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

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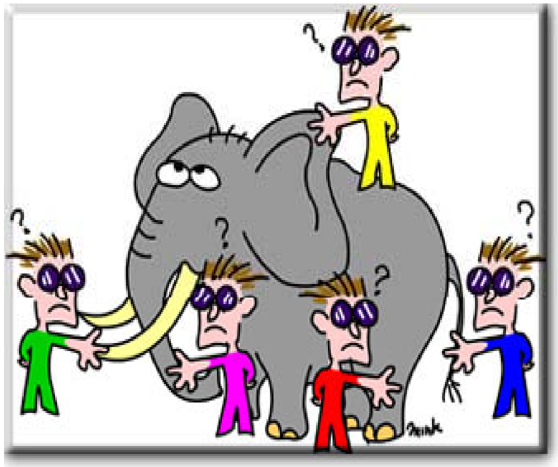
NIST Workshop on Advanced Greenhouse Gas Quantification Methods
March 24, 2010, Gaithersburg, MD

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

GCM Inversion Modeling



Eddy Flux Measurements/ FLUXNET

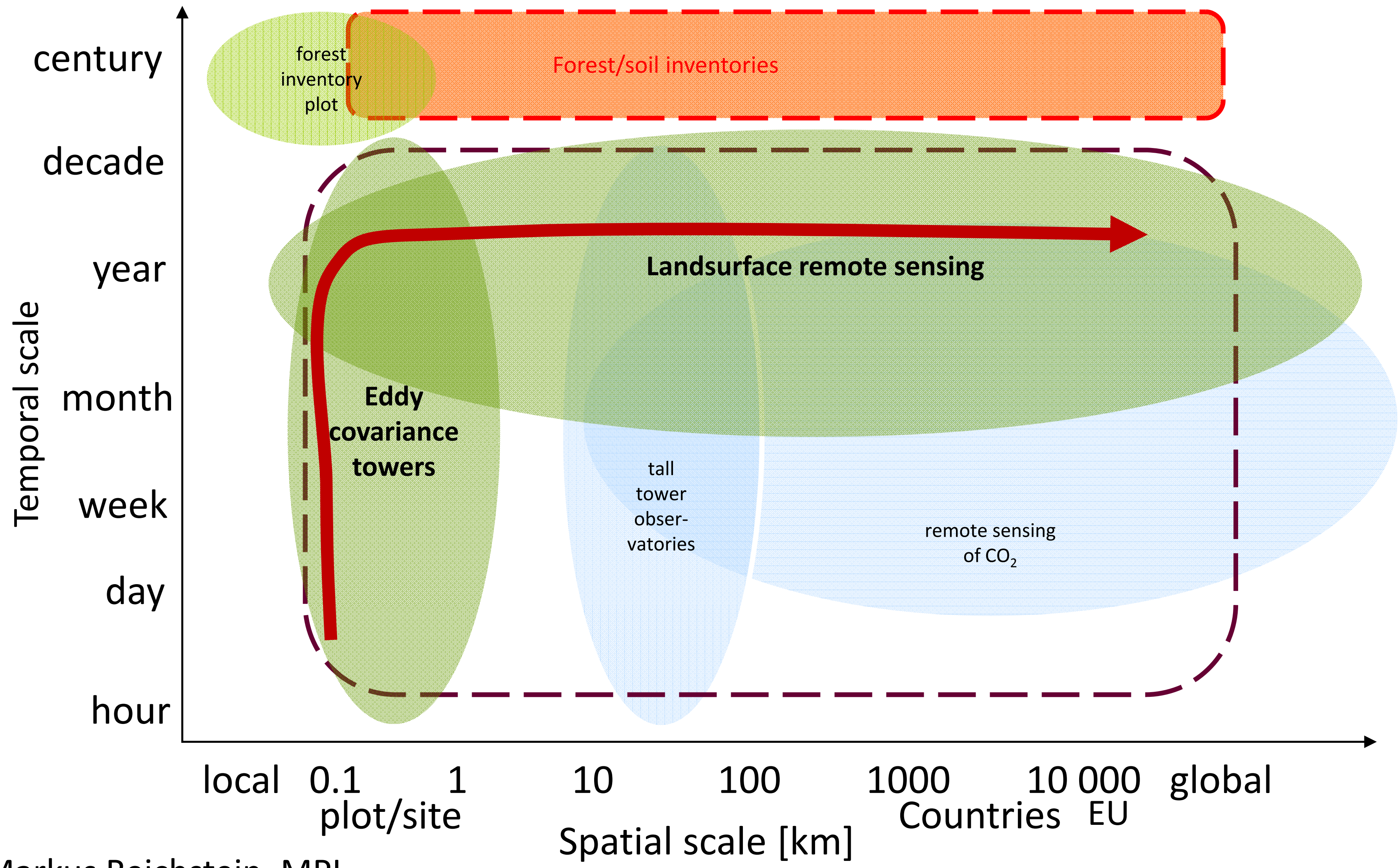
Remote Sensing/ MODIS

Forest/Biomass Inventories

Physiological Measurements/ Manipulation Expts.

Biogeochemical/ Ecosystem Dynamics Modeling

From point to globe via integration with remote sensing (and gridded metorology)



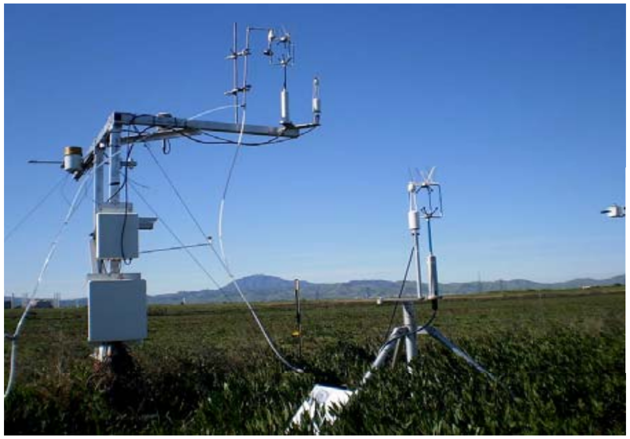
Markus Reichstein, MPI

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_2O)
- Measuring/Interpreting fluxes of temporally intermittent sources (CH_4, N_2O, O_3, C_5H_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_2O, $^{13}CO_2$, $C^{18}O_2$)

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

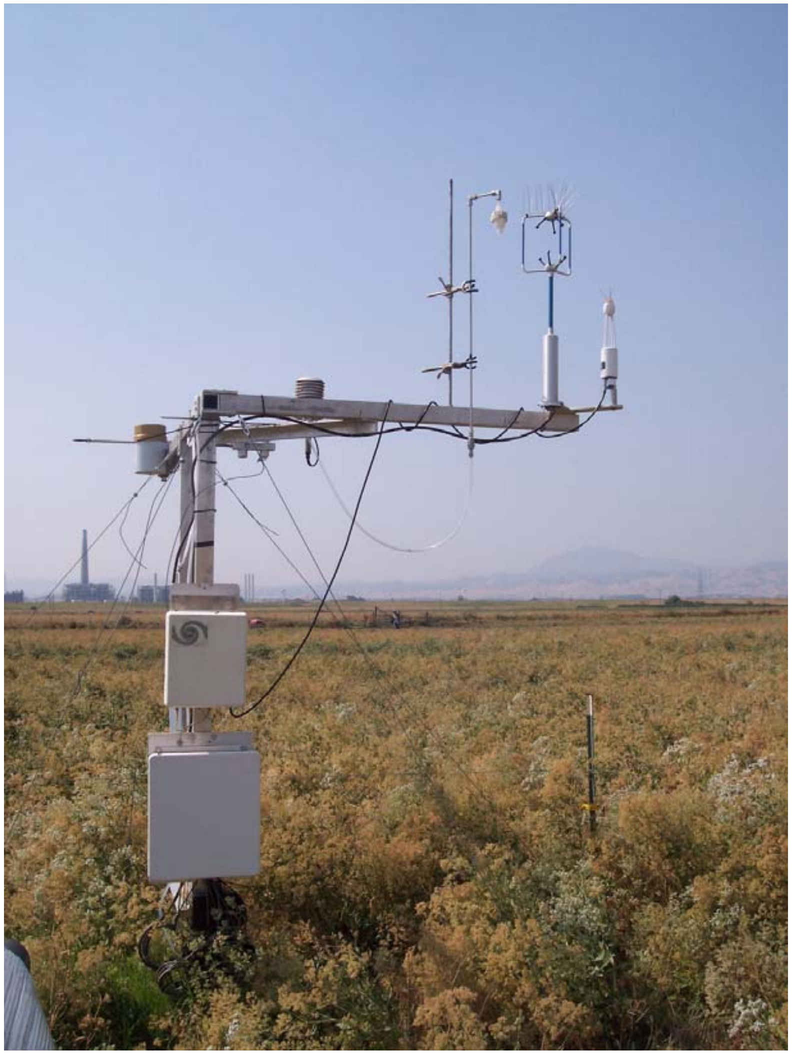


Eddy Covariance,
Flux Density: mol m^{-2} s^{-1} or J m^{-2} s^{-1}

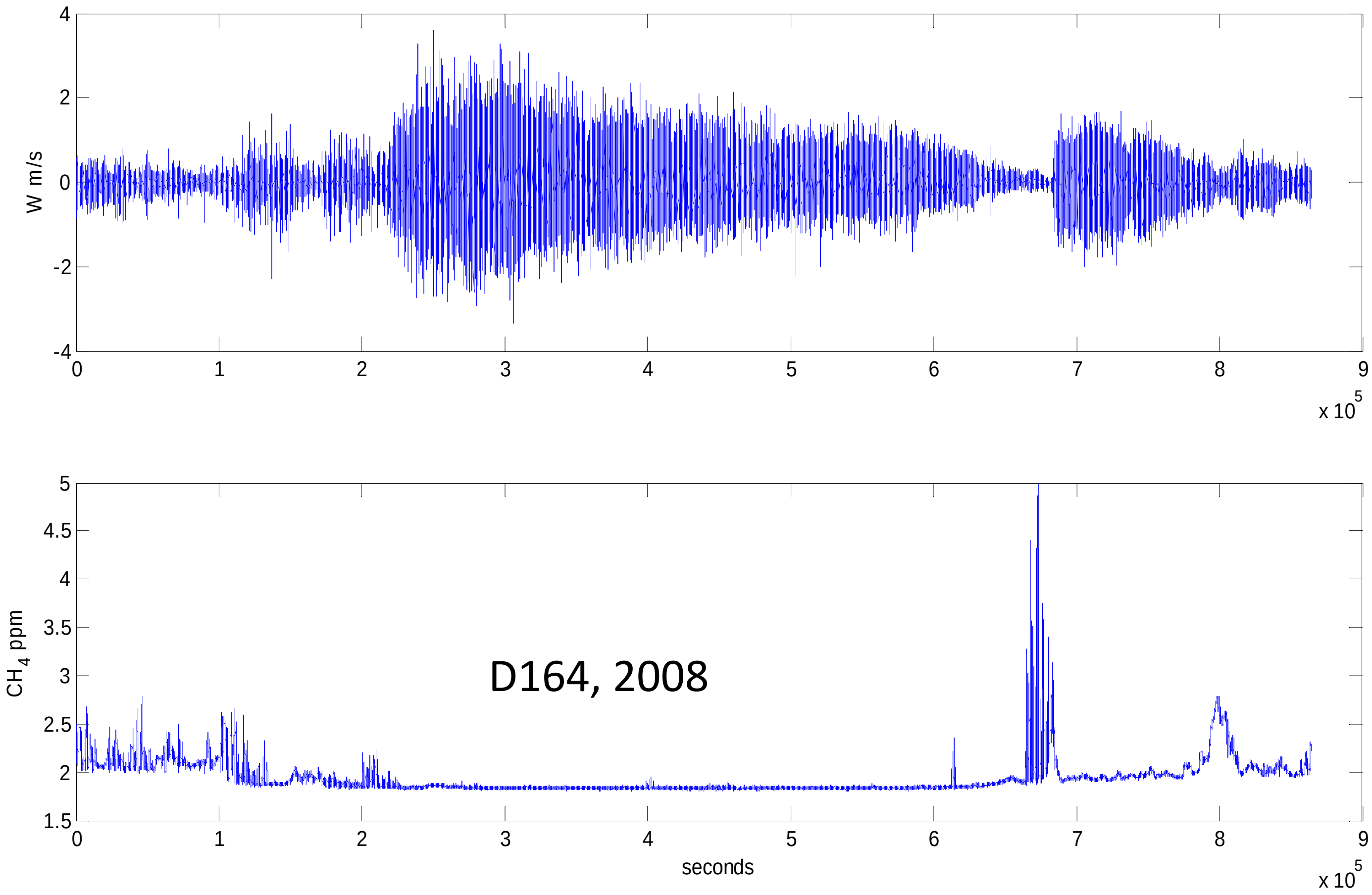
$$F = \overline{\rho_a w s} \sim \overline{\rho_a} \cdot \overline{w's'}$$

$$s = (\frac{\rho_c}{\rho_a})$$

Eddy Covariance Tower
Sonic Anemometer, CO2/H2O IRGA,
inlet for CH4 Tunable diode laser spectrometer &
Meteorological Sensors



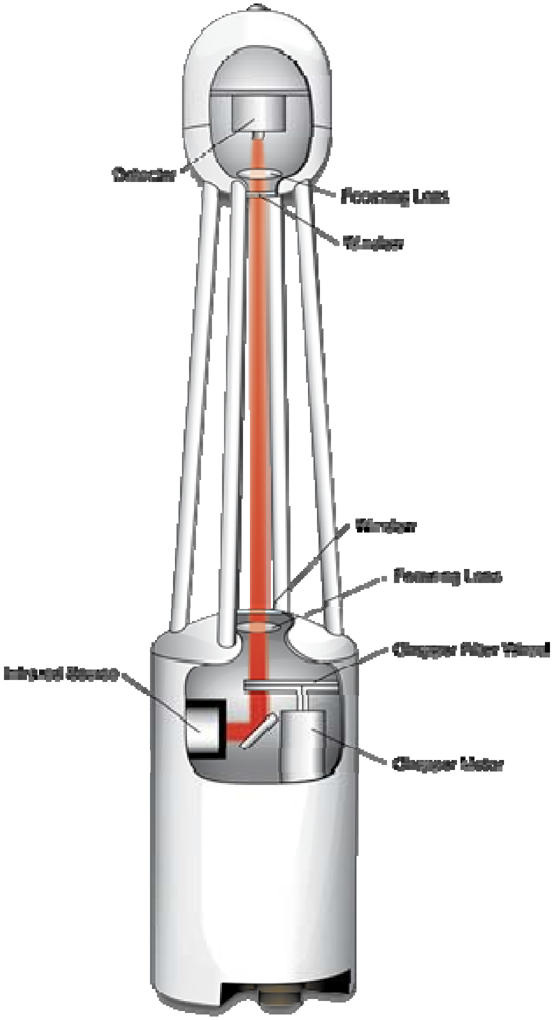
24 Hour Time Series of 10 Hz Data, Vertical Velocity (w) and Methane (CH_4) Concentration



D164, 2008

Sherman Island, CA: data of Detto and Baldocchi

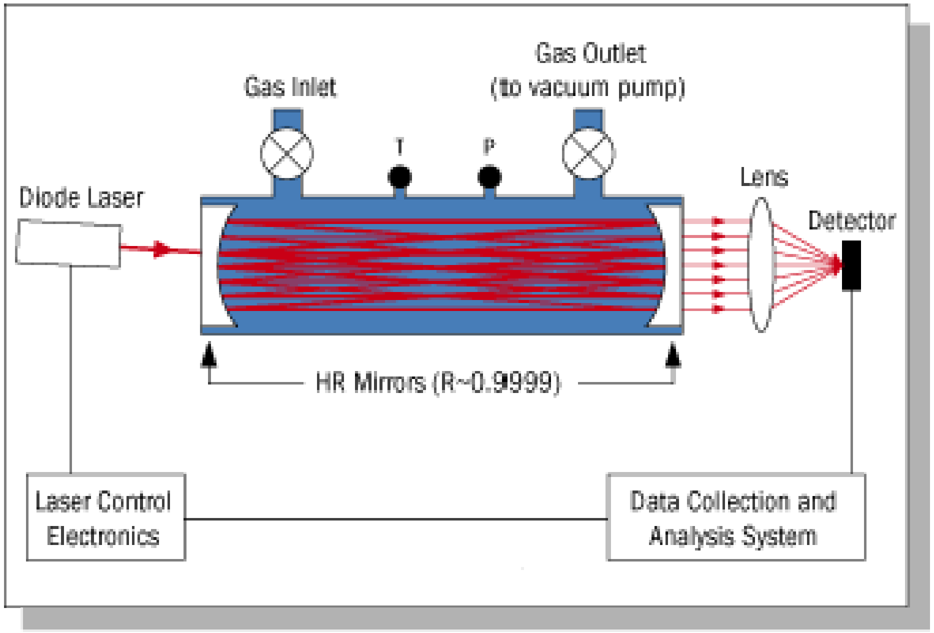
Non-Dispersive Infrared Spectrometer, CO_2 and H_2O



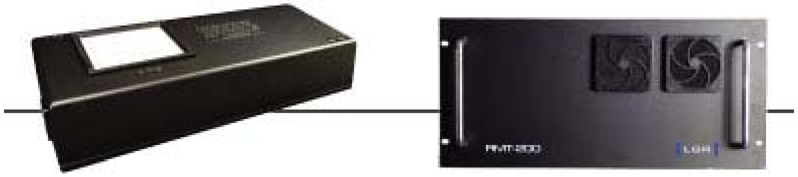
Open-path , 12.5 cm
Low Power, 10 W
Low noise, CO2: 0.16 ppm; H2O: 0.0047 ppth
Low drift, stable calibration
Low temperature sensitivity: 0.02%/degree C

LI 7500

Measuring Methane with Off-Axis Infrared Laser Spectrometer



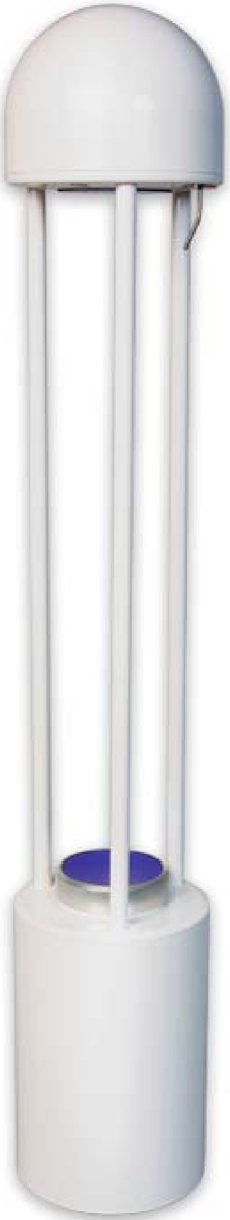
Closed path
Moderate Cell Volume, 400 cc
Long path length, kilometers
High power Use:
Sensor, 80 W
Pump, 1000 W; 30-50 lpm
Low noise: 1 ppb at 1 Hz
Stable Calibration



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

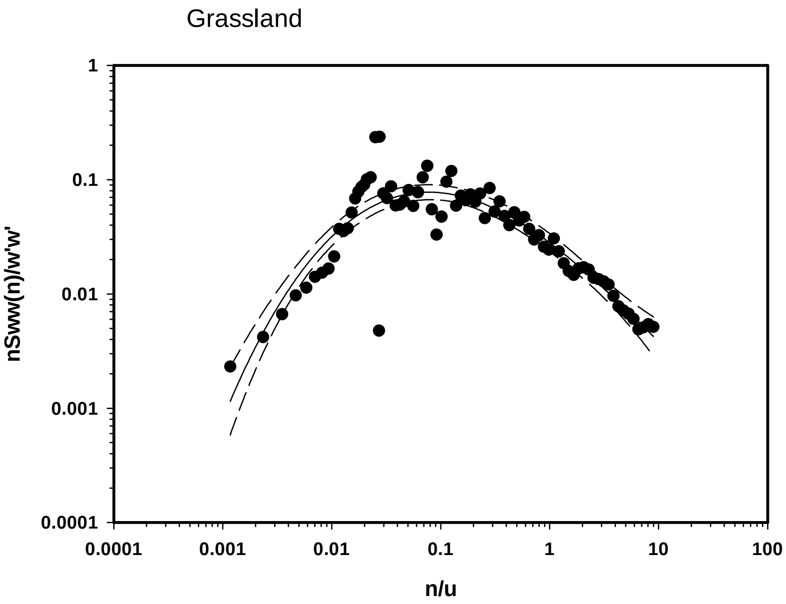
Power Spectrum

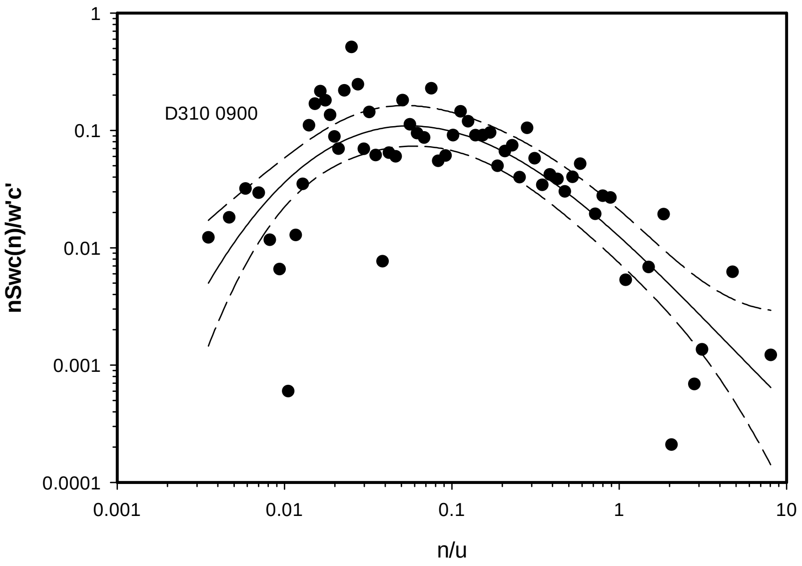
$$\overline{w'w'} = \int_0^\infty S_{ww}(\omega)d\omega$$

Co-Spectrum

$$F = \overline{w'c'} = \int_0^\infty S_{wc}(\omega)d\omega$$

Power and Co-Spectra

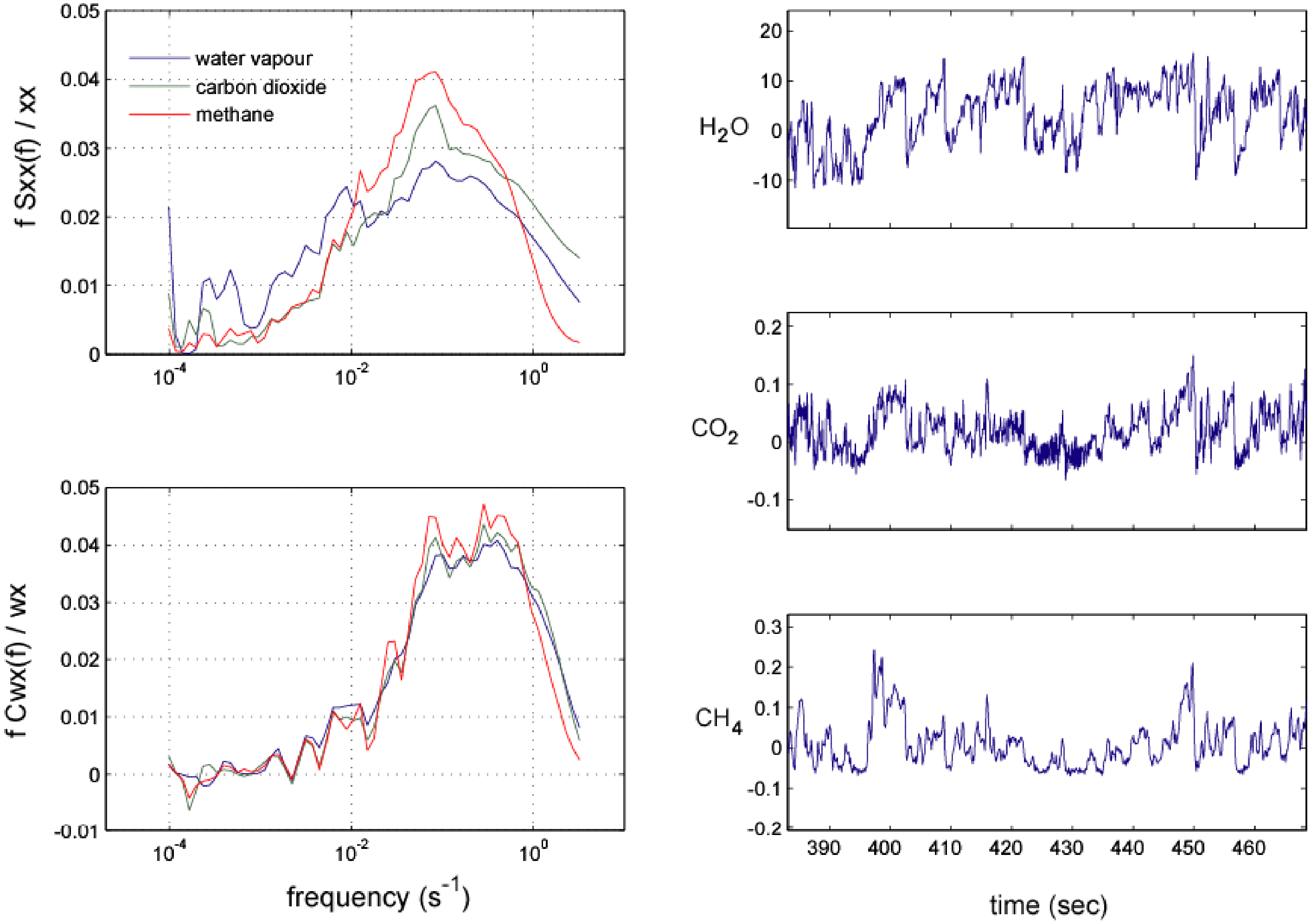




Must Sample Eddies up to 10 times per second for 30 to 60 minutes

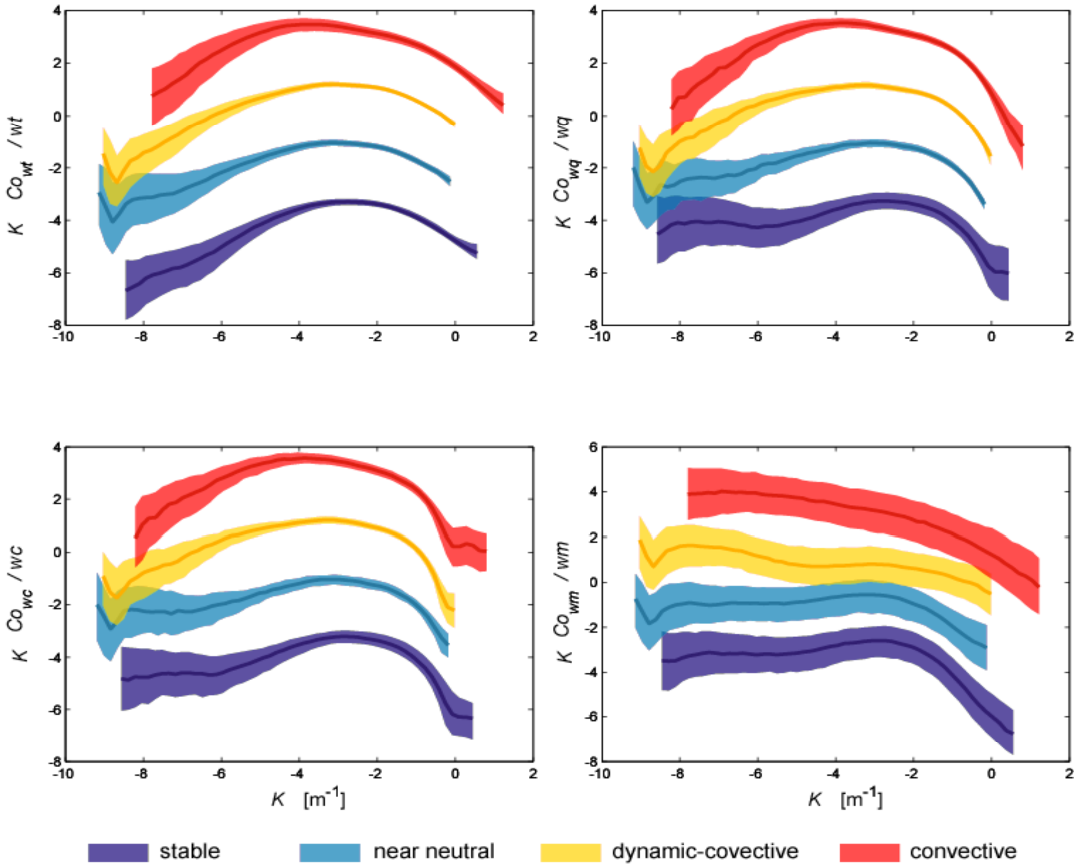
Comparing Co-spectra of open-path CO2 & H2O sensor and closed-path CH4 sensor

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

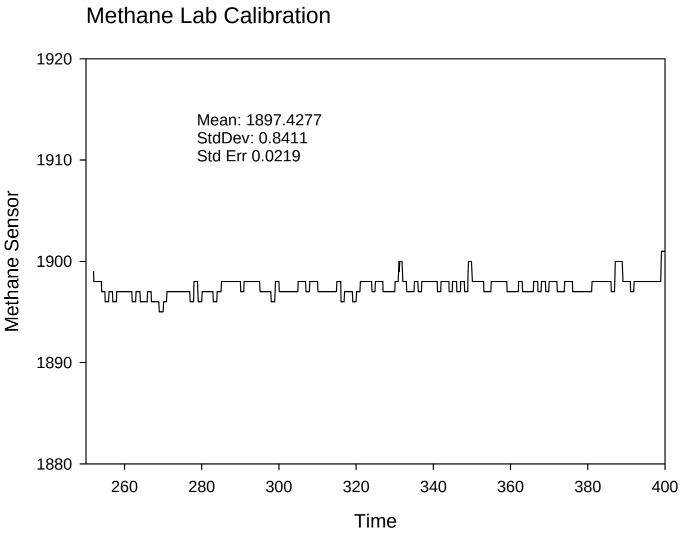
Zero-Flux Detection Limit, Detecting Signal from Noise

$$F = \overline{w'c'} \approx r_{wc}\sigma_w\sigma_c$$

r_{wc} ~ 0.5

σ_{ch4} ~ 0.84 ppb

σ_{co2} ~ 0.11 ppm



U* m/s	σ_w m/s	$F_{min,}$ CH4 nmol m^{-2} s^{-1}	$F_{min,}$ CO2 μmol m^{-2} s^{-1}
0.1	0.125	2.1	0.275
0.2	0.25	4.2	0.55
0.3	0.375	6.3	0.825
0.4	0.5	8.4	1.1
0.5	0.625	10.5	1.375

Most Sensors Measure Mole Density, Not Mixing Ratio

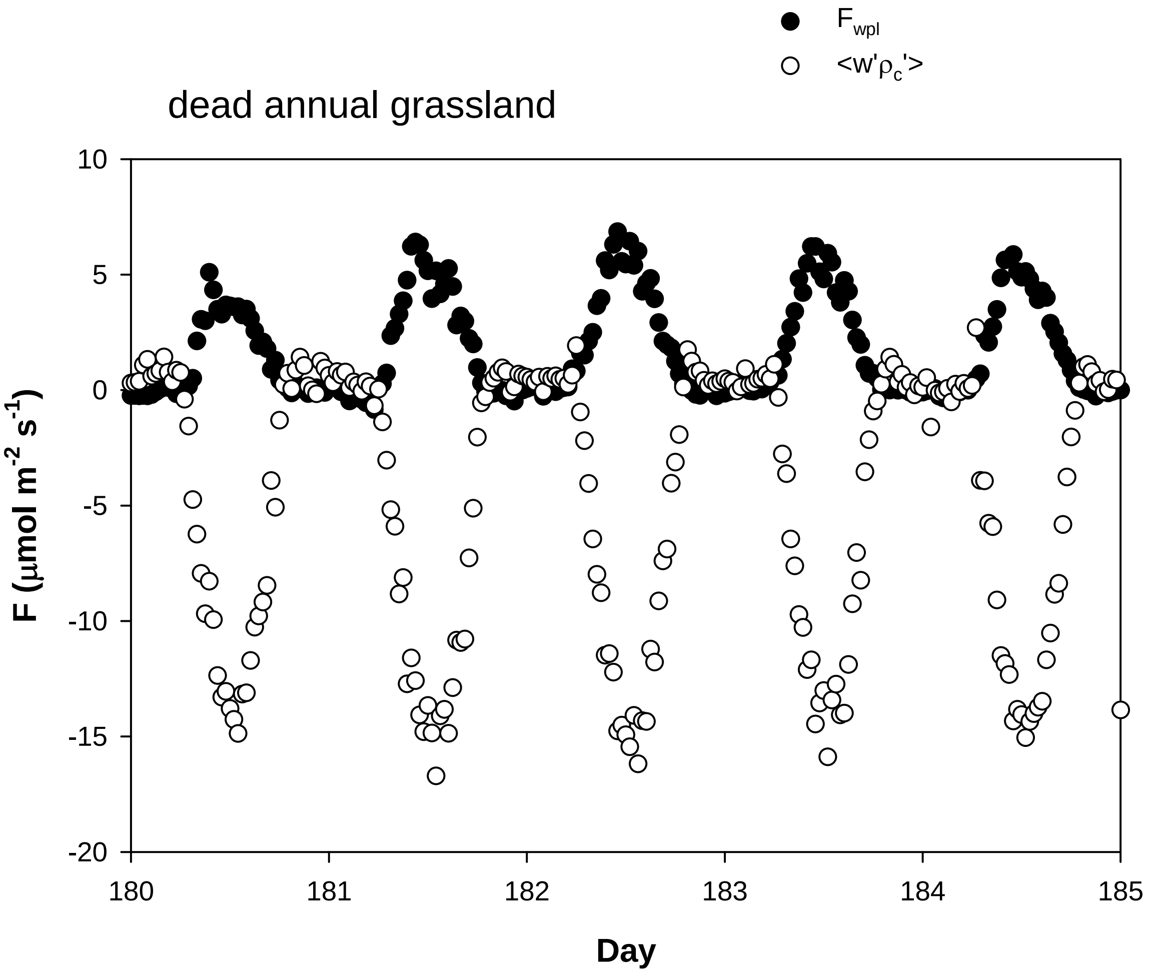
Formal Definition of Eddy Covariance, V2

$$F = \overline{\rho_a w s} \approx \overline{\rho_a} \cdot \overline{w' s'} = \overline{w \rho_c} = \overline{w' \rho_c '} + \overline{w}\,\overline{\rho_c}$$

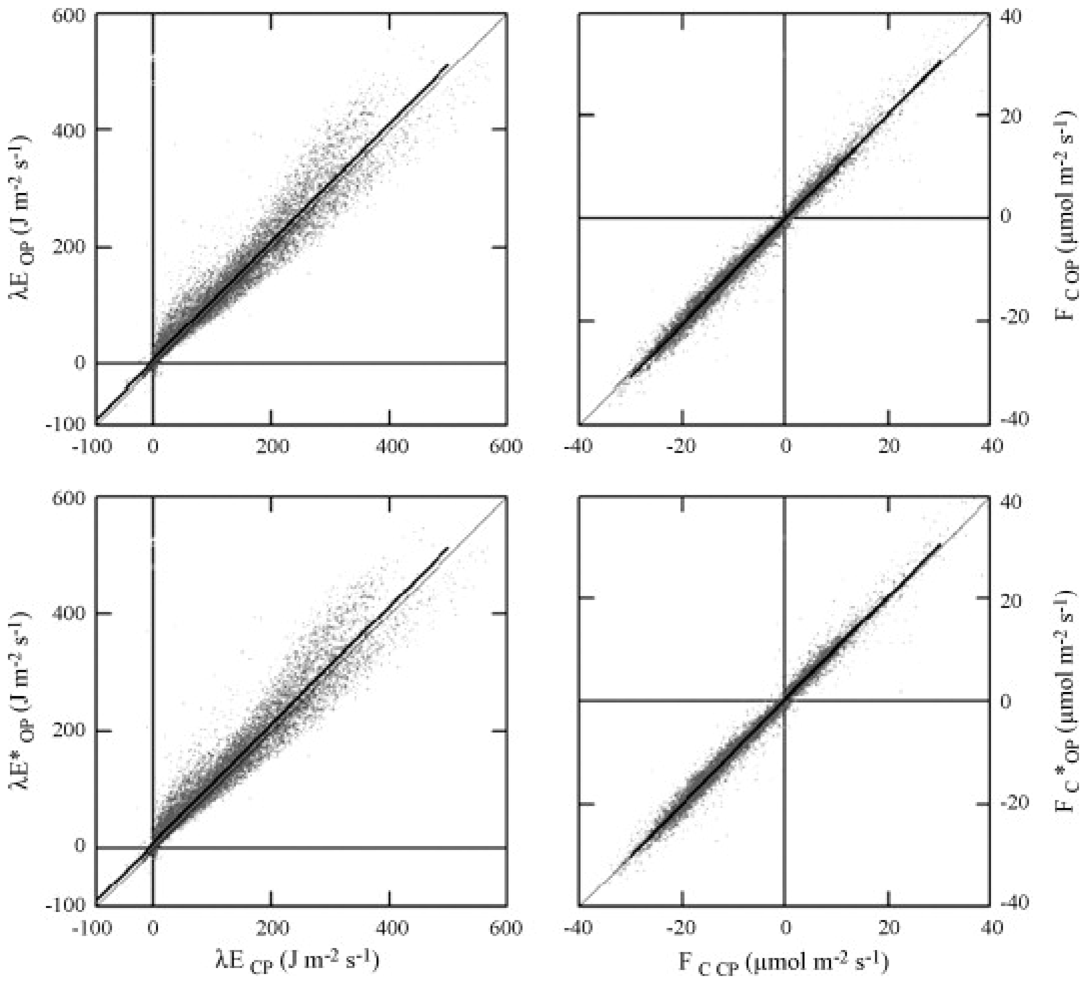
Webb, Pearman, Leuning Algorithm: ‘Correction’ for Density Fluctuations when using Open-Path Sensors

$$F_c = \overline{w'\rho_c'} + \frac{m_a}{m_v}\frac{\overline{\rho_c}}{\overline{\rho_a}}\overline{w'\rho_v'} + (1 + \frac{\overline{\rho_v} m_a}{\overline{\rho_a} m_v})\frac{\overline{\rho_c}}{\overline{T}}\overline{w'T'}$$

Raw <w'c'> signal, without density 'corrections', will infer Carbon Uptake when the system is Dead and Respiring

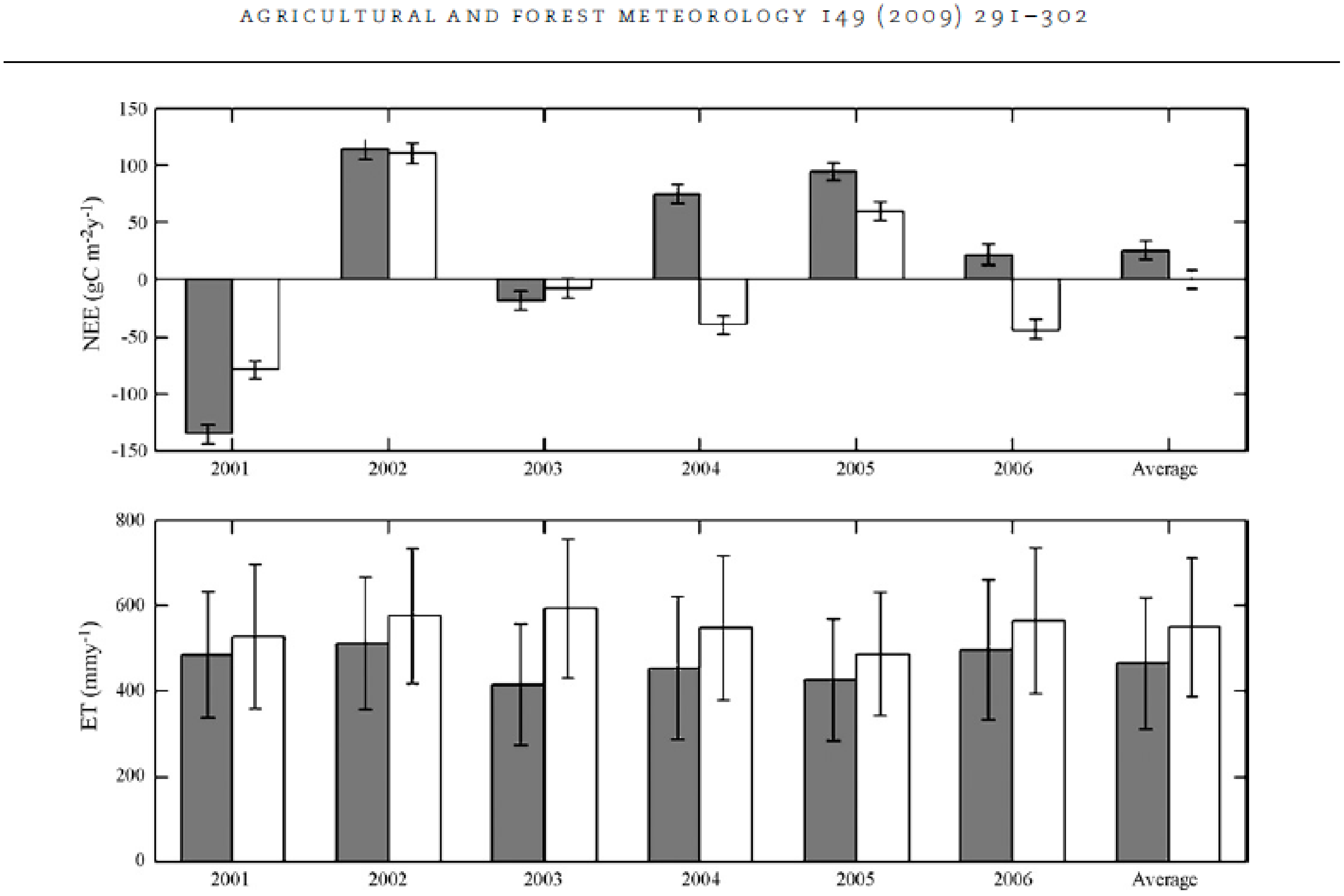


Annual Time Scale, Open vs Closed sensors



Hanslwanter et al 2009
AgForMet

Annual Sums comparing Open and Closed Path Irgas



AGRICULTURAL AND FOREST METEOROLOGY 149 (2009) 291–302

Hanslwanter et al 2009 AgForMet

Flux Methods Appropriate for Slower Sensors, e.g. FTIR

- Relaxed Eddy Accumulation

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

- Modified Gradient Approach

$$F_c \sim F_s \frac{\Delta c_z}{\Delta s_z}$$

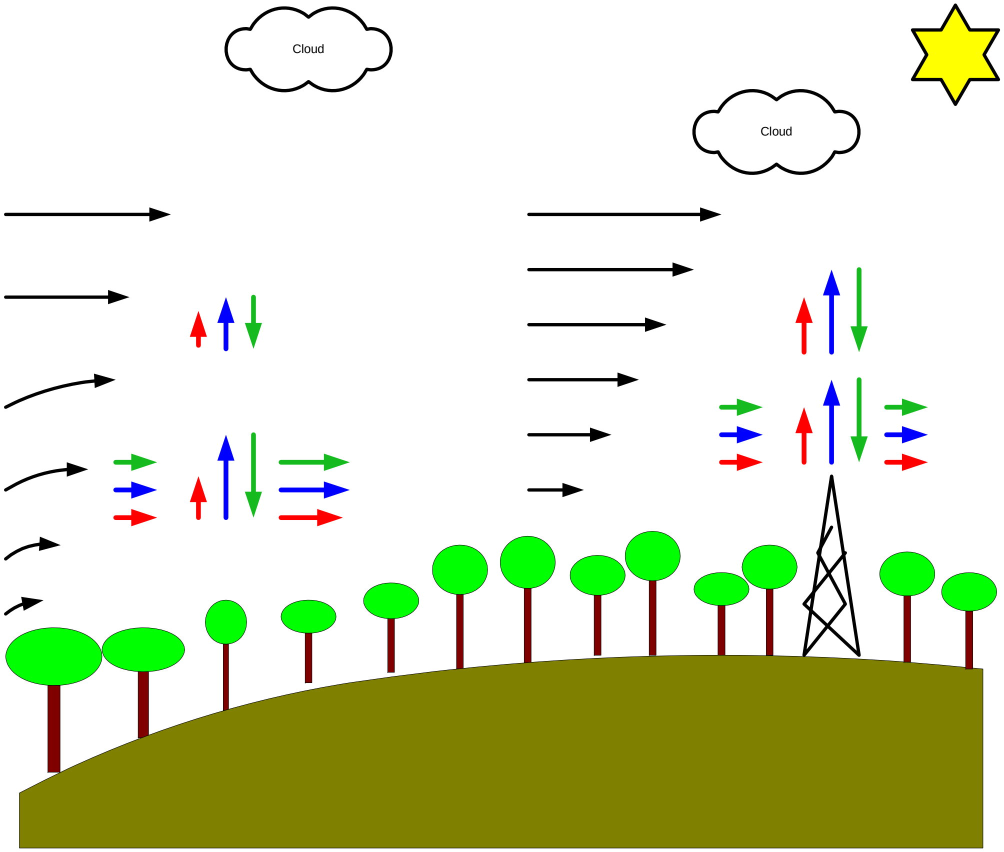
- Integrated Profile

$$F = \frac{1}{x}\int_0^z \overline{u(\rho_c - \rho_{background})}\,dz$$

- 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

$$\frac{d\bar{c}}{dt} = \frac{\partial \bar{c}}{\partial t} + \bar{u}\frac{\partial \bar{c}}{\partial x} + \bar{v}\frac{\partial \bar{c}}{\partial y} + \bar{w}\frac{\partial \bar{c}}{\partial z} = -\frac{\partial \overline{u_j'c'}}{\partial x_j} = -\frac{\partial \overline{u'c'}}{\partial x} - \frac{\partial \overline{v'c'}}{\partial y} - \frac{\partial \overline{w'c'}}{\partial z}$$

I II III

I: Time Rate of Change

II: Advection

III: Flux Divergence

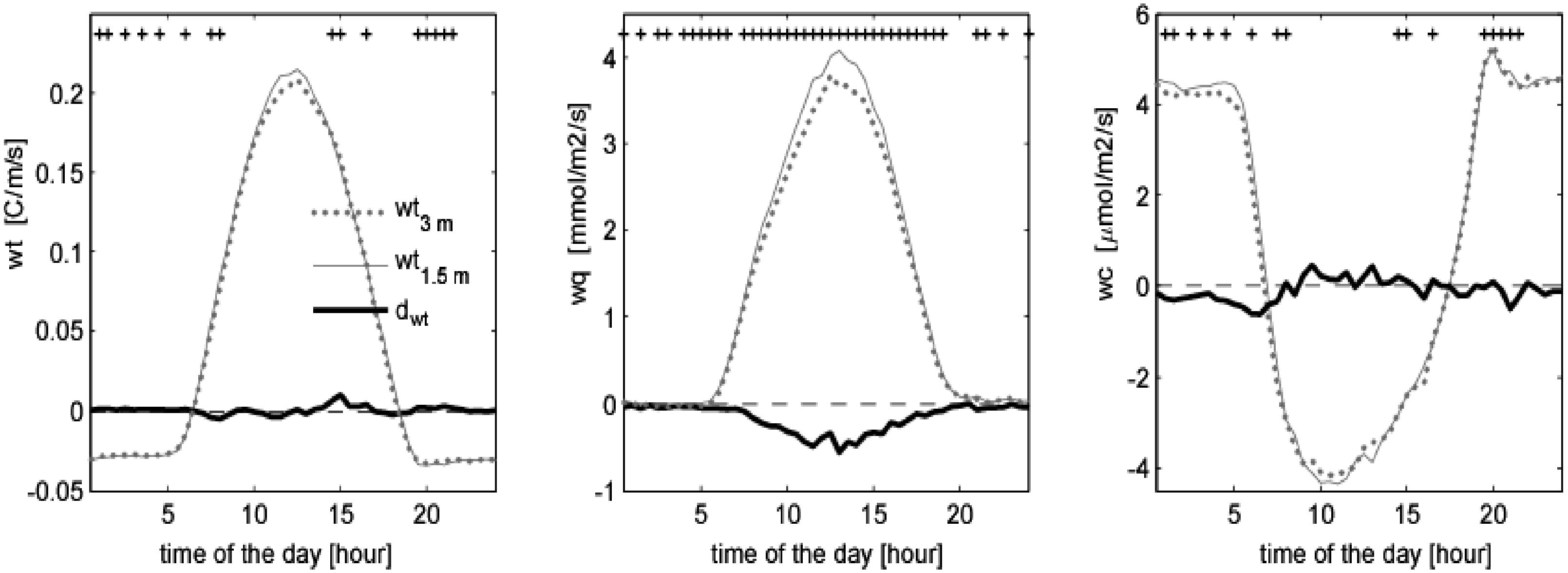
Daytime and Nightime Footprints over an Ideal, Flat Paddock

$$\frac{\partial F}{\partial z} = 0$$

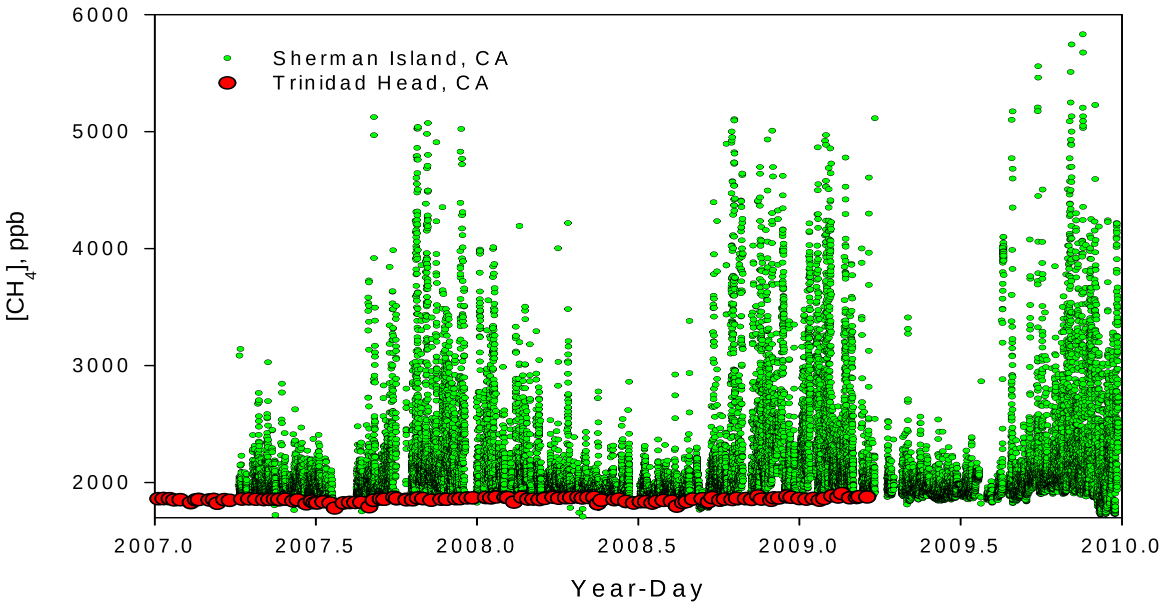
$$F = \int \frac{\partial F}{\partial z} dz = Const$$

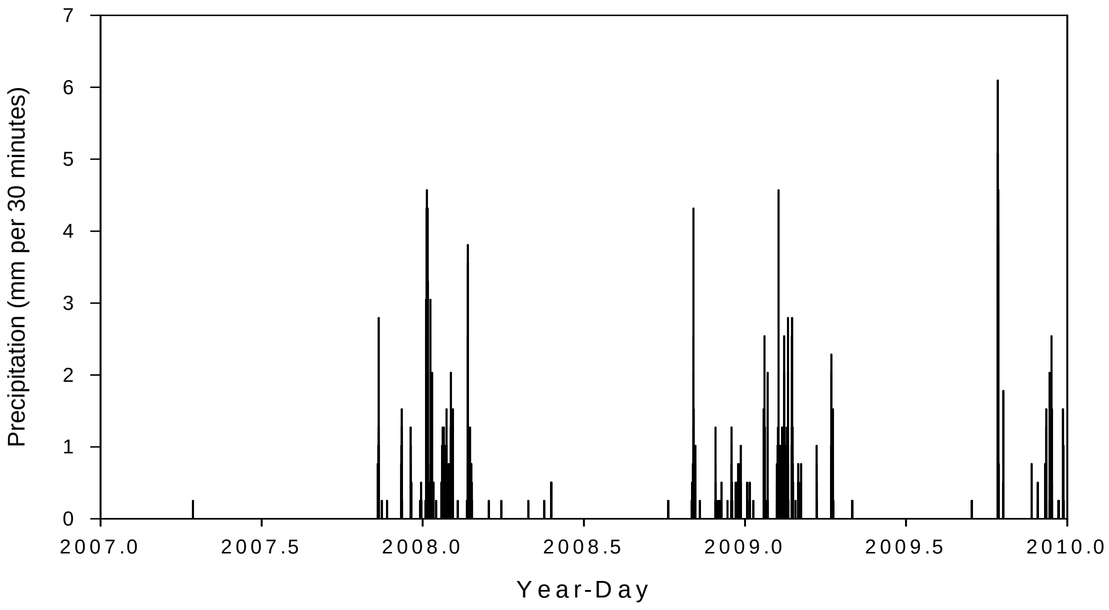
Detto et al. Boundary Layer Meteorology, conditionally accepted

Examine Flux Divergence

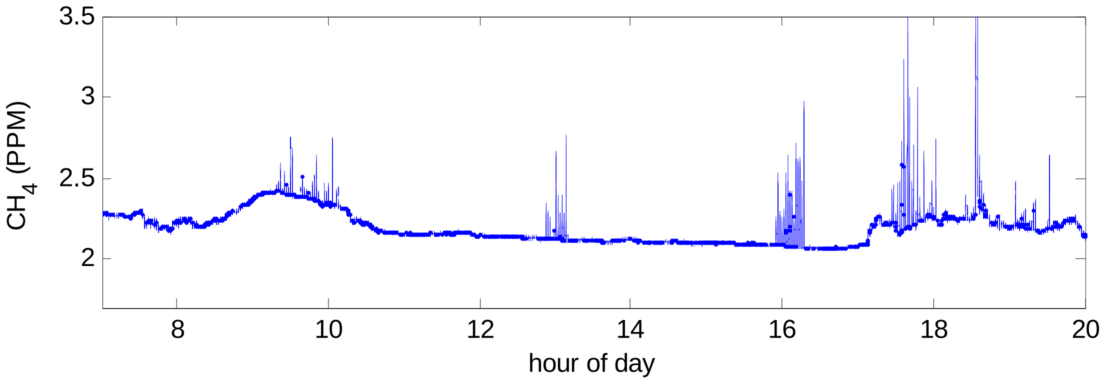


Detto, Baldocchi and Katul,
Boundary Layer Meteorology, conditionally accepted

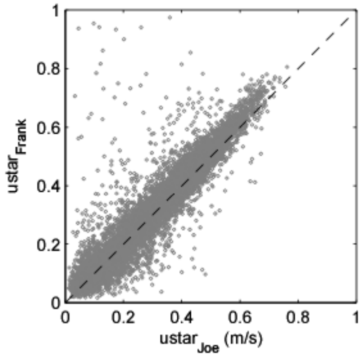

Sherman Island, CA
Trinidad Head, CA
[CH$_4$], ppb
6000
5000
4000
3000
2000
2007.0
2007.5
2008.0
2008.5
2009.0
2009.5
2010.0
Year-Day

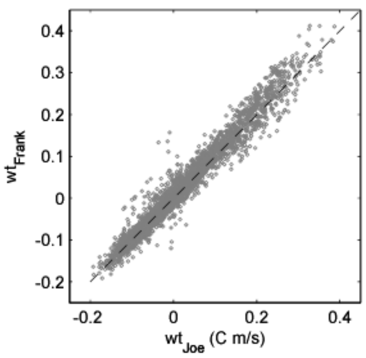

Precipitation (mm per 30 minutes)
7
6
5
4
3
2
1
0
2007.0
2007.5
2008.0
2008.5
2009.0
2009.5
2010.0
Year-Day

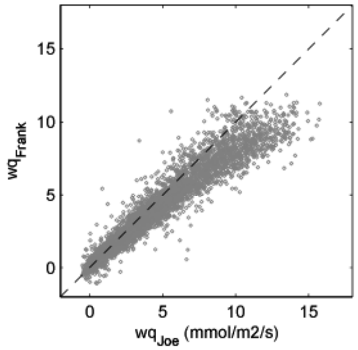
Cows, Near-Field Diffusion and CH_4 Spikes

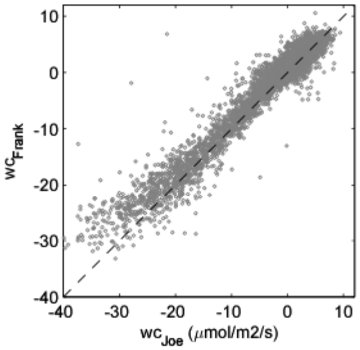


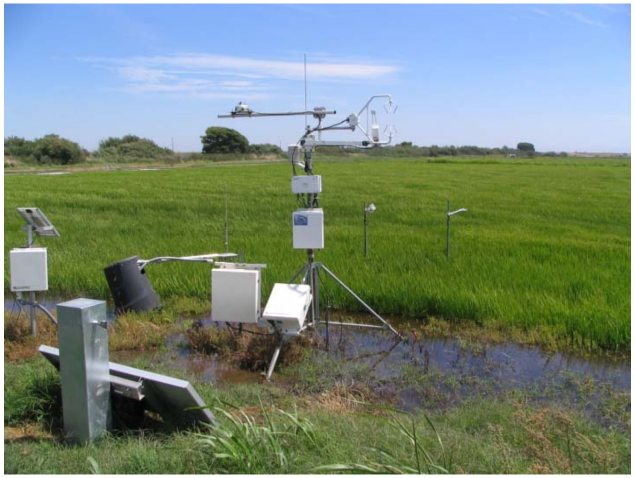
Estimating Flux Uncertainties:
Two Towers over Rice





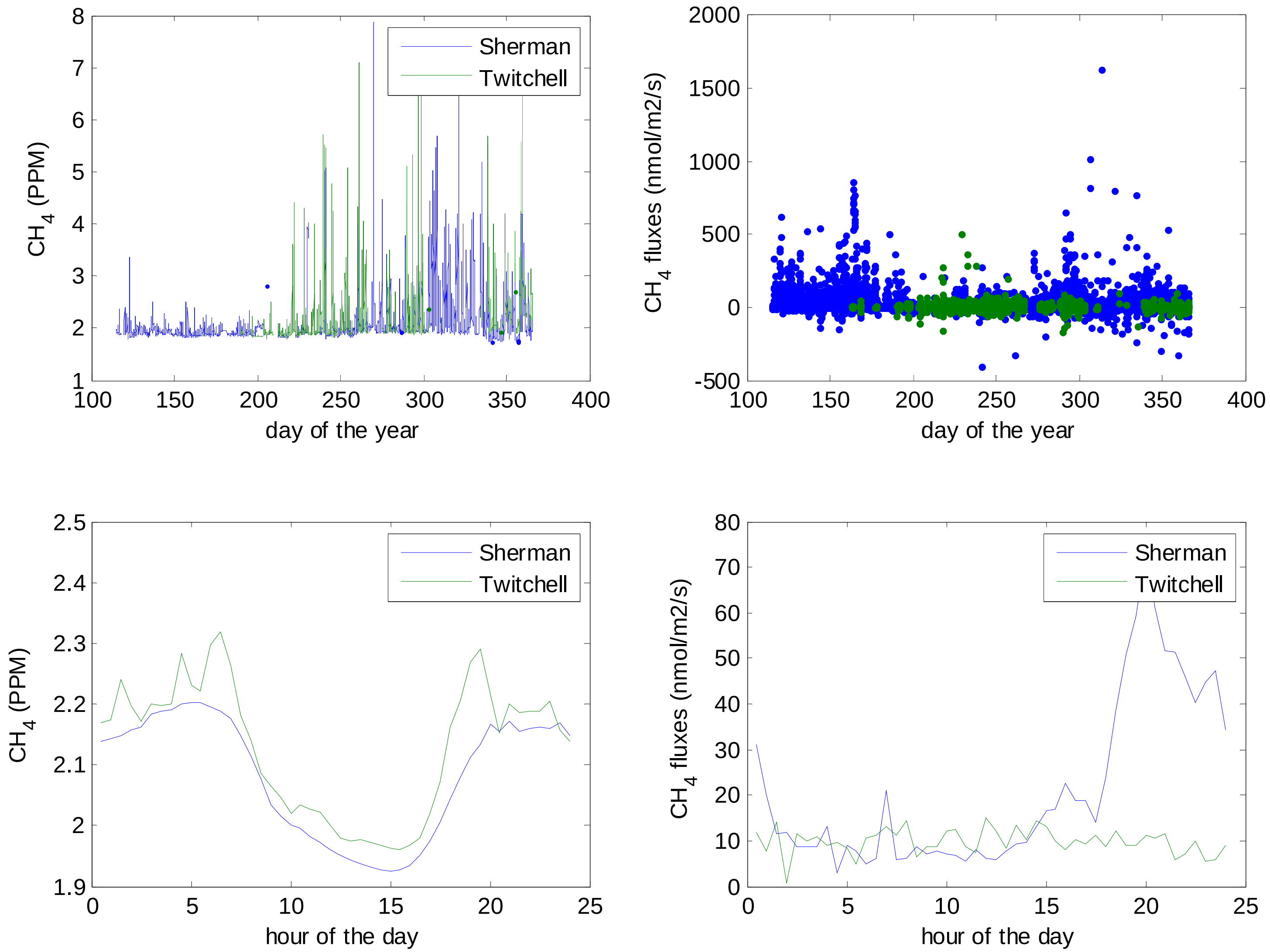






Detto, Anderson, Verfaillie, Baldocchi, unpublished

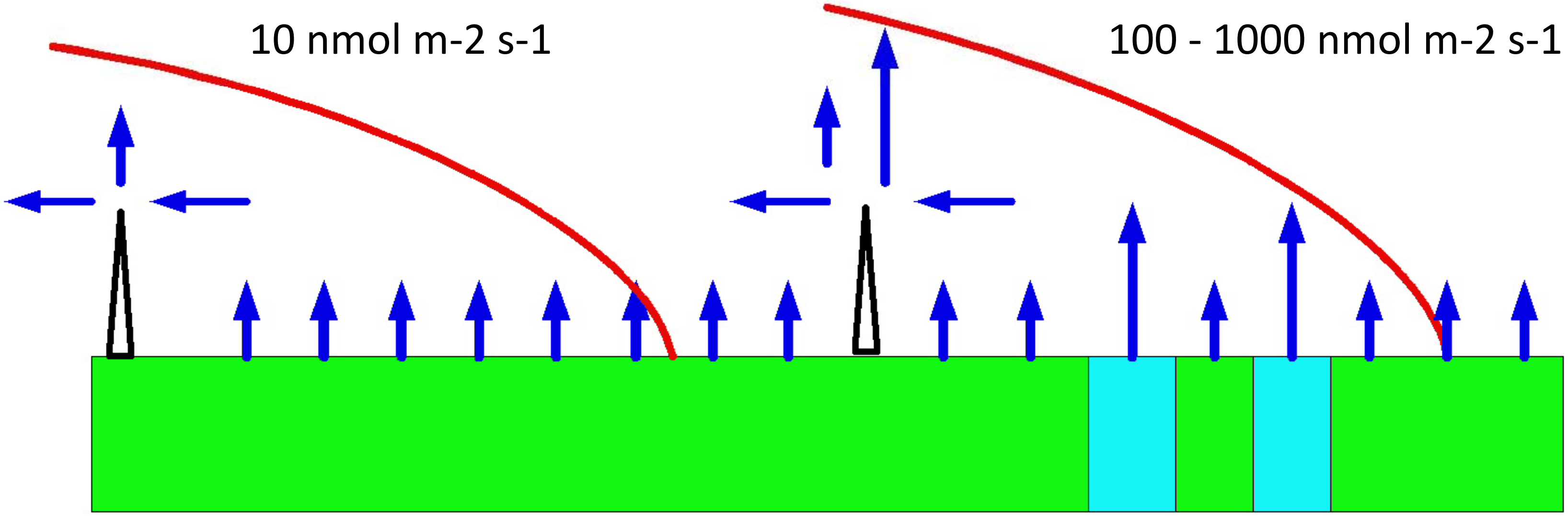
Typical Methane Fluxes Rice vs Peatland



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)



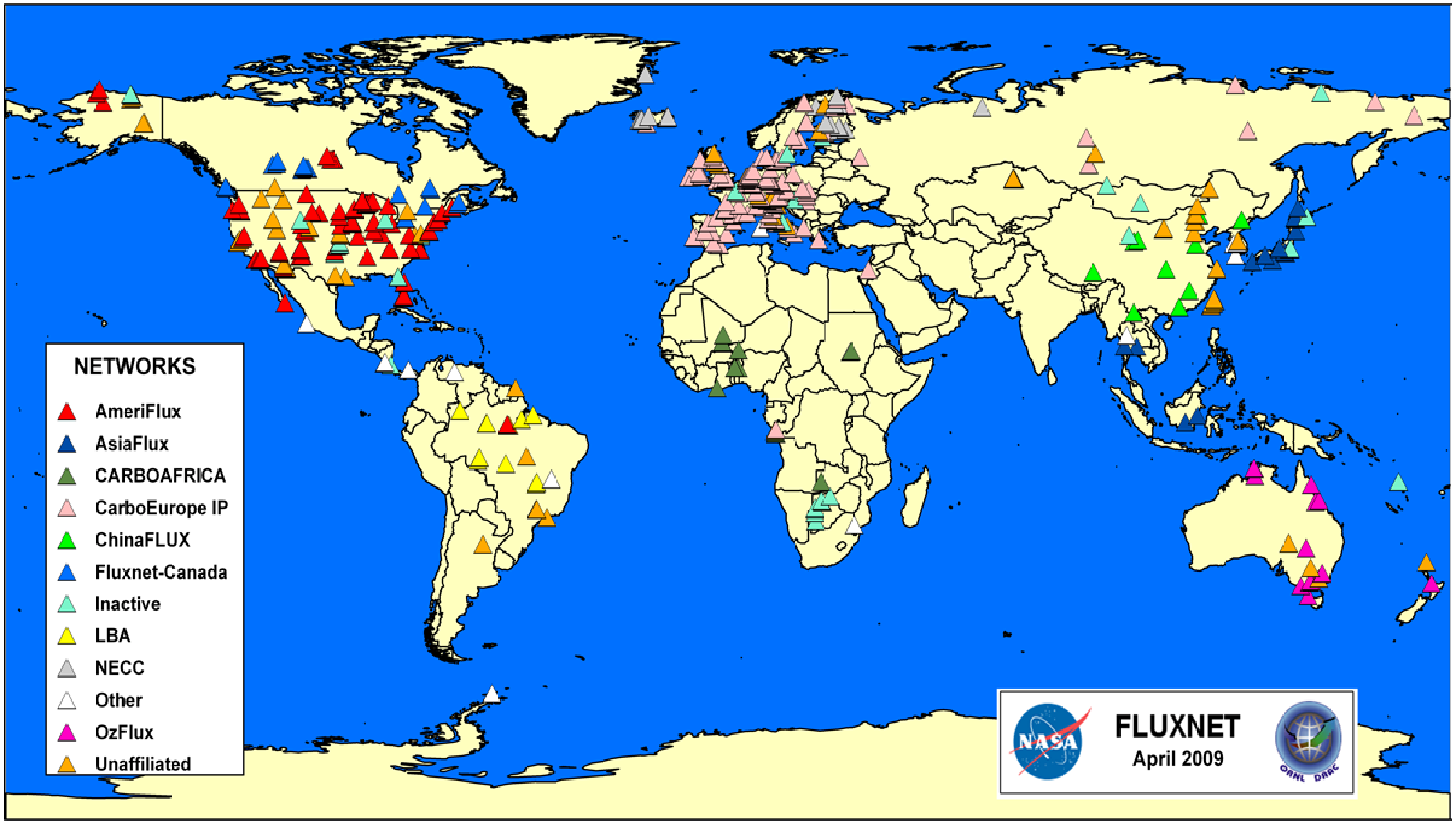
Such Advection is Less Pronounced for Water Vapor and CO2 Fluxes Because Flux Differences Emanating from the Different LandForms are Smaller

Take-Home Message for Application of Eddy Covariance Method under Non-Ideal Conditions

- Comply with Governing Principles of Conservation Equation

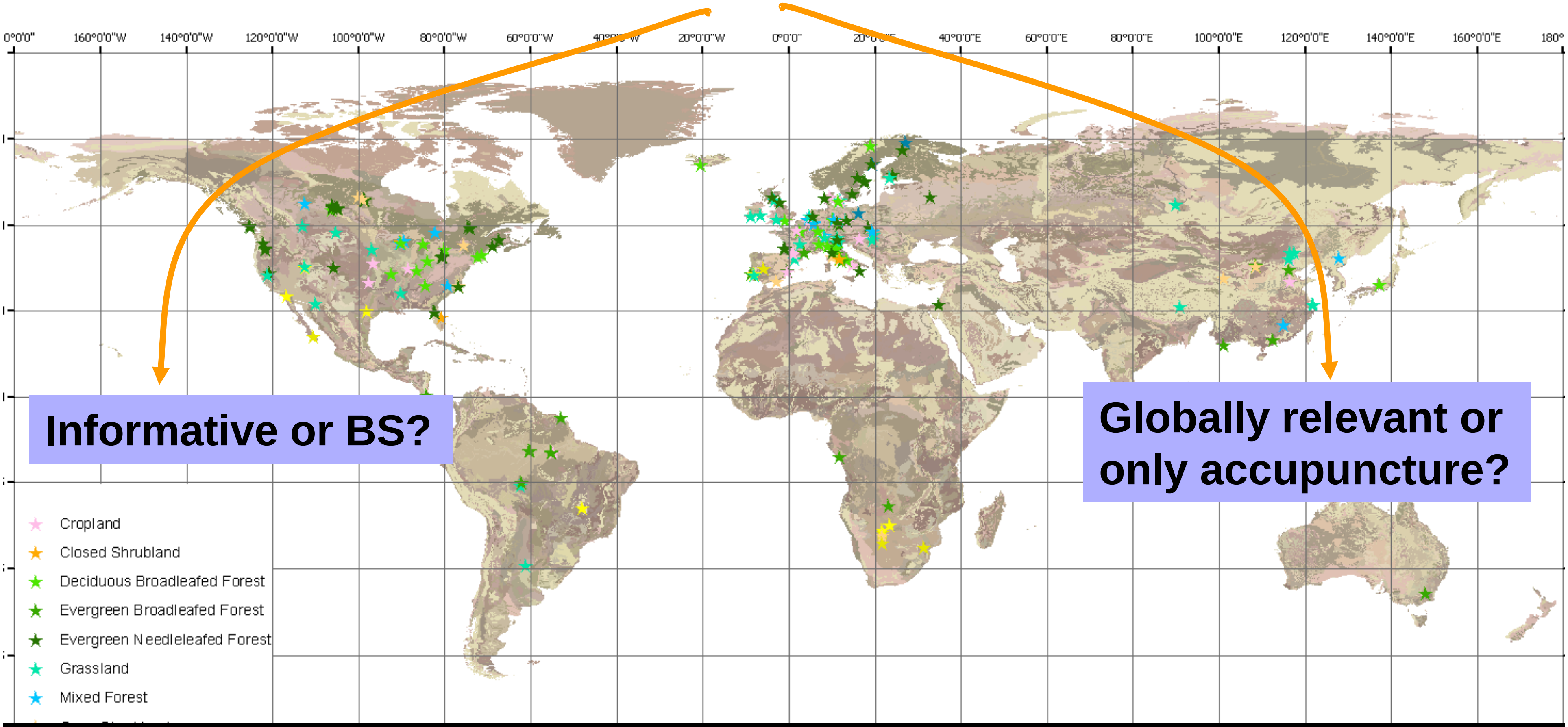
- Design Experiment that measures Flux Divergence and Storage, in addition to Covariance

FLUXNET: From Sea to Shining Sea
500+ Sites, *circa* 2009



The global FLUXNET data base

Two major questions…



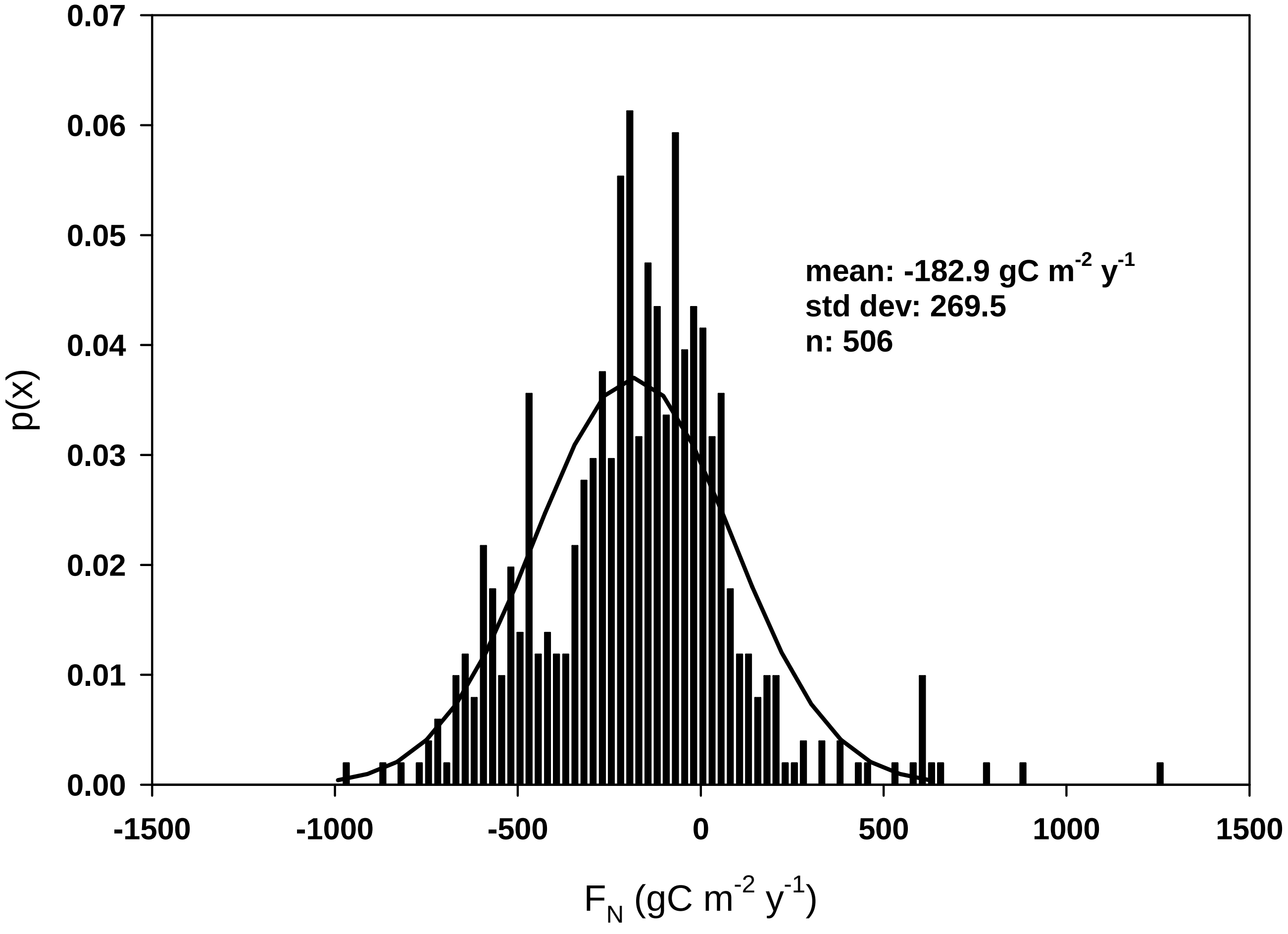
Informative or BS?

Globally relevant or only accupuncture?

- **>1000 site-years from >250 sites**
- **Standardized u*-filtering, gap-filling, flux-partitioning and uncertainties (Aubinet et al. 2001, Foken et al. 2003, Reichstein et al. 2005, Papale et al. 2006, Moffat et al. 2007, Desai et al., Lasslop et al. 2008)**

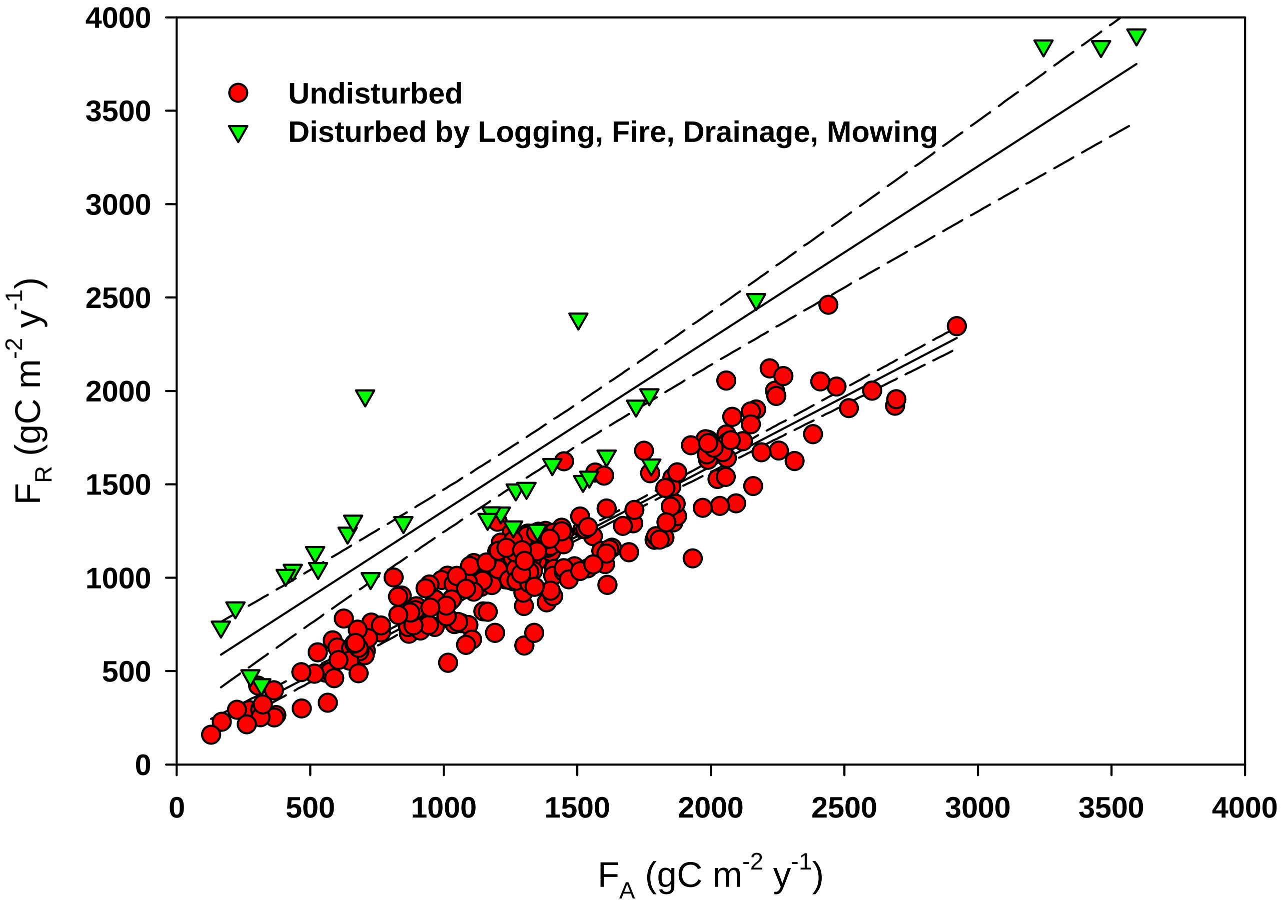
M Reichstein, MPI

Probability Distribution of Published NEE Measurements, Integrated Annually



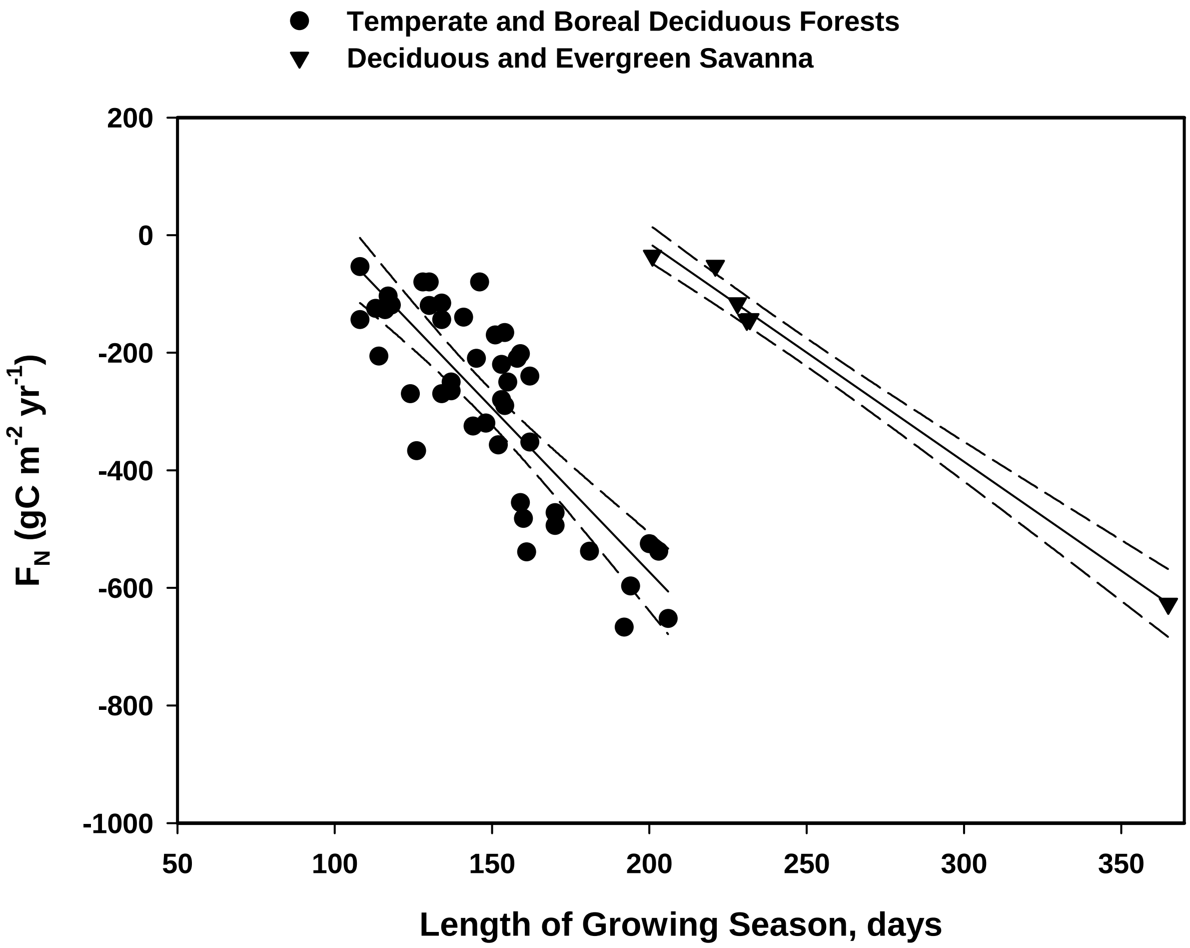
Baldocchi, Austral J Botany, 2008

Ecosystem Respiration Scales Tightly with Ecosystem Photosynthesis, But Is with Offset by Disturbance



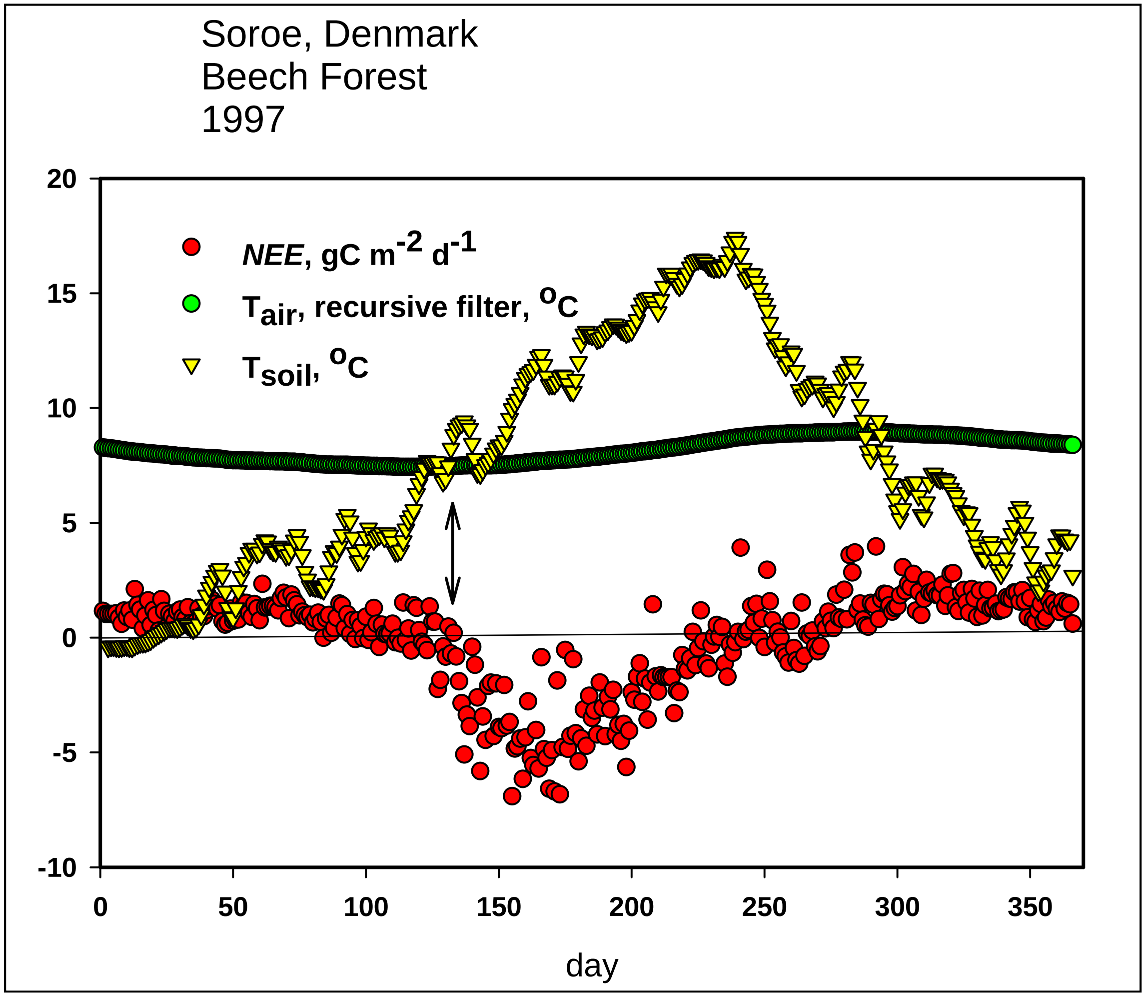
Baldocchi, Austral J Botany 2008

Net Ecosystem Carbon Exchange Scales with Length of Growing Season



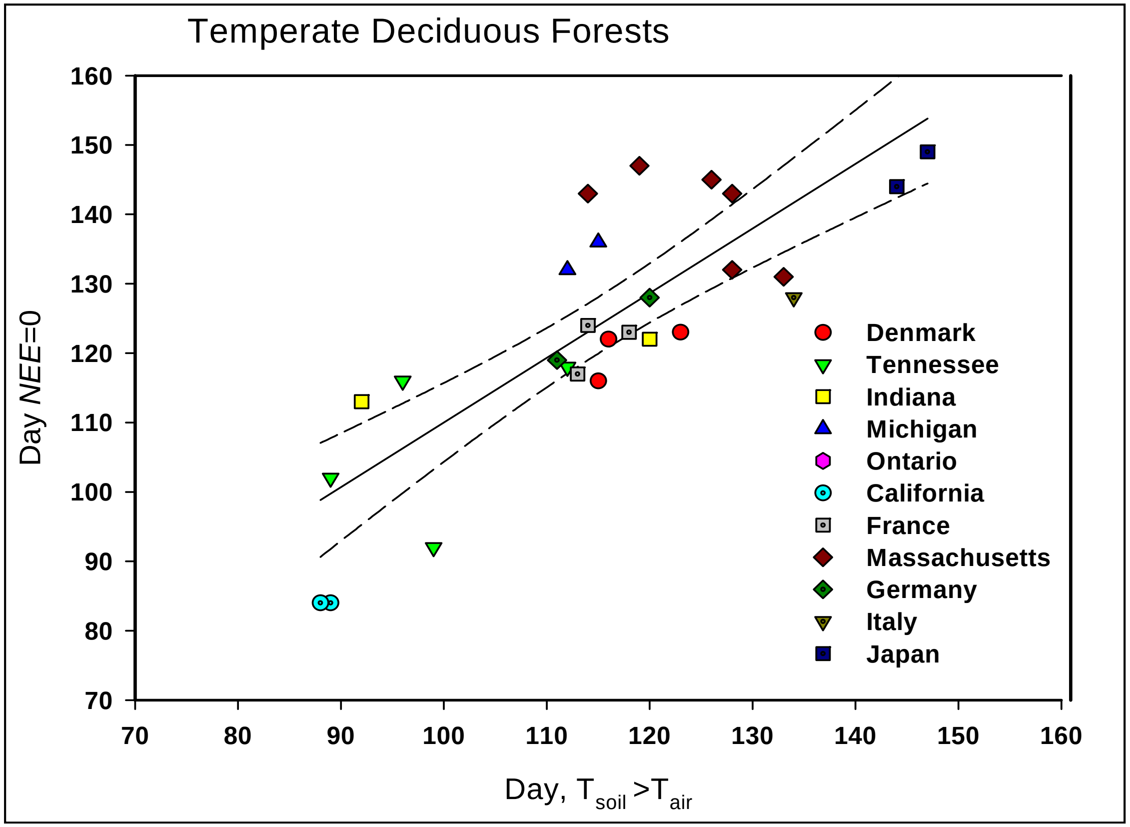
Baldocchi, Austral J Botany, 2008

Soil Temperature:
An Objective Indicator of Phenology??



Data of Pilegaard et al.

Soil Temperature:
An Objective Measure of Phenology, part 2

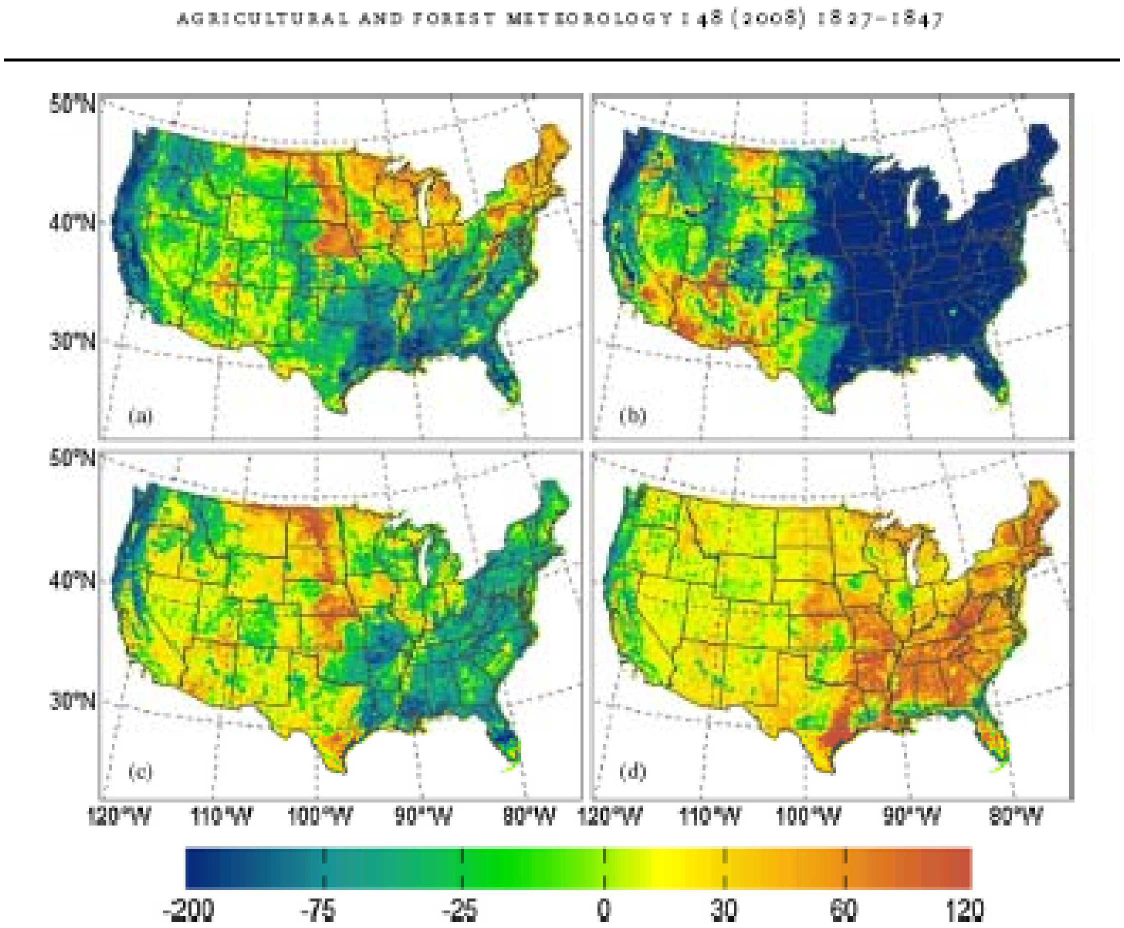


Baldocchi et al. Int J. Biomet, 2005

Spatial Variations in C Fluxes

spring

summer



AGRICULTURAL AND FOREST METEOROLOGY 148 (2008) 1827–1847

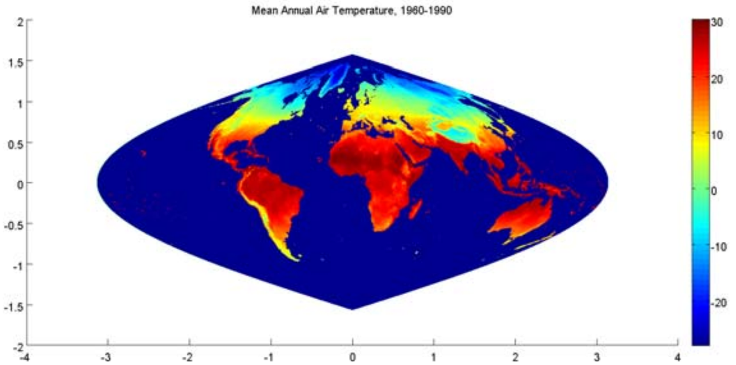
autumn

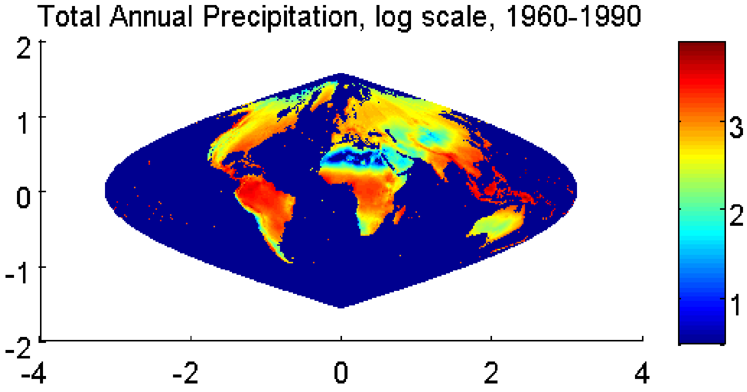
winter

Xiao et al. 2008, AgForMet

Upscale NEP, Globally, Explicitly

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

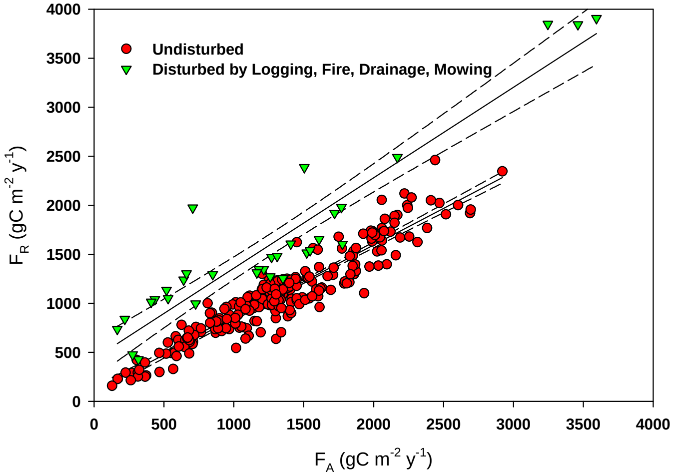




Leith-Reichstein Model

$$GPP = \min\left[f(MAT), g(P)\right] =$$

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



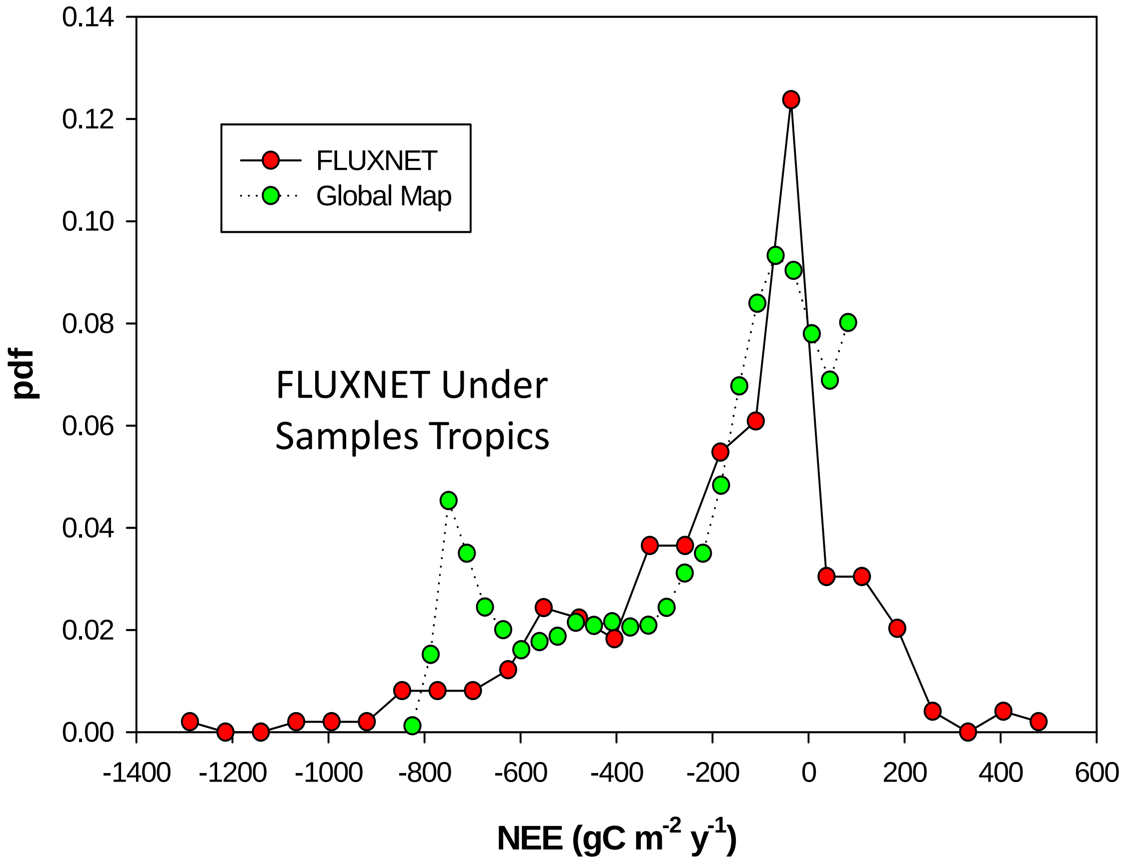
FLUXNET Synthesis
Baldocchi, 2008, Aust J Botany

R_{eco} = 101 + 0.7468 * GPP

R_{eco}, disturbed= 434.99 + 0.922 * GPP

Explicit Climate-Based Upscaling
Under Represents Disturbance Effects

FLUXNET Database



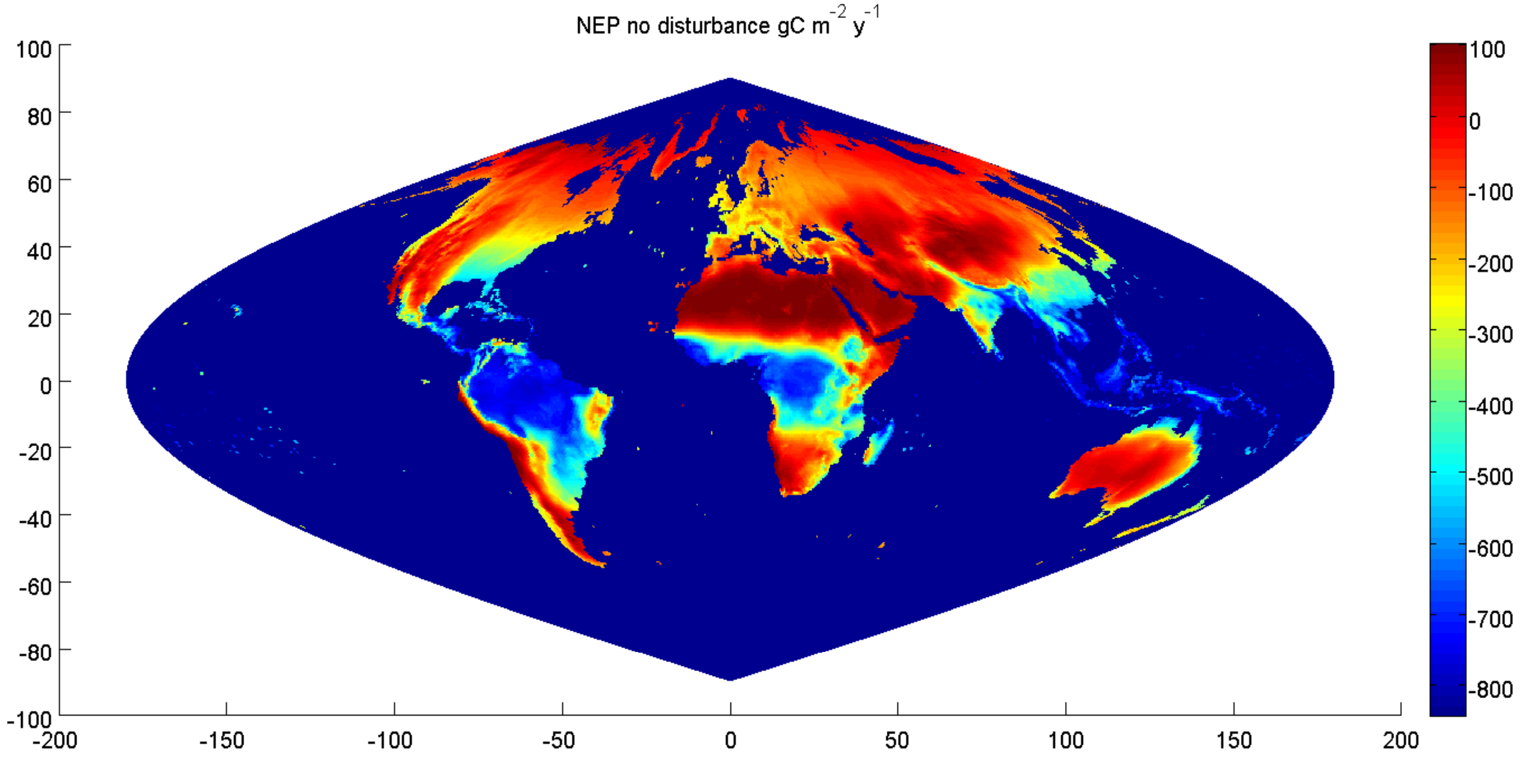
FLUXNET Under
Samples Tropics

Statistically Sampling and Climate Upscaling Agree

<NEE: FLUXNET> = -225 +/- 164 gC m-2 y-1

<NEE 0% dist: sinusoidal> = -222 gC m-2 y-1

Don’t Get Too Confident , Yet

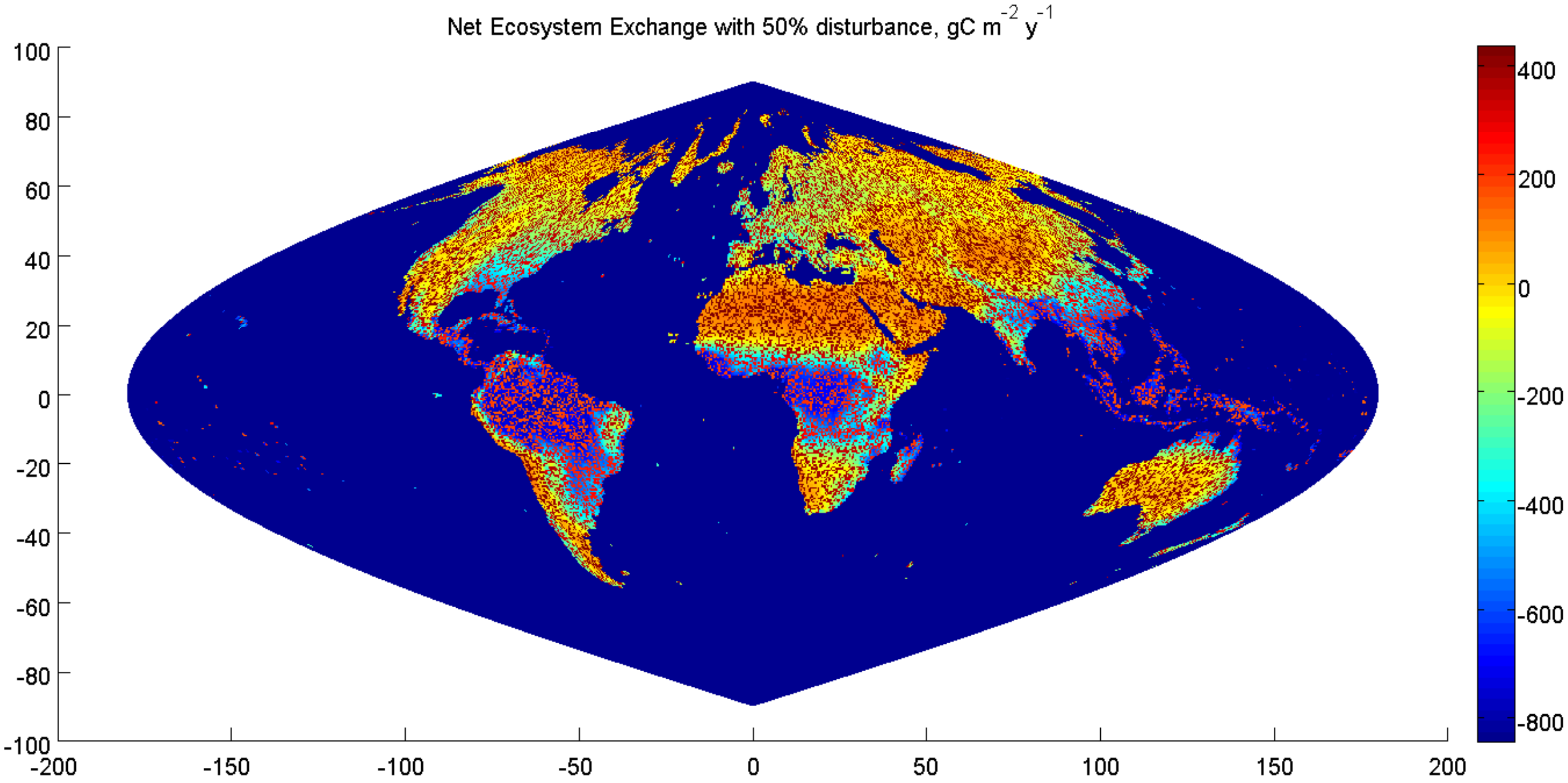


<NEE> = -222 gC m^{-2} y^{-1}

This Flux Density Matches FLUXNET (-225) well, but Σ NEE = -31 PgC/y!!

Implies too Large NEE (|-700 gC m^{-2} y^{-1}| Fluxes in Tropics

To Balance Carbon Fluxes infers that Disturbance Effects May Be Greater than Presumed

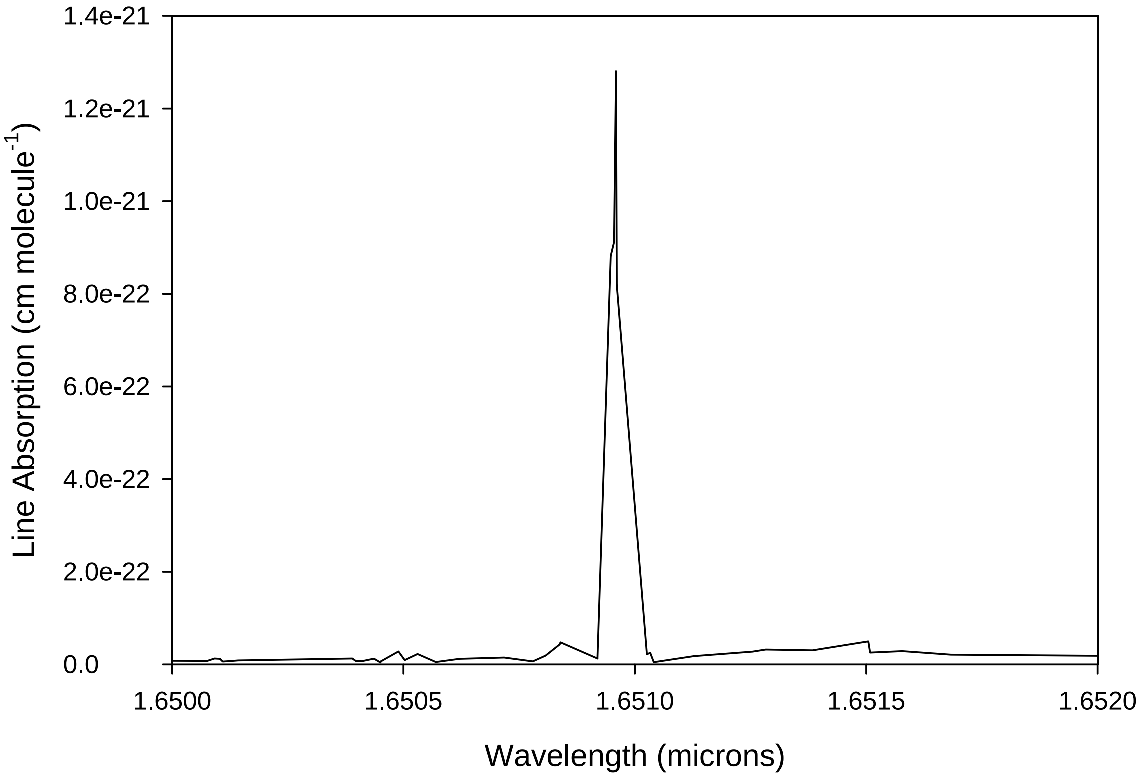


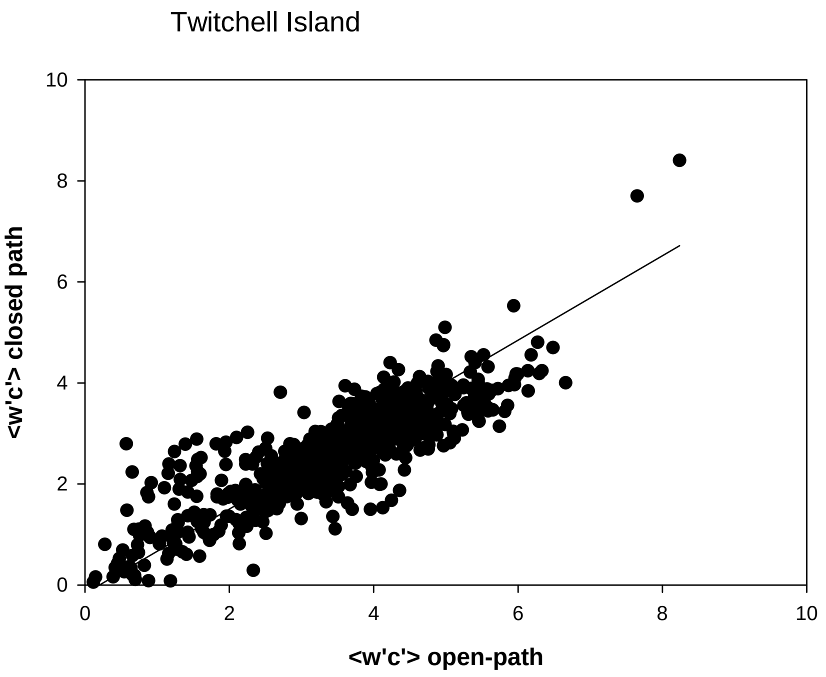
<NEE> = -4.5 gC m^{-2} y^{-1}

Σ NEE = -1.58 PgC/y

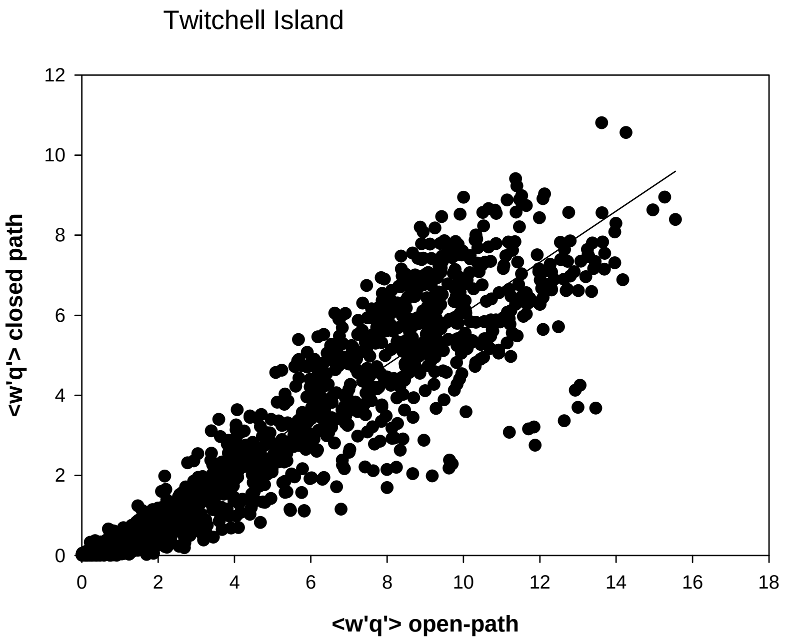
Conclusions

HI Tran Methane Spectra
1651 nm band IR absorption for Laser system





With Density 'Corrections' Open- and Close-Path Flux Systems Yield 'Similar' Results



Raw Covariances for <w'q'> and <w'c'>

Data of Detto, Verfaillie, Anderson and Baldocchi