Spectrum

\[ F = w' c' = \int_{0}^{\infty} S_{wc}(\omega)d\omega \]
Power and Co-Spectra

Must Sample Eddies up to 10 times per second for 30 to 60 minutes
Comparing Co-spectra of open-path CO2 & H2O sensor and closed-path CH4 sensor

Co-Spectra are More Forgiving of Inadequate Sensor Performance than Power Spectra

M. Detto and D. Baldocchi
Co-Spectra is a Function of Atmospheric Stability:
Shifts to Shorter Wavelengths under Stable Conditions
Shifts to Longer Wavelengths under Unstable Conditions

Detto, Baldocchi and Katul, Boundary Layer Meteorology, conditionally accepted
Signal Attenuation:
The Role of Filtering Functions

• High and Low-pass filtering via Mean Removal
  – Sampling Rate (1-10Hz) and Averaging Duration (30-60 min)
• Digital sampling and Aliasing
• Sensor response time
• Sensor Attenuation of signal
  – Tubing length and Volumetric Flow Rate
  – Sensor Line or Volume averaging
• Sensor separation
  – Lag and Lead times between w and c
Zero-Flux Detection Limit, Detecting Signal from Noise

\[ F = \frac{w'c'}{\sigma_w \sigma_c} \]

- \( r_{wc} \approx 0.5 \)
- \( \sigma_{\text{ch4}} \approx 0.84 \text{ ppb} \)
- \( \sigma_{\text{co2}} \approx 0.11 \text{ ppm} \)

<table>
<thead>
<tr>
<th>U* (m/s)</th>
<th>( \sigma_w ) (m/s)</th>
<th>( F_{\text{min, CH4}} ) (nmol m(^{-2}) s(^{-1}))</th>
<th>( F_{\text{min, CO2}} ) ((\mu\text{mol m}(^{-2}) s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.125</td>
<td>2.1</td>
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<td>0.3</td>
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<td>0.5</td>
<td>8.4</td>
<td>1.1</td>
</tr>
<tr>
<td>0.5</td>
<td>0.625</td>
<td>10.5</td>
<td>1.375</td>
</tr>
</tbody>
</table>

Methane Lab Calibration

Mean: 1897.4277
StdDev: 0.8411
Std Err: 0.0219
Most Sensors Measure Mole Density, Not Mixing Ratio

Formal Definition of Eddy Covariance, V2

\[ F = \rho_a w s \approx \rho_a \cdot w' s' = w \rho_c = w' \rho_c' + w \rho_c \]
Webb, Pearman, Leuning Algorithm: ‘Correction’ for Density Fluctuations when using Open-Path Sensors

\[ F_c = \overline{w' \rho_c'} + \frac{m_a}{m_v} \overline{\rho_c'} \overline{w' \rho_v'} + (1 + \frac{\overline{\rho_v m_a}}{\rho_a m_v} \overline{\rho_c} \overline{w' T'}} \]
Raw $\langle w'c' \rangle$ signal, without density ‘corrections’, will infer Carbon Uptake when the system is Dead and Respiring.
Annual Time Scale, Open vs Closed sensors

Hanslwanter et al 2009
AgForMet

ESPM 228 Adv Topics Micromet & Biomet
Annual Sums comparing Open and Closed Path Irgas

Hanslwanter et al. 2009 AgForMet

ESPM 228 Adv Topics Micromet & Biomet
Flux Methods Appropriate for Slower Sensors, e.g. FTIR

• Relaxed Eddy Accumulation

\[ F = w' c' = \beta \sigma_w (\bar{c}_{up} - \bar{c}_{dn}) \]

• Modified Gradient Approach

\[ F_c \sim F_s \frac{\Delta c_z}{\Delta s_z} \]

• Integrated Profile

\[ F = \frac{1}{x} \int_0^z u(\rho_c - \rho_{\text{background}})dz \]

• Disjunct Sampling
The Real World is Not Kansas, which is Flatter than a Pancake
Eddy Covariance in the Real World
Diagnosis of the Conservation Equation for C for Turbulent Flow

\[
\frac{dc}{dt} = \frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} + w \frac{\partial c}{\partial z} = - \frac{\partial u'c'}{\partial x} - \frac{\partial v'c'}{\partial y} - \frac{\partial w'c'}{\partial z}
\]

I: Time Rate of Change  
II: Advection  
III: Flux Divergence
Daytime and Nighttime Footprints over an Ideal, Flat Paddock

\[ \frac{\partial F}{\partial z} = 0 \]

\[ F = \int \frac{\partial F}{\partial z} dz = \text{Const} \]

Detto et al. Boundary Layer Meteorology, conditionally accepted
Examine Flux Divergence

Detto, Baldocchi and Katul, Boundary Layer Meteorology, conditionally accepted
Cows, Near-Field Diffusion and CH₄ Spikes

![Graph showing CH₄ (PPM) over time with various hours highlighted.]

- **CH₄ (PPM)**
- **hour of day**

- Images of cows at different times throughout the day.
Estimating Flux Uncertainties:  
Two Towers over Rice

Detto, Anderson, Verfaillie, Baldocchi, unpublished
Typical Methane Fluxes Rice vs Peatland

Detto, Anderson, Verfaillie, Baldocchi, unpublished
Even Over Perfect Flat Sites with Extensive Fetch
Advection can/does Occur with Methane:

Source Strength of Hot spots and Cold Spots can Differ by 1 to 2 orders of Magnitude (10x to 100x)

Such Advection is Less Pronounced for Water Vapor and CO2 Fluxes Because Flux Differences Emanating from the Different Landforms are Smaller
Take-Home Message for Application of Eddy Covariance Method under Non-Ideal Conditions

• Comply with Governing Principles of Conservation Equation

• Design Experiment that measures Flux Divergence and Storage, in addition to Covariance
FLUXNET: From Sea to Shining Sea
500+ Sites, *circa* 2009
The global FLUXNET data base

Two major questions...

Informative or BS?  Globally relevant or only accupuncture?

- >1000 site-years from >250 sites

M Reichstein, MPI
Probability Distribution of Published NEE Measurements, Integrated Annually

![Histogram diagram showing the probability distribution of NEE measurements.](image)

- Mean: $-182.9$ gC m$^{-2}$ y$^{-1}$
- Standard deviation: 269.5
- Total measurements: 506

Source: Baldocchi, Austral J Botany, 2008
Ecosystem Respiration Scales Tightly with Ecosystem Photosynthesis, But Is with Offset by Disturbance

Baldocchi, Austral J Botany 2008
Net Ecosystem Carbon Exchange Scales with Length of Growing Season

Baldocchi, Austral J Botany, 2008
Soil Temperature: An Objective Indicator of Phenology??

Soroe, Denmark
Beech Forest
1997

Data of Pilegaard et al.
Soil Temperature: An Objective Measure of Phenology, part 2

Temperate Deciduous Forests

Day, $T_{soil} > T_{air}$

Day, $\text{NEE}=0$

Baldocchi et al. Int J. Biomet, 2005
Spatial Variations in C Fluxes

Xiao et al. 2008, AgForMet
Upscale NEP, Globally, Explicitly

1. Compute $GPP = f(T, \text{ppt})$
2. Compute $R_{\text{eco}} = f(GPP, \text{Disturbance})$
3. Compute $\text{NEP} = GPP - R_{\text{eco}}$

Leith-Reichstein Model

$$GPP = \min(f(MAT), g(P)) =$$

$$\min\left( \frac{GPP_{15^\circ C}}{1 + e^{a_1 - a_2 \cdot 15^\circ C}}, \frac{GPP_{1000mm}}{1 + e^{a_1 - a_2 \cdot MAT}}, \frac{1 - e^{-k \cdot P}}{1 - e^{-k \cdot 1000mm}} \right)$$

FLUXNET Synthesis
Baldocchi, 2008, Aust J Botany

$$R_{\text{eco}} = 101 + 0.7468 \times GPP$$

$$R_{\text{eco}, \text{disturbed}} = 434.99 + 0.922 \times GPP$$
Statistically Sampling and Climate Upscaling Agree

\[
\langle \text{NEE: FLUXNET} \rangle = -225 \pm 164 \text{ gC m}^{-2} \text{ y}^{-1}
\]

\[
\langle \text{NEE 0\% dist: sinusoidal} \rangle = -222 \text{ gC m}^{-2} \text{ y}^{-1}
\]
Don’t Get Too Confident, Yet

\[ \text{NEE} = -222 \text{ gC m}^{-2} \text{ y}^{-1} \]

This Flux Density Matches FLUXNET (-225) well, but \( \Sigma \text{NEE} = -31 \text{ PgC/y}!! \)

Implies too Large NEE \((|-700 \text{ gC m}^{-2} \text{ y}^{-1}| \text{ Fluxes in Tropics})\)
To Balance Carbon Fluxes infers that Disturbance Effects May Be Greater than Presumed

Net Ecosystem Exchange with 50% disturbance, \( \text{gC m}^{-2} \text{ y}^{-1} \)

\[
<\text{NEE}> = -4.5 \text{ gC m}^{-2} \text{ y}^{-1}
\]

\[
\Sigma \text{NEE} = -1.58 \text{ PgC/y}
\]
Conclusions
HI Tran Methane Spectra
1651 nm band IR absorption for Laser system
Raw Covariances for $<w'c'>$ and $<w'q'>$

Data of Detto, Verfaillie, Anderson and Baldocchi