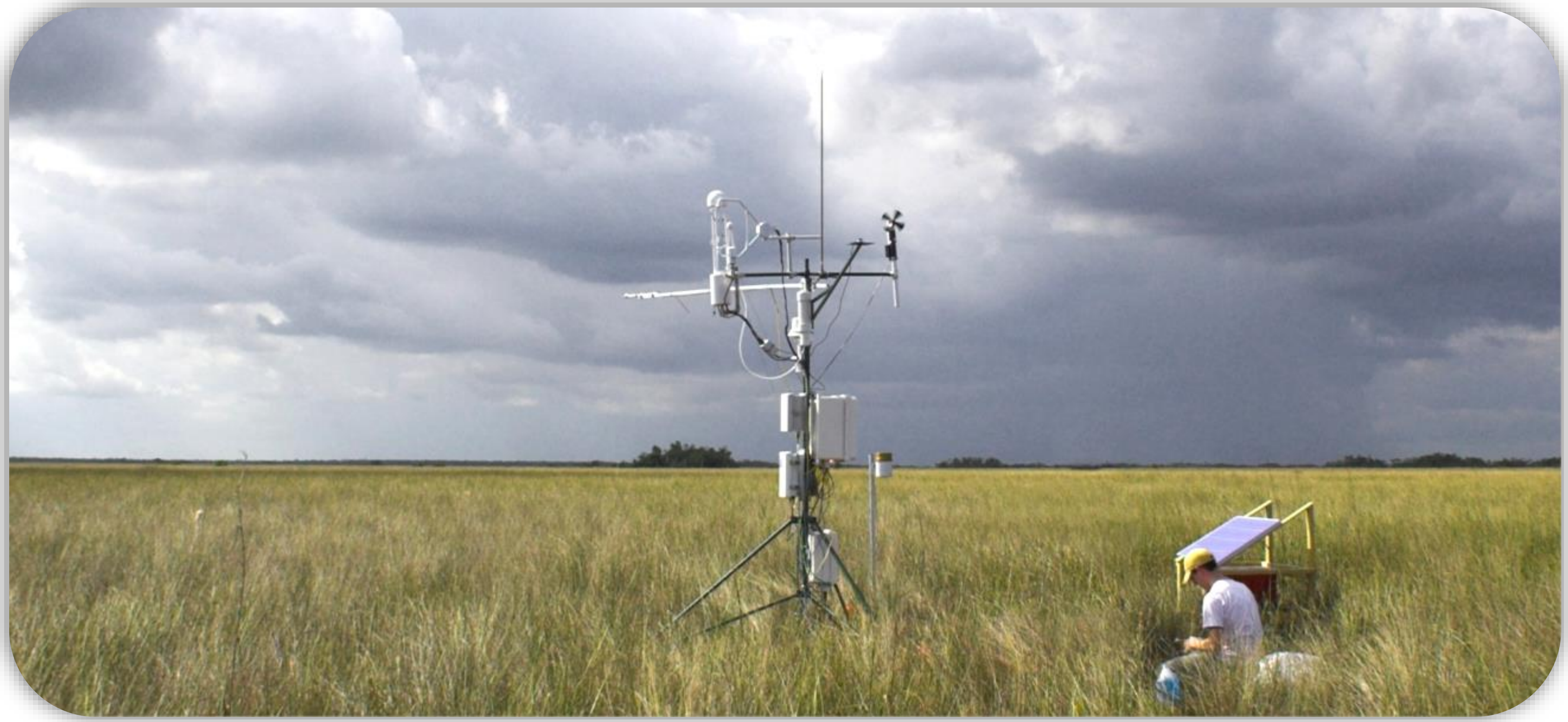
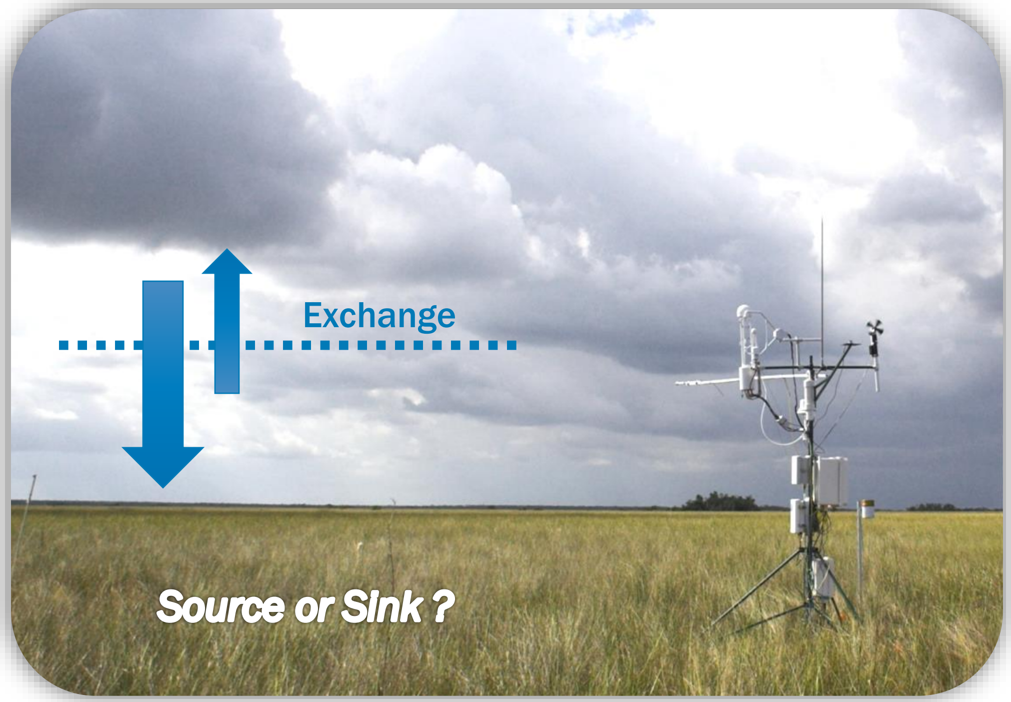


An Introduction to Eddy Covariance

LI-COR

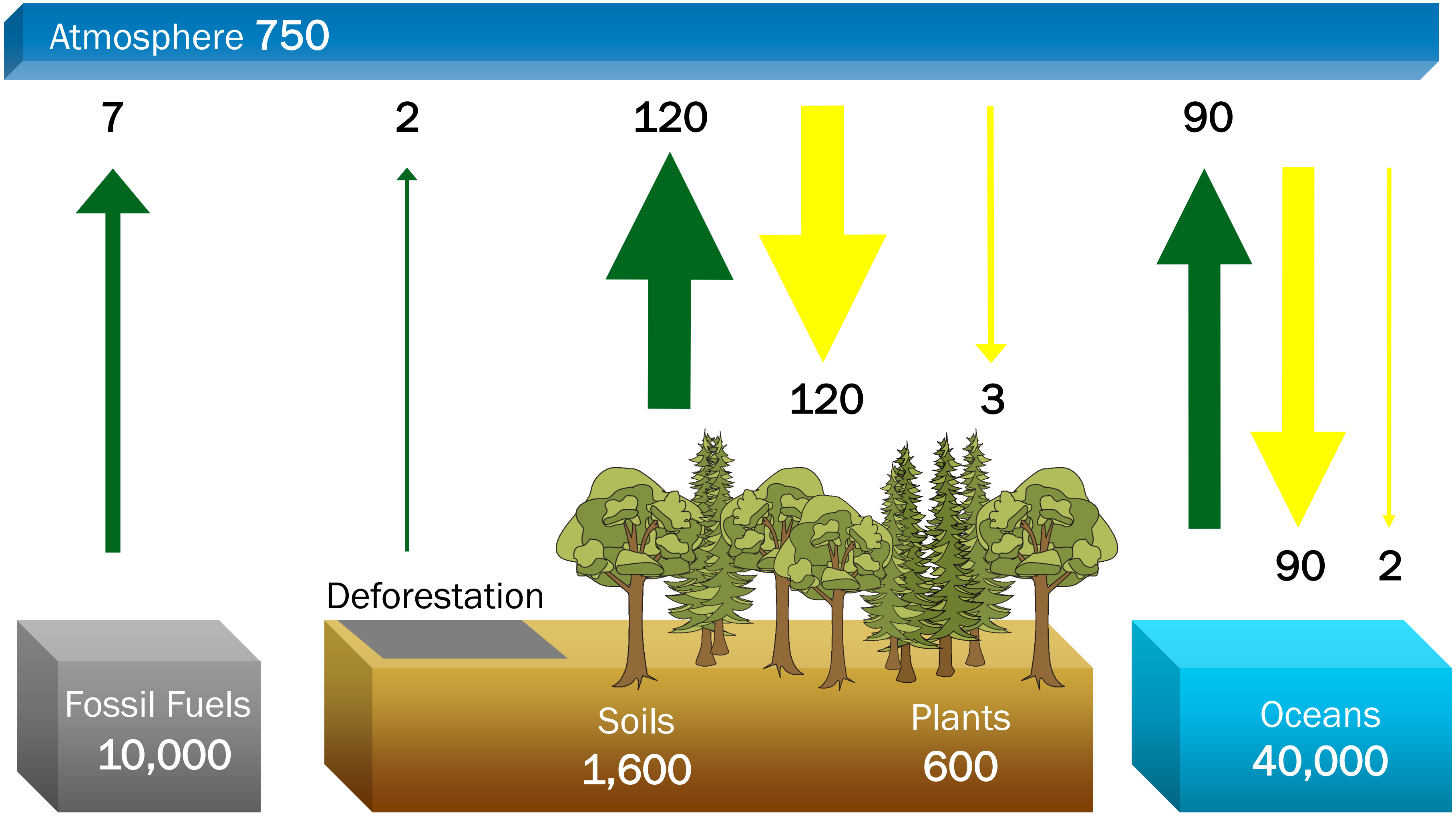
Objective

Estimate vertical turbulent flux of heat, water vapor, carbon dioxide, methane, …



The Carbon Cycle

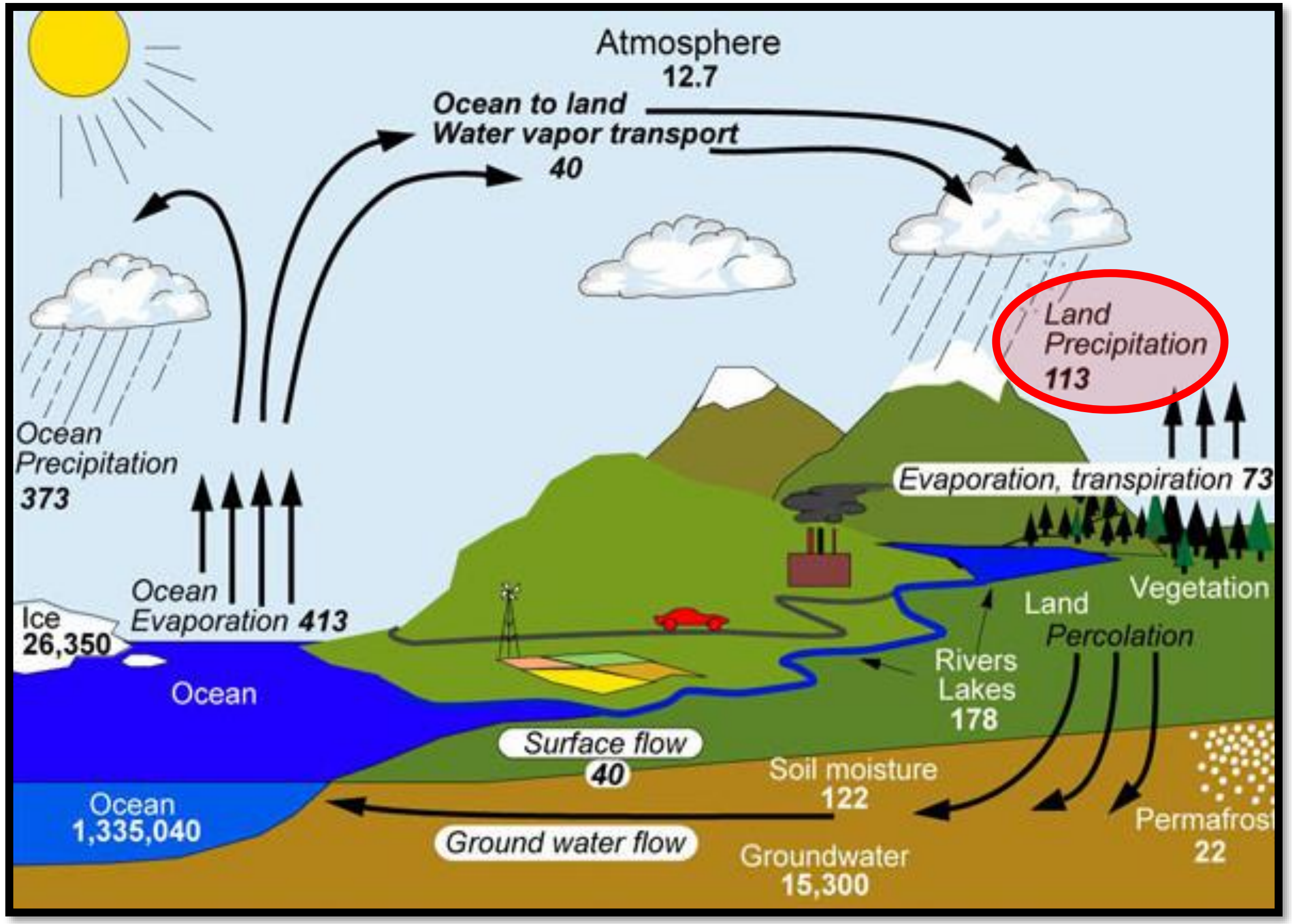
Data sources: USGS, DOE, and IPCC.



Global Carbon Flux (Gt/yr) and Storage (Gt)

LI-COR

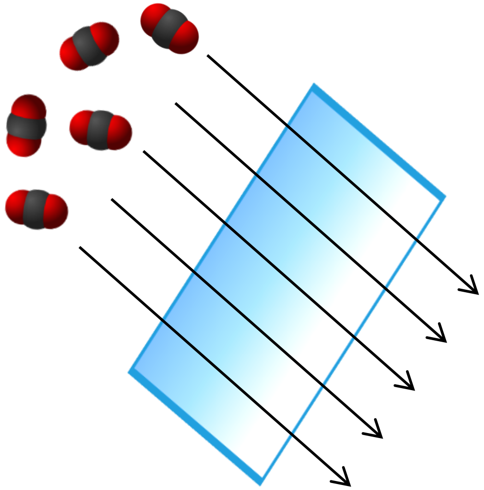
The Hydrological Cycle



Trenberth *et al.*, 2007. *Journal of Hydrometeorology*, 8: 758-769.

What is flux?

Flux – how much of an entity (heat, CO_2, H_2O, CH_4, etc) moves through a unit area per unit time



$$CO_2\left[\frac{mol}{m^2 s}\right]$$

mol: 6.022 x 10^{23}

CO_2: 44 g mol^{-1}

Terminology and units

Density: g air m^{-3}, mol air m^{-3}
g CO_2 m^{-3}, mol CO_2 m^{-3}

Mole Fraction: μmol CO_2 per mol total air (ppm)

Dry Mole Fraction: μmol CO_2 per mol dry air (ppm)

Mixing Ratio: mmol H_2O per mol dry air (pp**t, ‰**)

Terminology and units for CO_2, H2O, and CH_4 flux

CO_2 flux: $\mu mol\ CO_2\ m^{-2}\ s^{-1}$
$g\ C\ m^{-2}\ d^{-1}$
$g\ C\ m^{-2}\ yr^{-1}$

H_2O flux (E): $mmol\ H_2O\ m^{-2}\ s^{-1}$
$mm\ hr^{-1}$, $mm\ day^{-1}$

CH_4 flux: $nmol\ CH_4\ m^{-2}\ s^{-1}$
$g\ C\ m^{-2}\ d^{-1}$
$g\ C\ m^{-2}\ yr^{-1}$

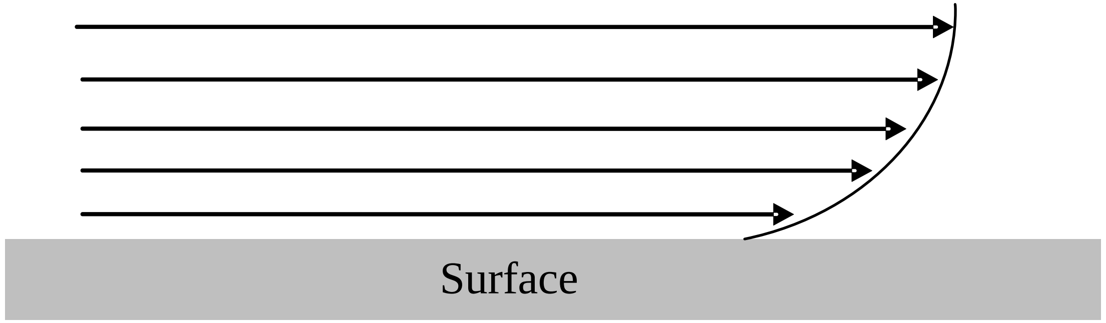
LI-COR

Terminology and units for energy flux

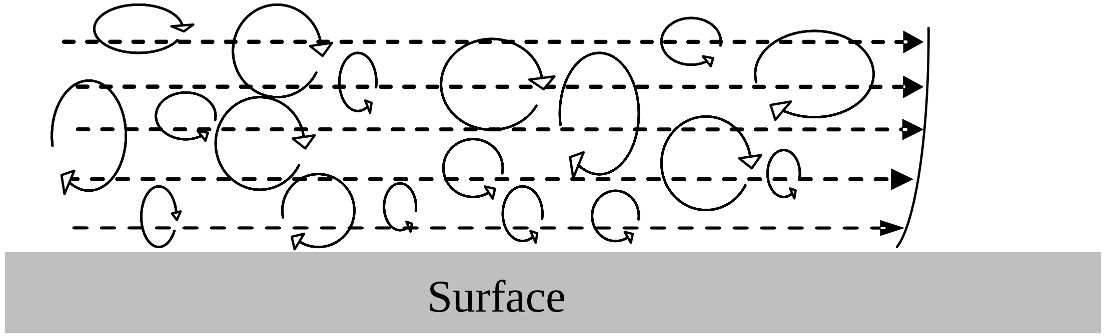
Net radiation (R_{net}):	$W\ m^{-2}$
Sensible heat flux (H):	$W\ m^{-2}$ ($J\ m^{-2}\ s^{-1}$)
Latent heat flux (LE): *(E is water vapor flux)*	$LE = \lambda E$ ($W\ m^{-2}$)
Soil heat flux (G):	$W\ m^{-2}$

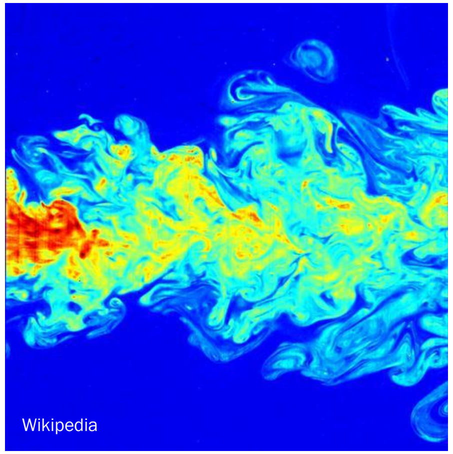
Air Flows

Laminar flow



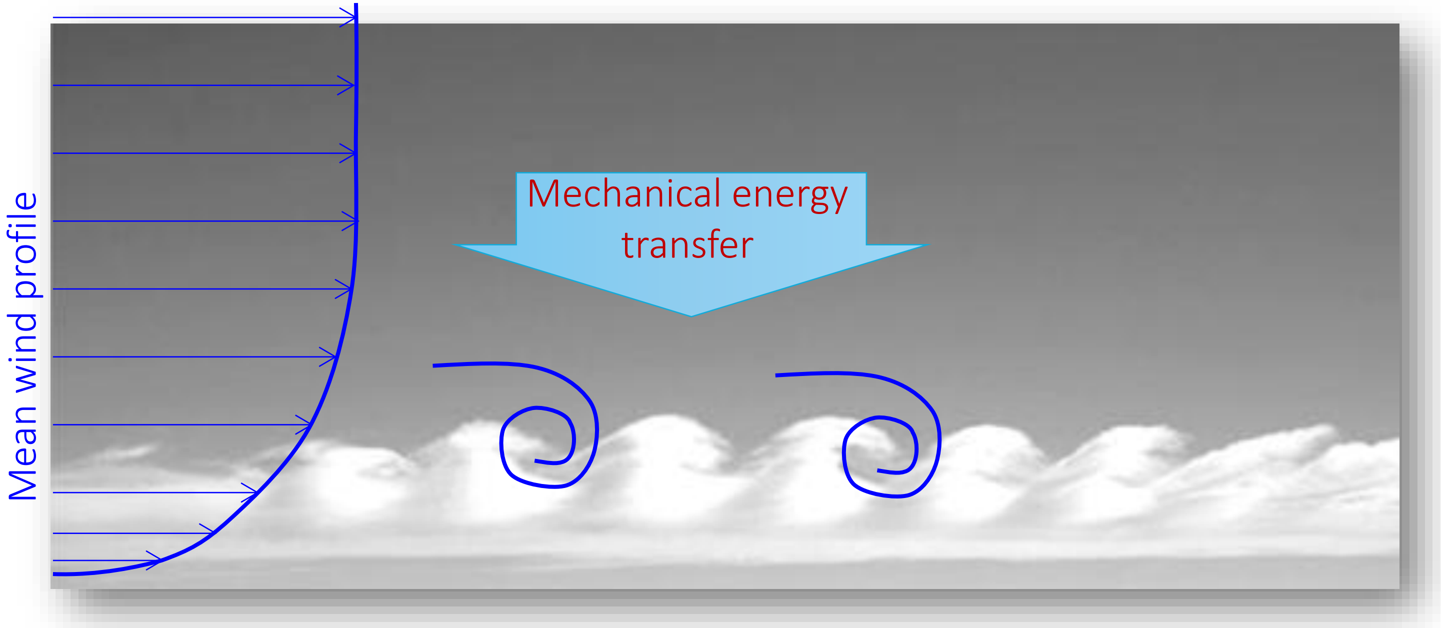
Turbulent flow (Eddies)





Turbulence generation

Mechanical turbulence and friction velocity *u**

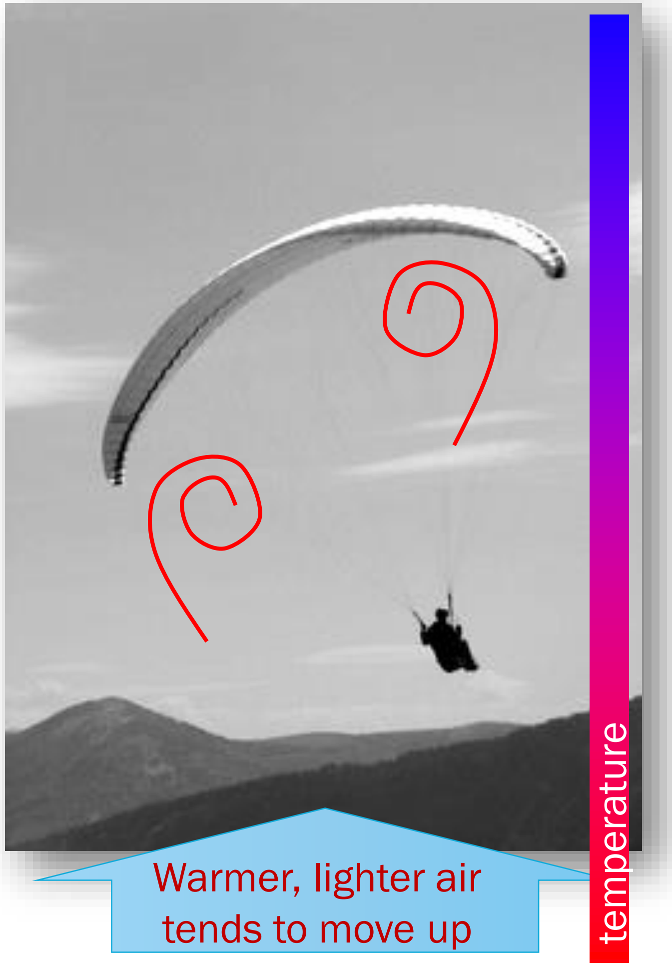


- ✓ The speed difference between different layers generates eddies → **turbulence**
- ✓ This results in a net kinetic energy transfer from upper to lower layers.
- ✓ This phenomenon is quantified by friction velocity *u**

Turbulence generation

Thermal turbulence

- ✓ Temperature gradient induced by earth surface heating generates upward-moving eddies → **convective turbulence**
- ✓ **Upward** eddies are then compensated by **downward** movements
- ✓ **Turbulence intensity** is proportional to the **vertical temperature gradient**



Fundamentals of Turbulence

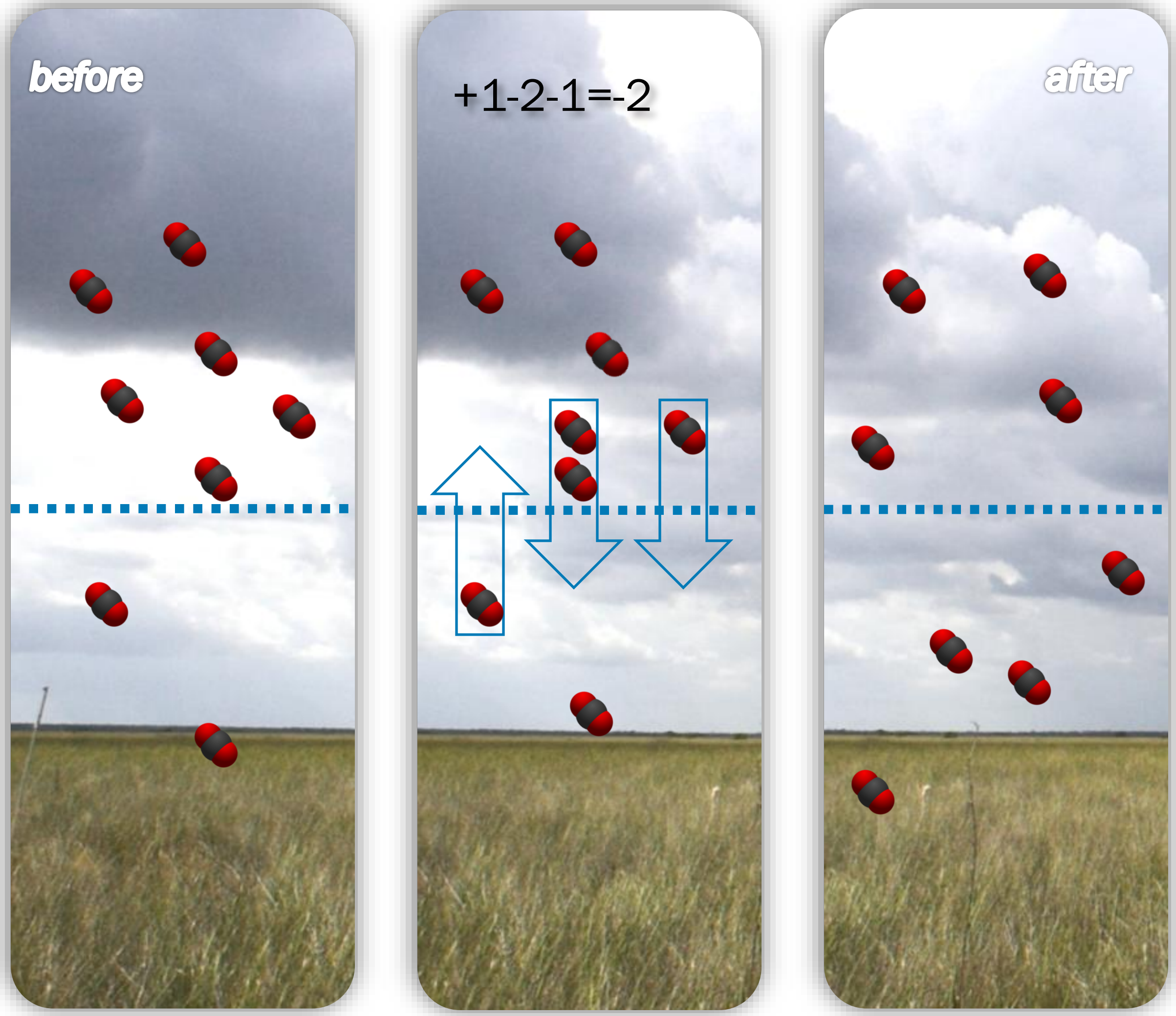
1. Randomness
   Chaotic and mechanistically unpredictable
   -> Statistics to describe turbulence

2. Rotationality
   Three-dimensional velocity
   -> Measure horizontal, lateral, and vertical wind speeds

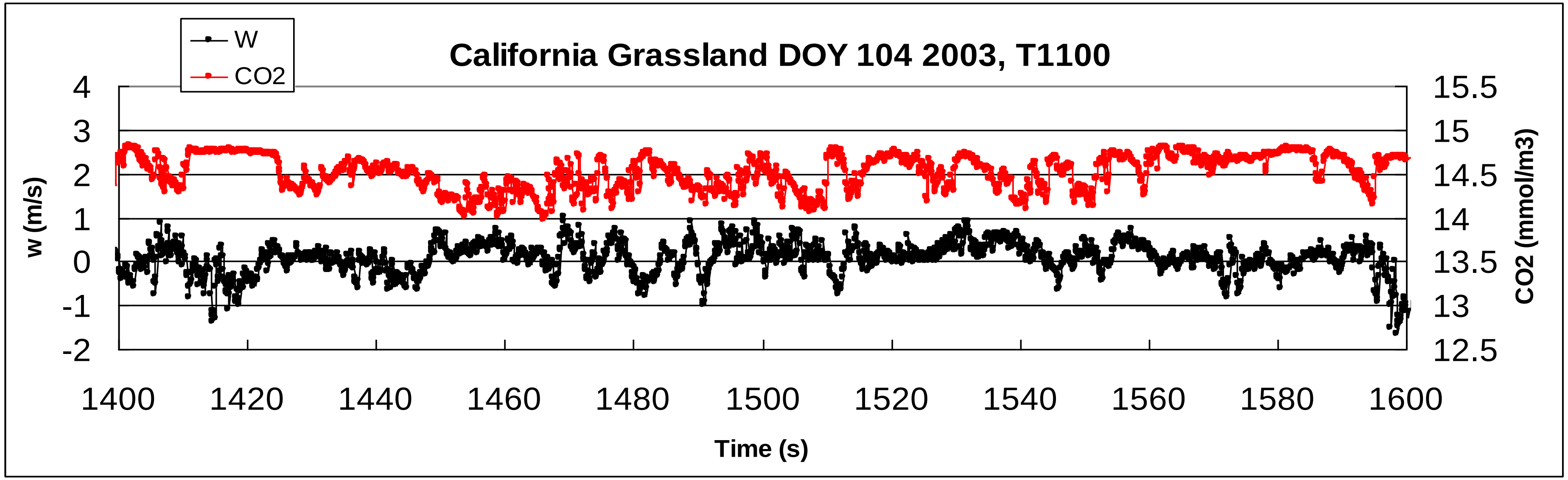
3. Multiple scales
   Eddy sizes: mm – km
   -> High-speed instruments and a proper averaging periods

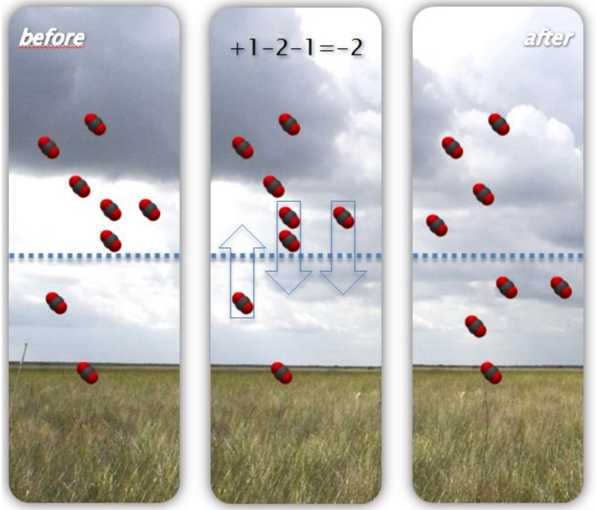
Reference: S. Pal Arya, Introduction to Micrometerology (2nd edition)

Eddy Covariance



Eddy Covariance

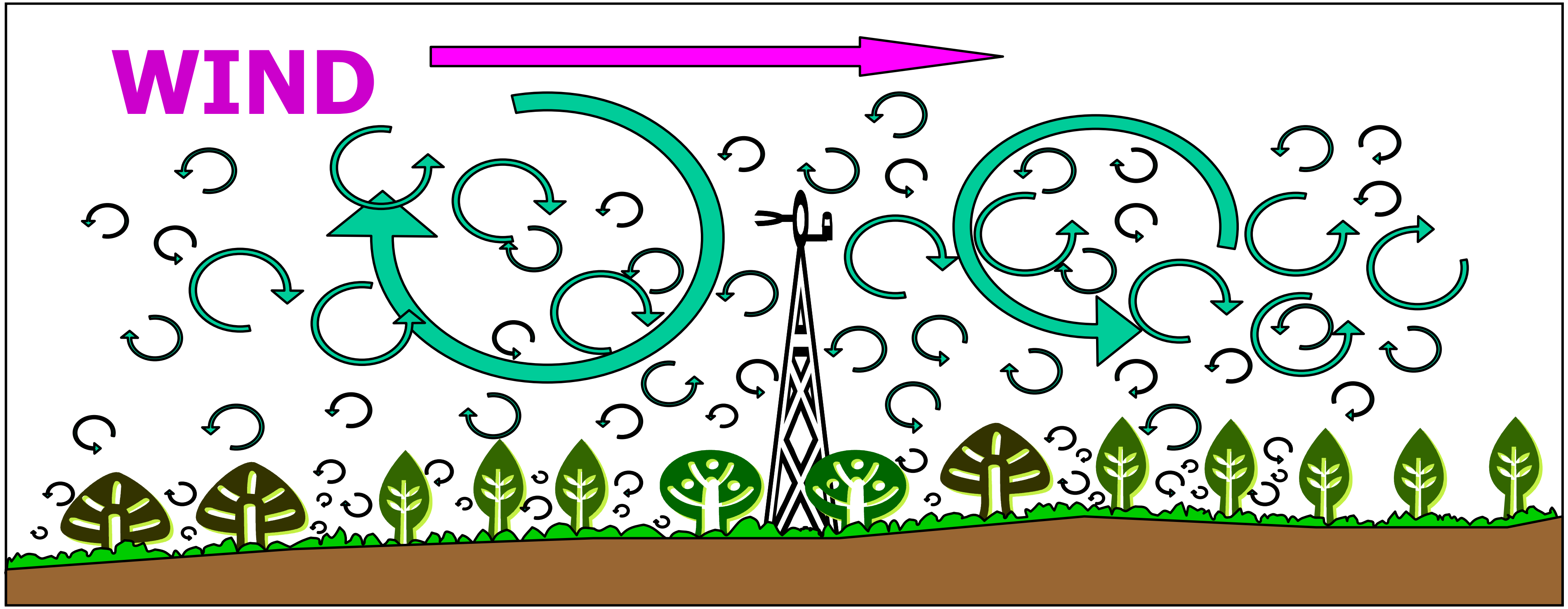




Covariance:

$$\overline{w'x'} = \frac{1}{N}\sum_{k=1}^{N}\left[\left(w_k - \overline{w}\right)\left(x_k - \overline{x}\right)\right]$$

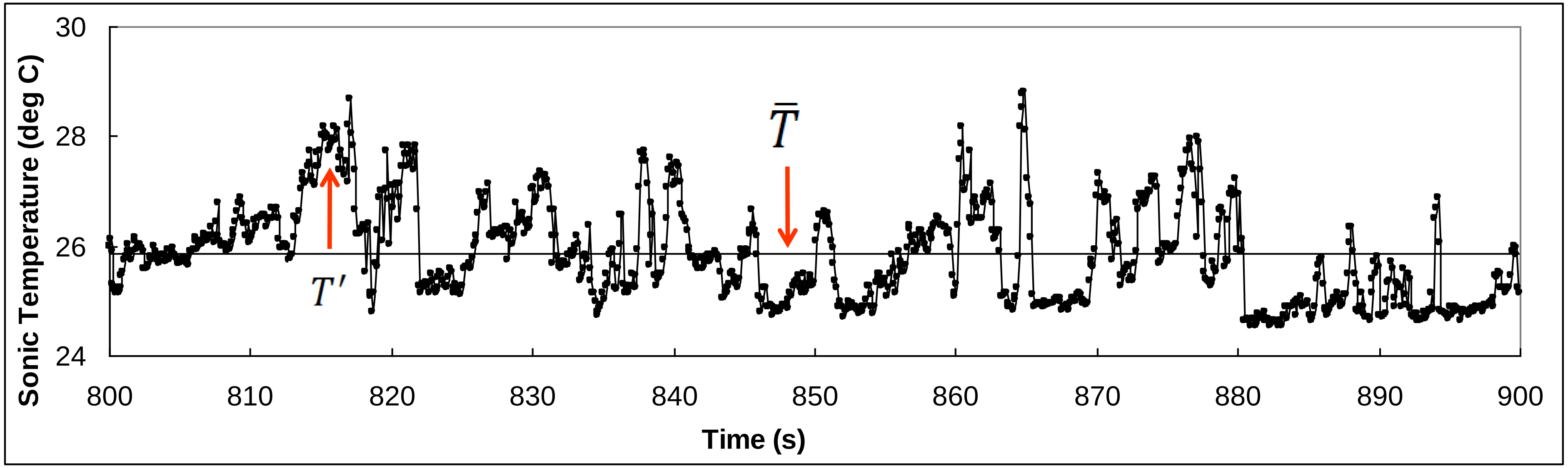
Measurement: how fast, how long?



how fast: capture small eddies, ~ 0.1 seconds (10 Hz)
how long: capture large eddies, ~ 30 minutes

Measurements at a point could represent an upwind area: "*Frozen Turbulence*" (Taylor hypothesis)

Reynolds' Averaging Rules



$$x = \bar{x} + x'$$

$$\overline{x'} = 0$$

$$\overline{x + y} = \bar{x} + \bar{y}$$

$$\overline{xy} = \bar{\bar{x}}\bar{\bar{y}} + \overline{x'y'}$$

EC theory: Complete equations

$$F = \overline{\rho_a w s}$$

$$\frac{g\ dry\ air}{m^3} \times \frac{m}{s} \times \frac{g\ CO_2}{g\ dry\ air} = \frac{g\ CO_2}{m^2 s}$$

$$F = \overline{(\overline{\rho_a} + \rho'_a)(\overline{w} + w')(\overline{s} + s')}$$

$$F = (\overline{\overline{\rho_a}\,\overline{w}\,\overline{s}} + \overline{\overline{\rho_a}\,\overline{w}\,s'} + \overline{\overline{\rho_a}\,w'\,\overline{s}} + \overline{\rho_a}\,\overline{w's'} + \overline{\rho'_a\,\overline{w}\,\overline{s}} + \overline{\overline{w}\,\rho'_a s'} + \overline{\overline{s}\,\rho'_a w'} + \overline{\rho'_a w' s'})$$

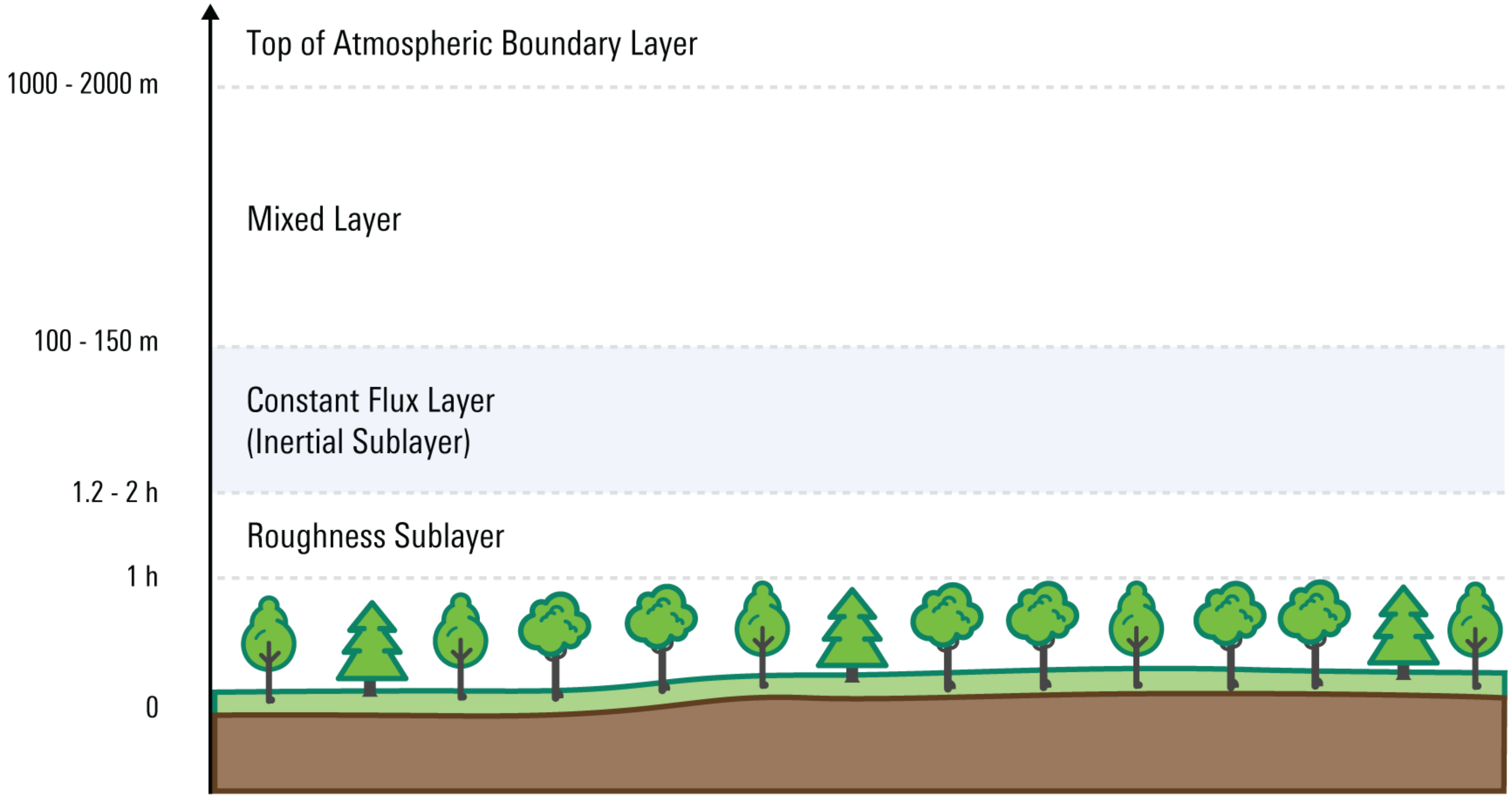
Averaged deviation from the average is zero

Quantitatively negligible terms

Mean vertical velocity assumed negligible for horizontal homogeneous terrain (no divergence/convergence)

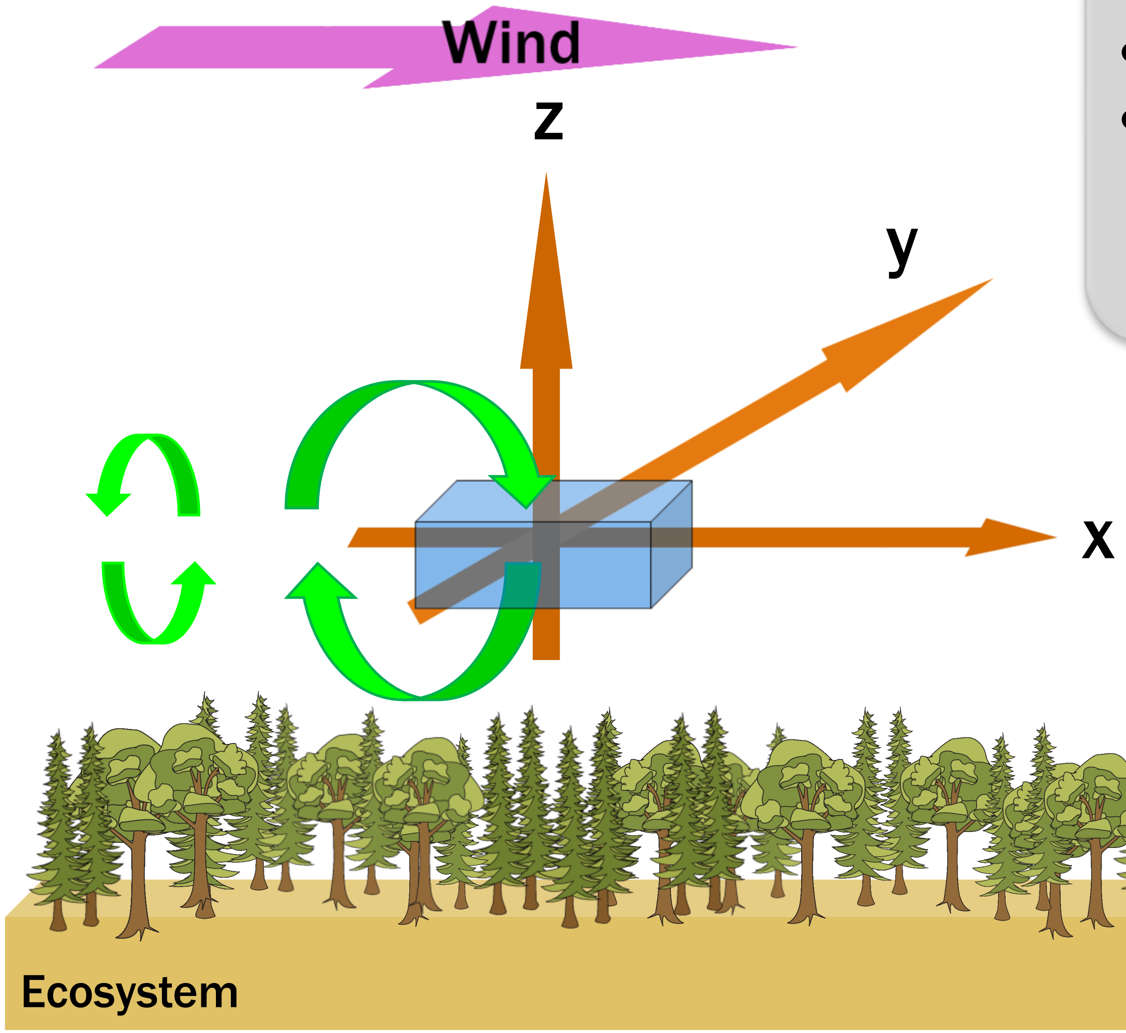
$$F \approx \overline{\rho_a}\,\overline{w's'}$$

s is dry mole fraction of e.g. CO_2



Top of Atmospheric Boundary Layer
1000 - 2000 m
Mixed Layer
100 - 150 m
Constant Flux Layer
(Inertial Sublayer)
1.2 - 2 h
Roughness Sublayer
1 h
0

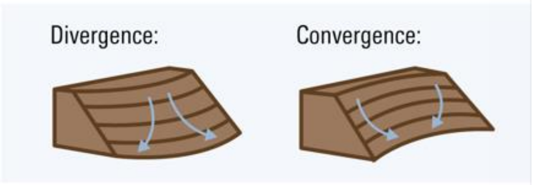
Gas Transfer in the 'Constant Flux' Layer

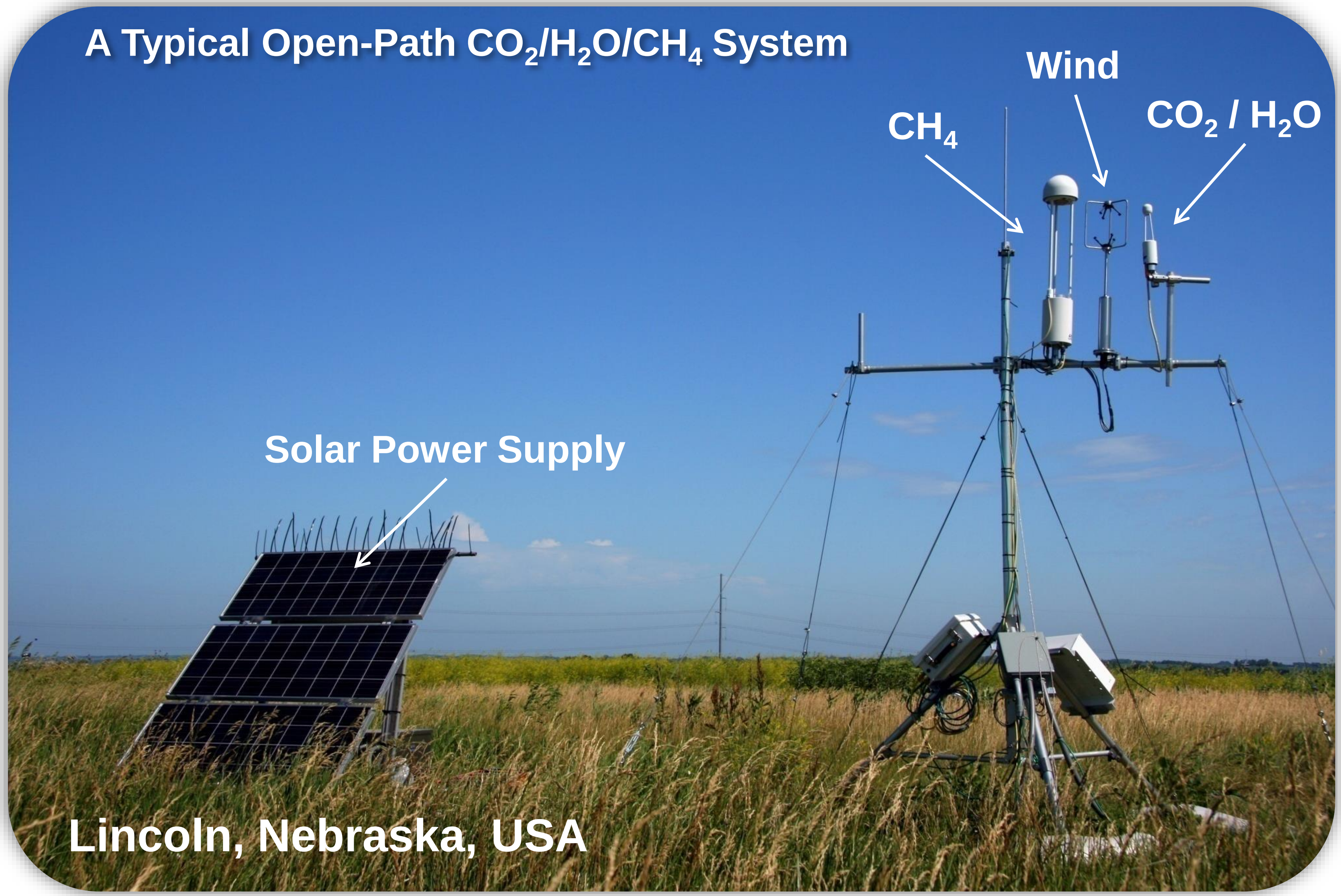


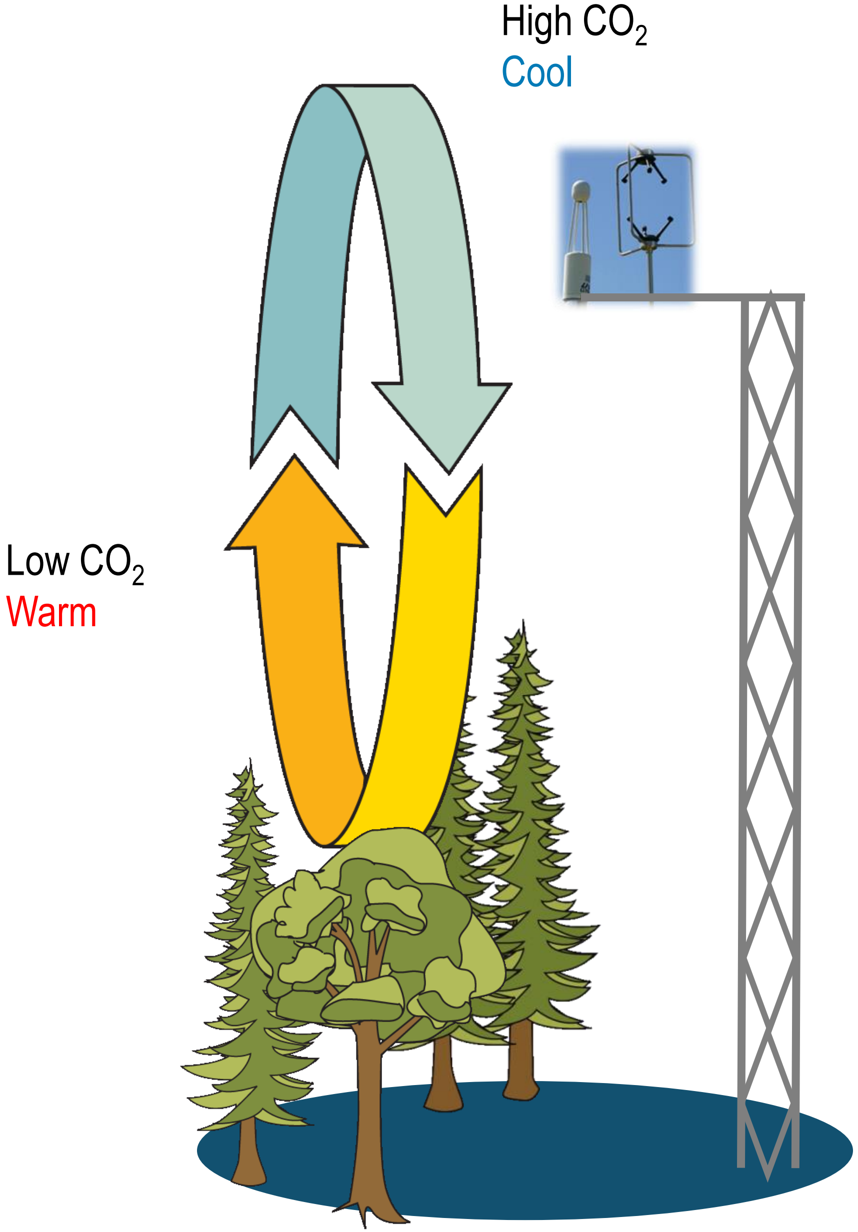
Assumptions:

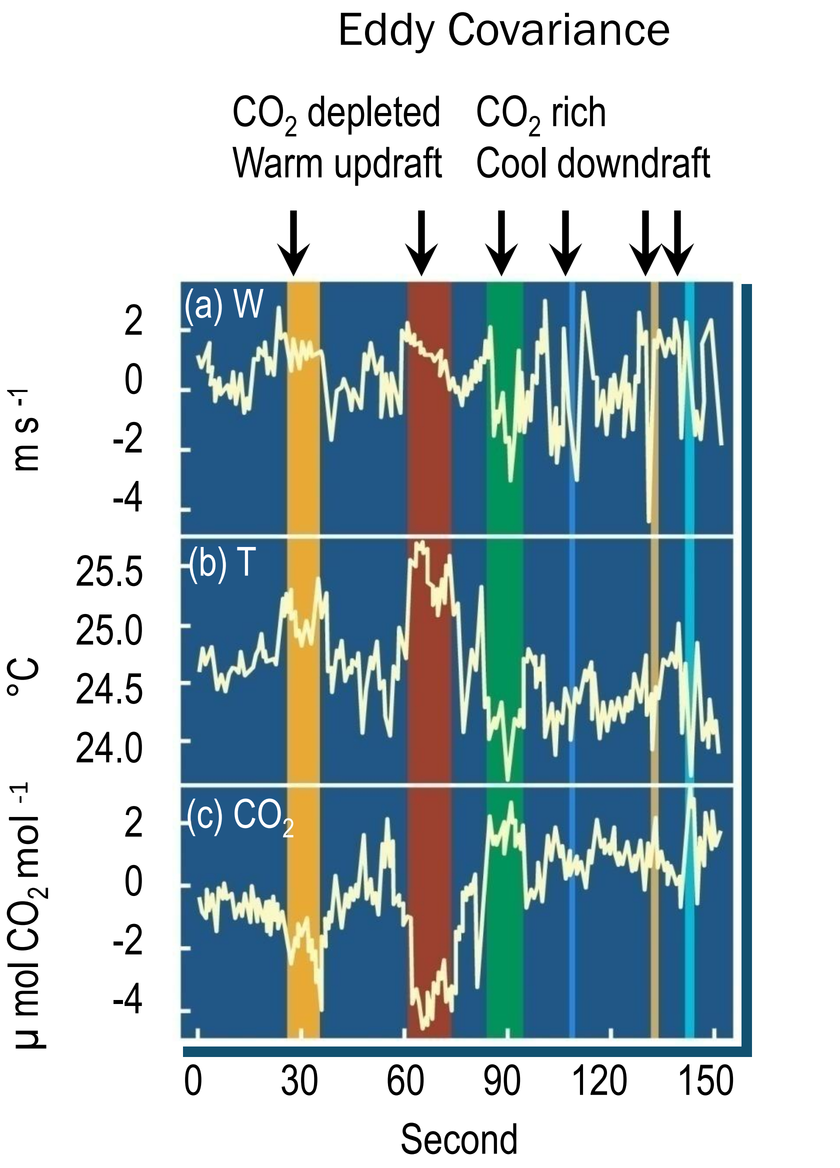
- Turbulent mixing
- No mean vertical flow
- Divergence and convergence for homogeneous & horizontal terrain negligible

Adapted from Galvagno et al (2013)




A Typical Open-Path $CO_2/H_2O/CH_4$ System
Wind
CH_4
CO_2 / H_2O
Solar Power Supply
Lincoln, Nebraska, USA





Courtesy of Dr. Hank Margolis, Laval University

Selected Eddy Covariance data processing principles

Design → **Implement** → **Data Processing/Analysis**

Design

- Set purpose and variables
- Decide on hardware (instruments, tower, etc.)
- Decide on software (data collection, processing)
- Establish location
- Make maintenance plan

Implement

- Place tower
- Place instruments
- Test data collection
- Test data retrieval
- Collect data
- Test data processing
- Keep up maintenance

Data Processing/Analysis

Instantaneous Data:

- Convert units
- Despike
- Apply calibrations
- Rotate
- Correct for time delay
- De-trend (if needed)
- Average

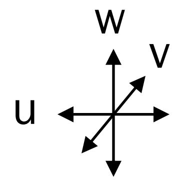
- Apply corrections

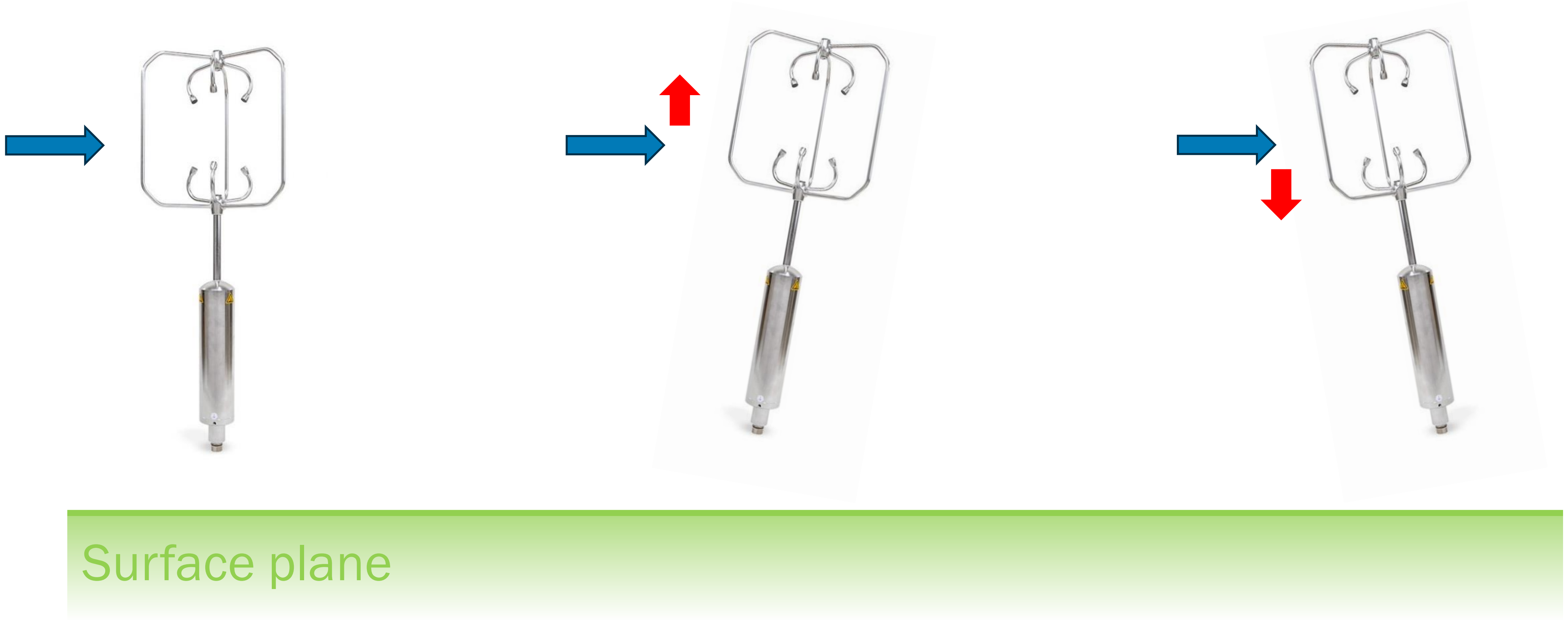
Averaged Data:

- Quality control & gap-fill
- Integrate
- Analyze/publish

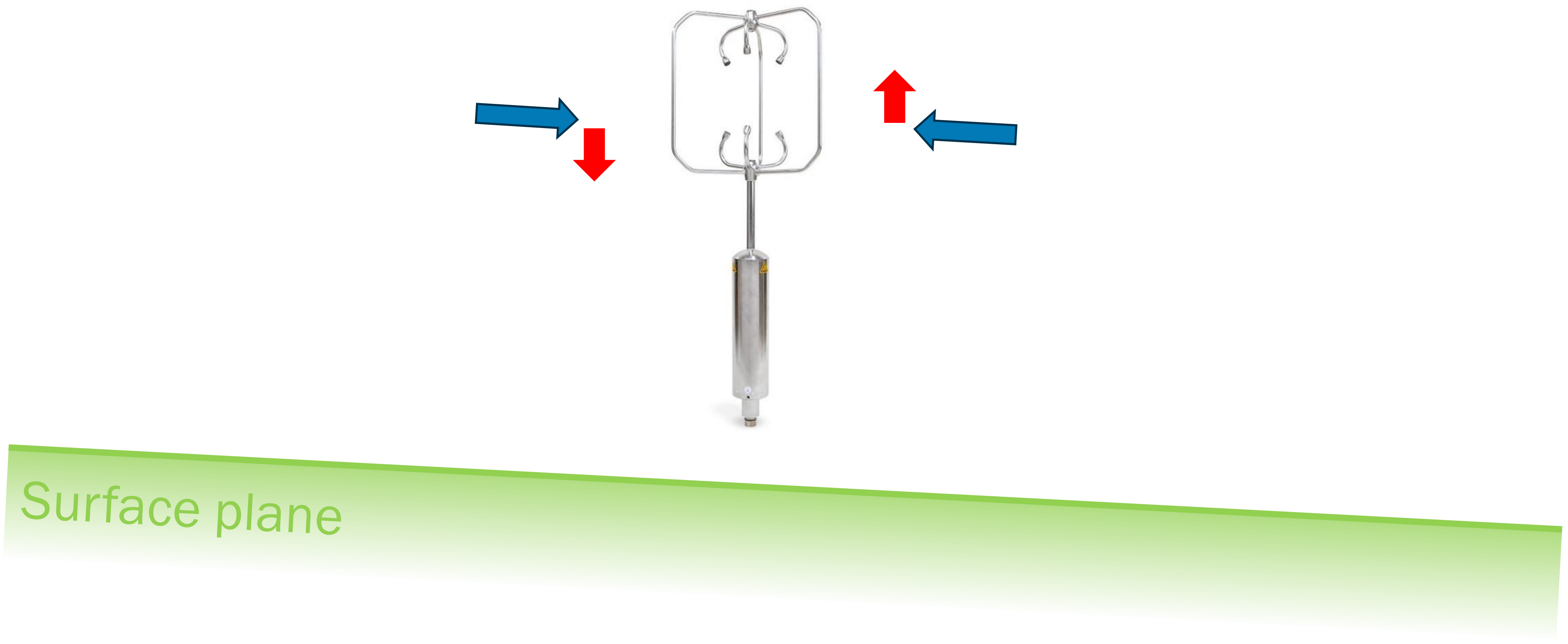
First two stages help prevent/minimize errors

Data Processing: Coordinate rotation

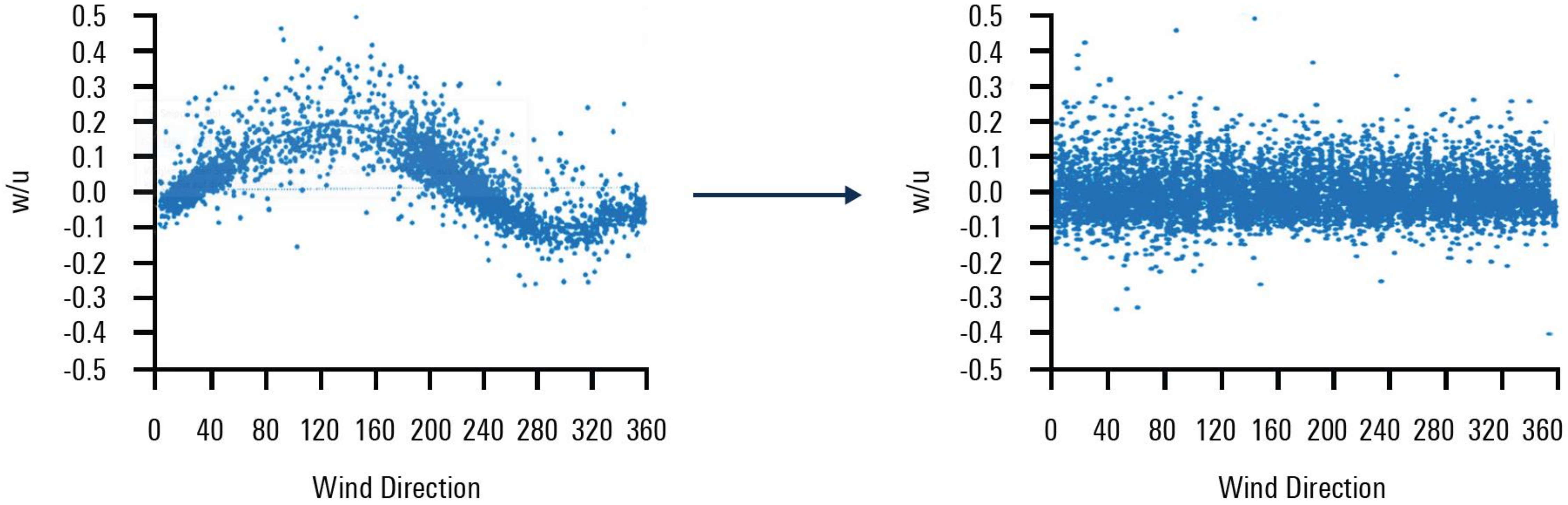




Data Processing: Coordinate rotation



Data Processing: Coordinate rotation



Data Processing: 2-D rotation

1st rotation: get velocity components in direction of mean wind vector

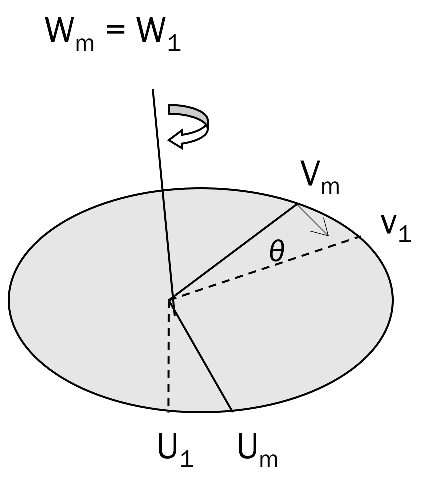
$$u_1 = u_m \cos\theta + v_m \sin\theta$$

$$v_1 = -u_m \sin\theta + v_m \cos\theta$$

$$w_1 = w_m$$

$$\theta = \tan^{-1}\left(\frac{\overline{v_m}}{\overline{u_m}}\right)$$

sets $\overline{v} = 0$



Tanner and Thurtell (1969), Kaimal and Finnigan (1994)

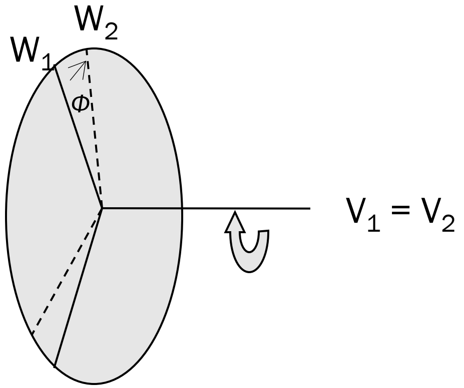
Data Processing: 2-D rotation

2nd rotation: get velocity components in streamline of terrain

$$u_2 = u_1 \cos\phi + w_1 \sin\phi$$
$$v_2 = v_1$$
$$w_2 = -u_1 \sin\phi + w_1 \cos\phi$$

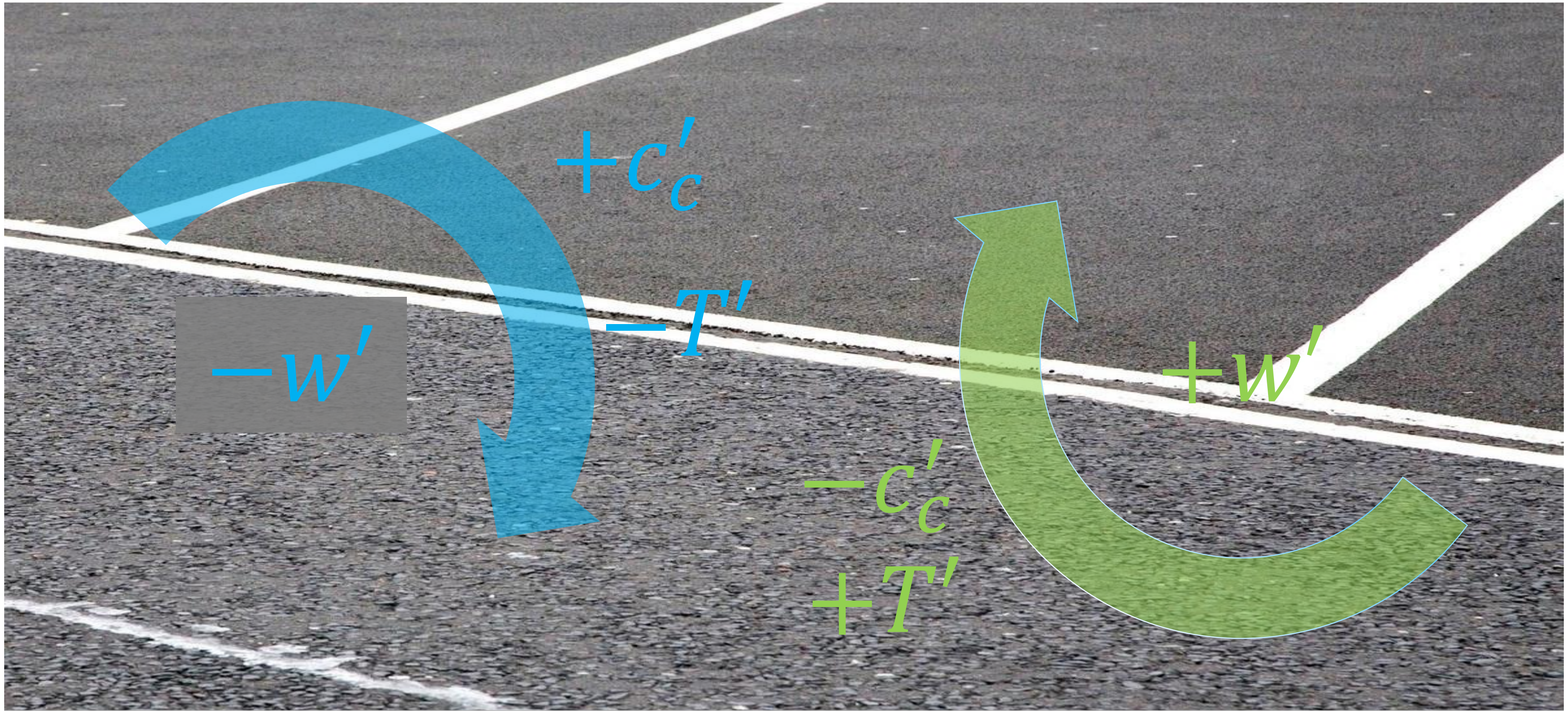
$$\phi = \tan^{-1}\left(\frac{\overline{w_1}}{\overline{u_1}}\right)$$

sets $\overline{w} = 0$



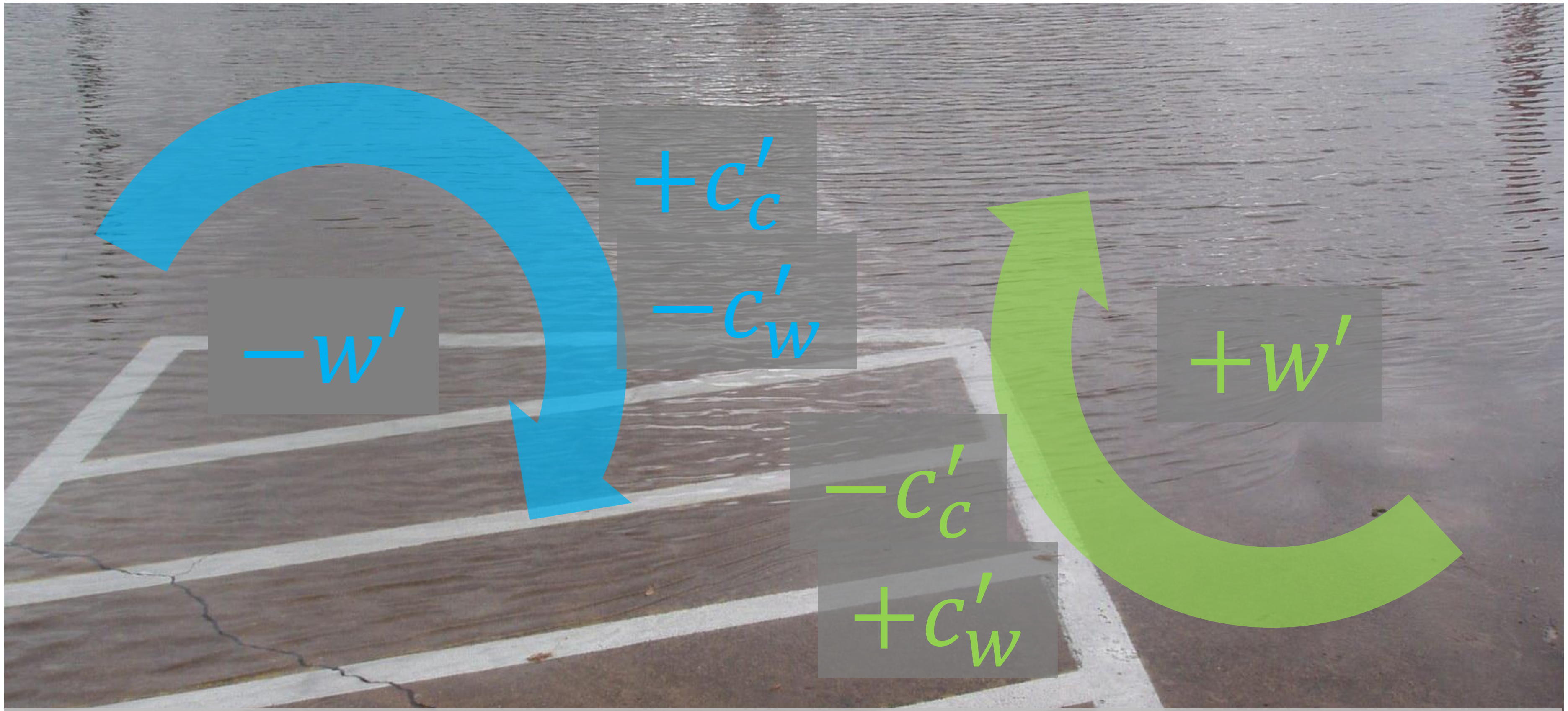
Tanner and Thurtell (1969), Kaimal and Finnigan (1994)

Dilution due to thermal expansion



No change in the total number of CO_2 molecules going up or down. Only more (cooler) or less (warmer) molecules per volume of air.

Dilution due to water vapor flux



No change in the total number of CO_2 molecules going up or down.
Only more (dry) or less (wet) CO_2 molecules per volume of air.

Final density correction equation (WPL)

Webb, Pearman, Leuning Algorithm:
Correction for Density Fluctuations when using OpenPath Sensors

Dilution

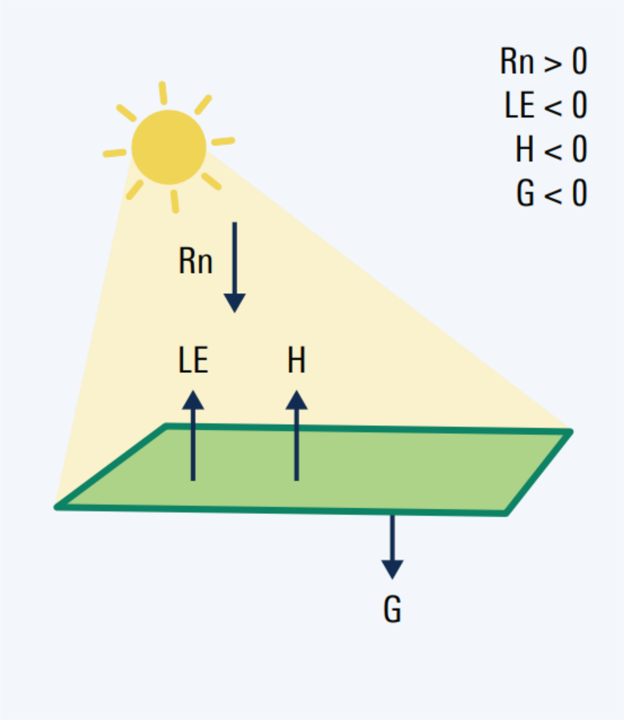
Expansion

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

Webb et al., 1980

Magnitude of the density correction

Surface Energy Balance



Short Equation:

$$Rn + H + LE + G \approx 0$$

Rn	Net Radiation
LE	Latent Heat Flux
H	Sensible Heat Flux
G	Sum of Soil Heat Flux & Soil Heat Storage

$$Rn = K\uparrow + K\downarrow + I\uparrow + I\downarrow$$

Rn net radiation

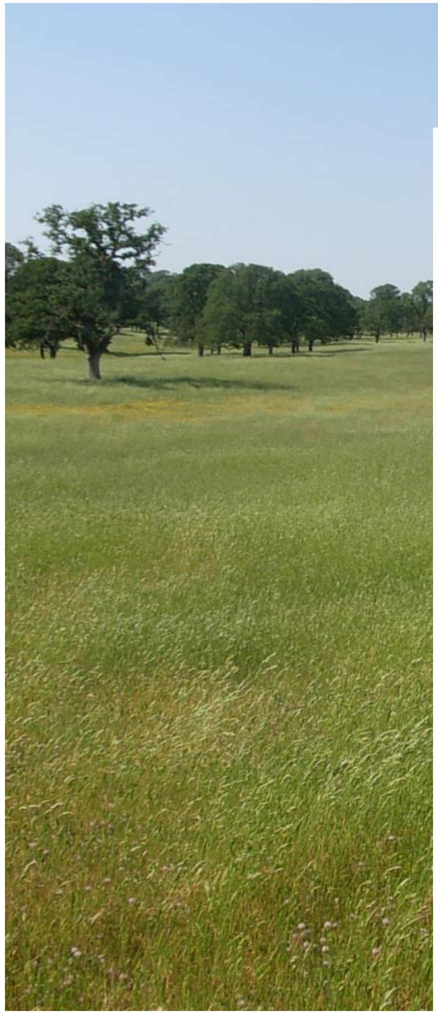
$K\downarrow$ incoming short-wave radiation

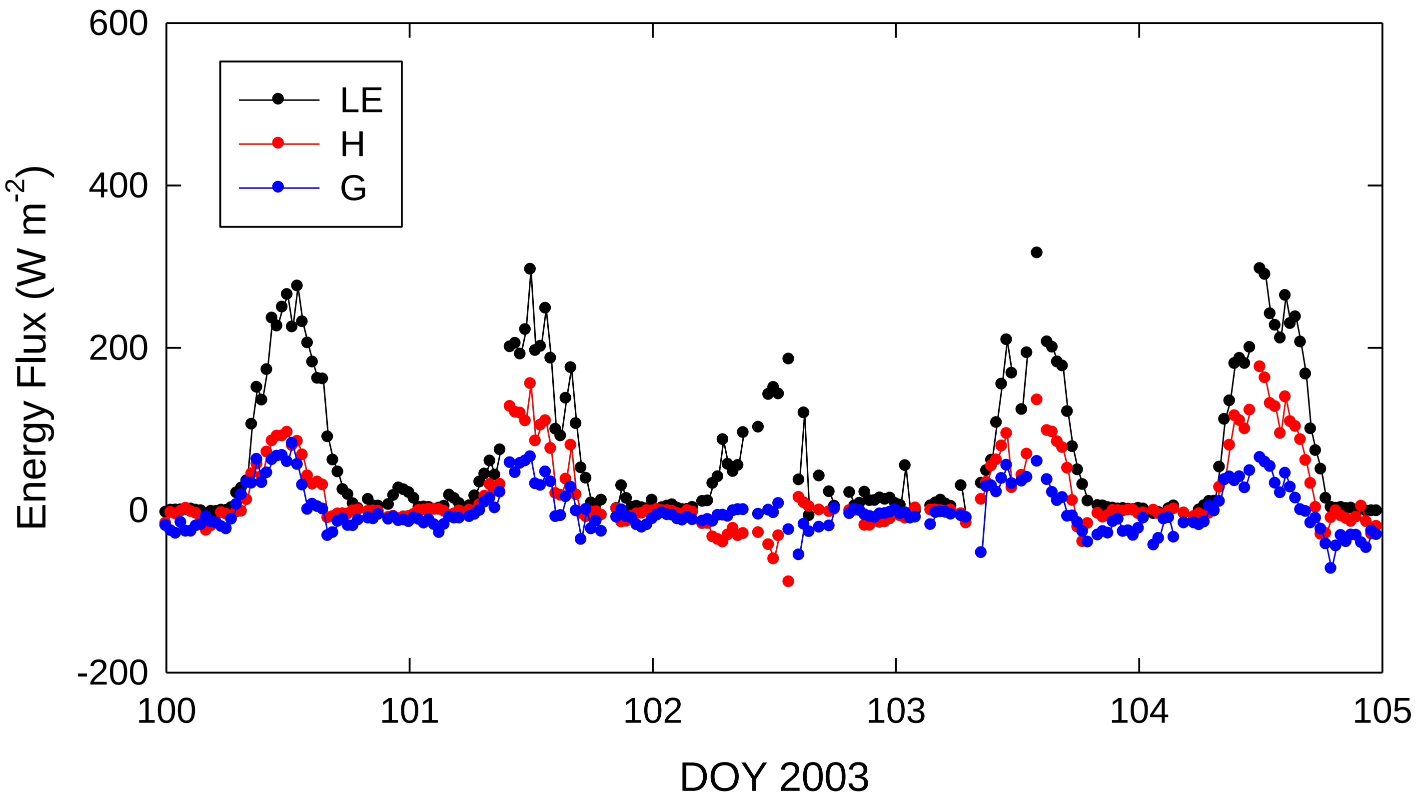
$K\uparrow$ reflected short-wave radiation

$I\uparrow$ upward long-wave radiation

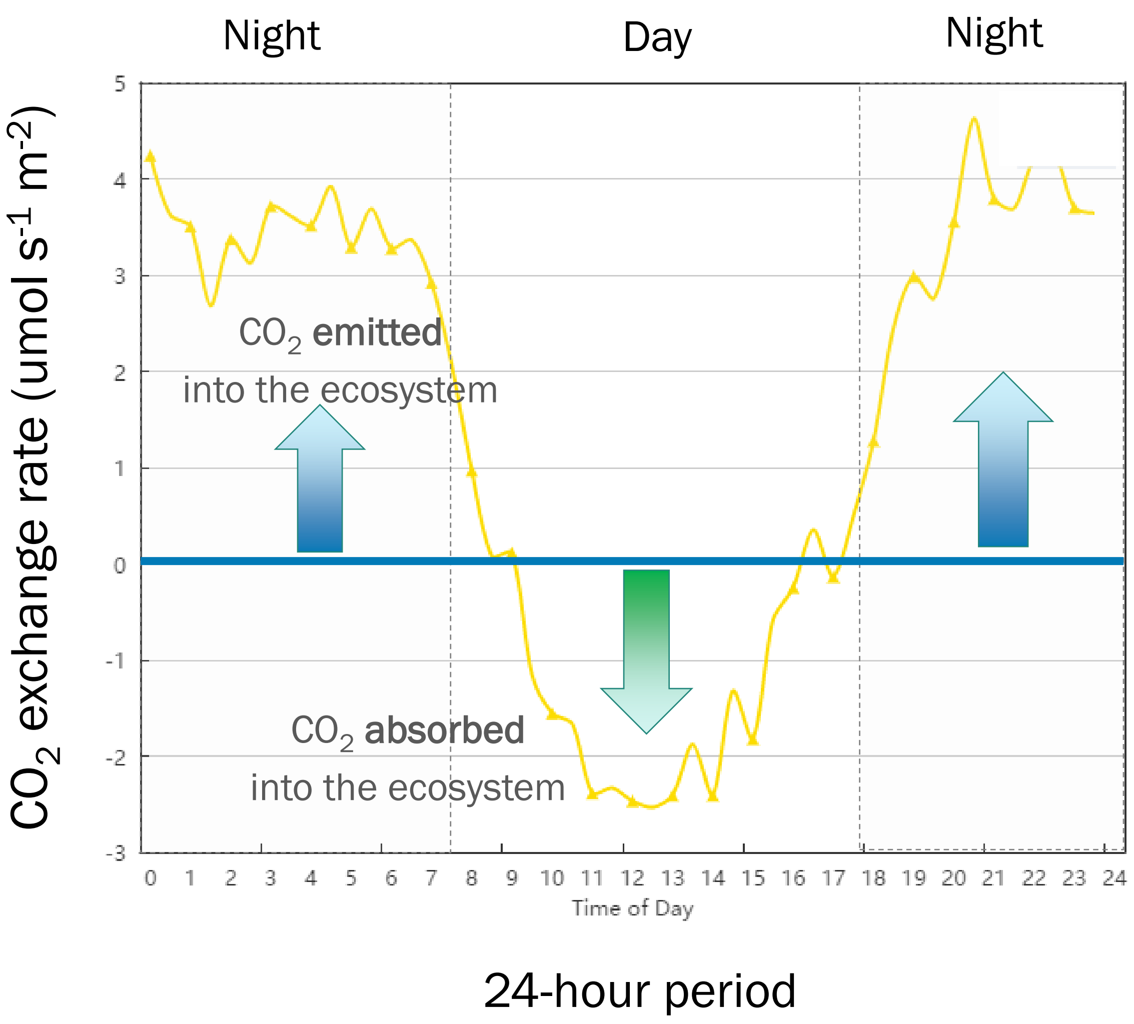
$I\downarrow$ downward long-wave radiation

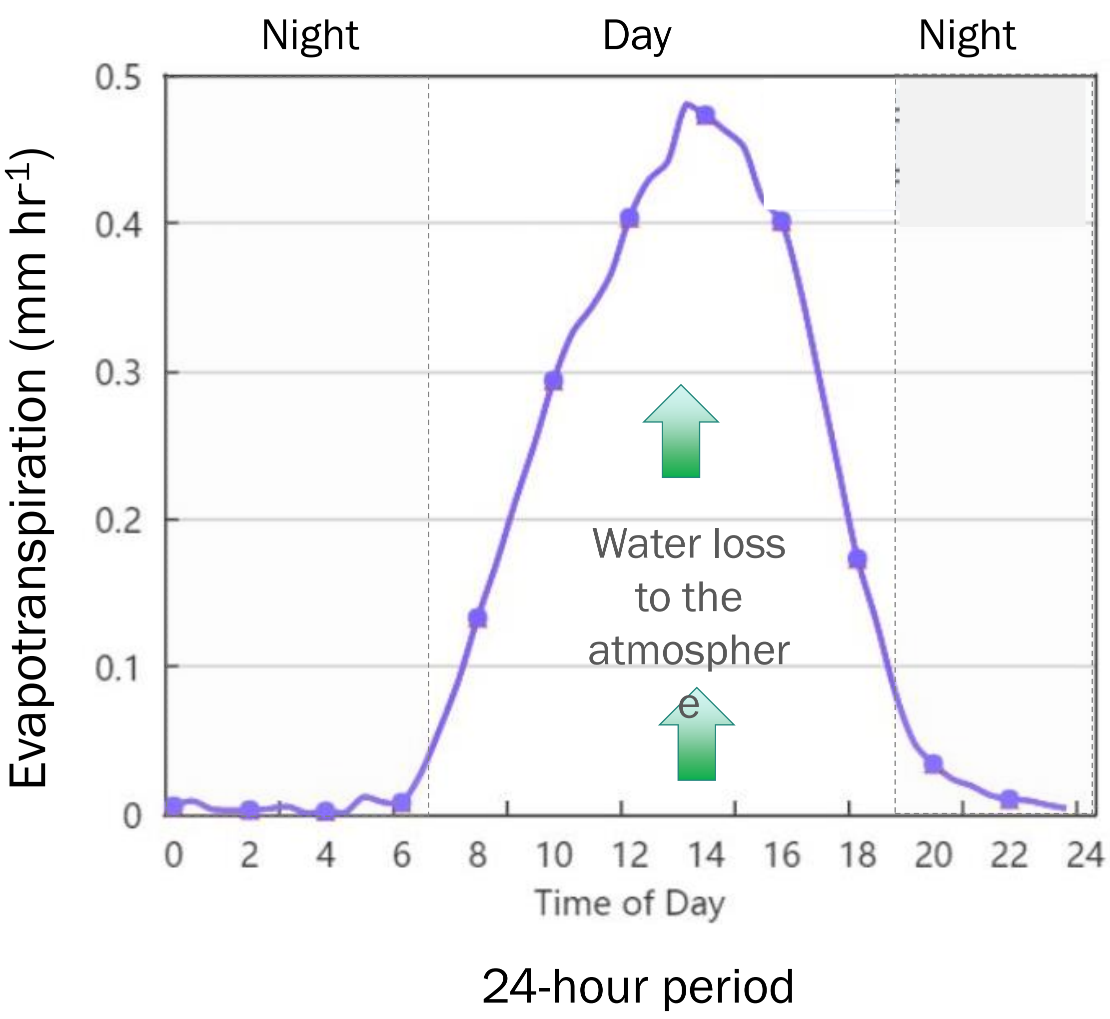
Magnitude of the density correction



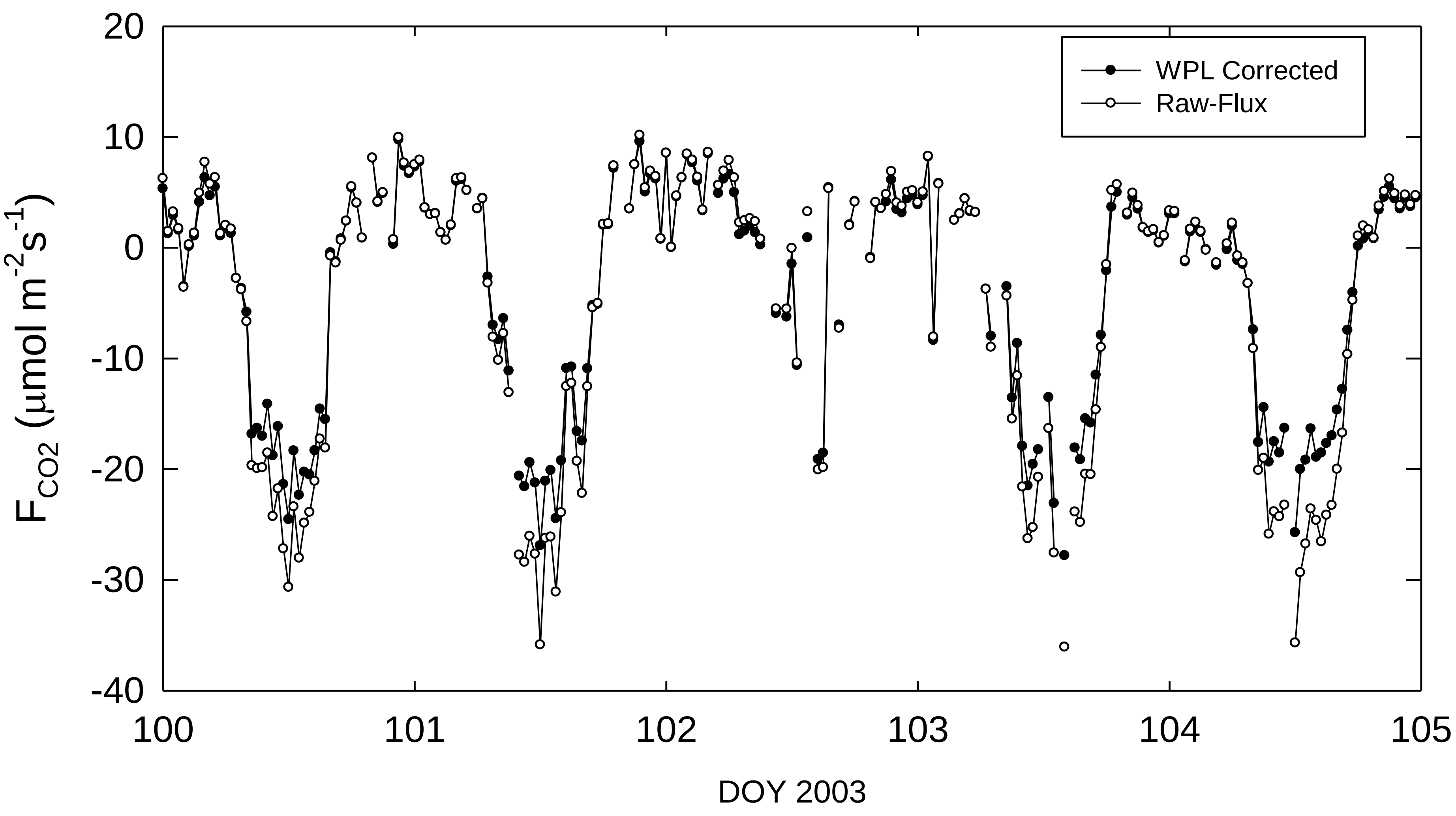


Typical Flux Results (Diurnal ensemble)



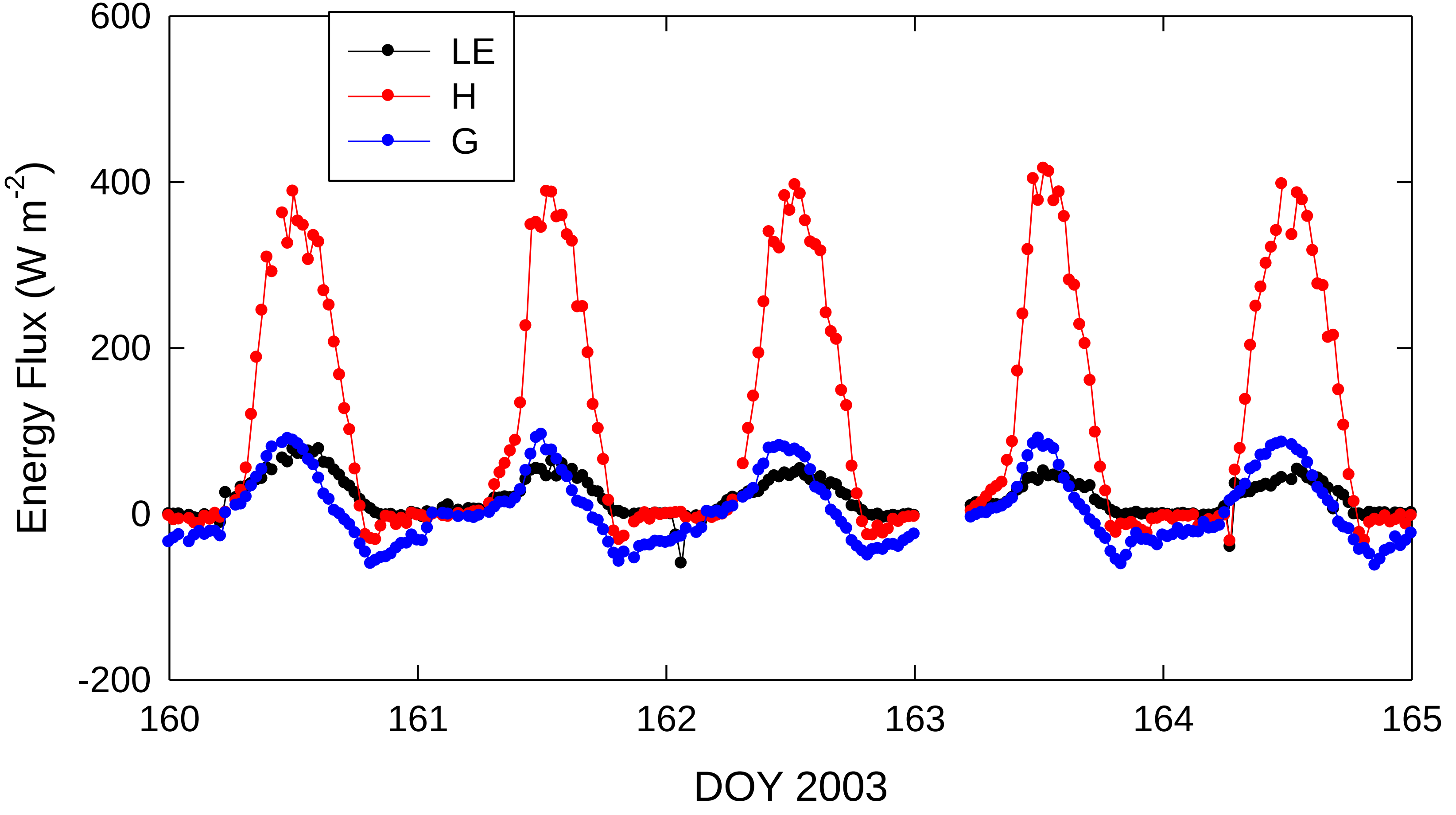


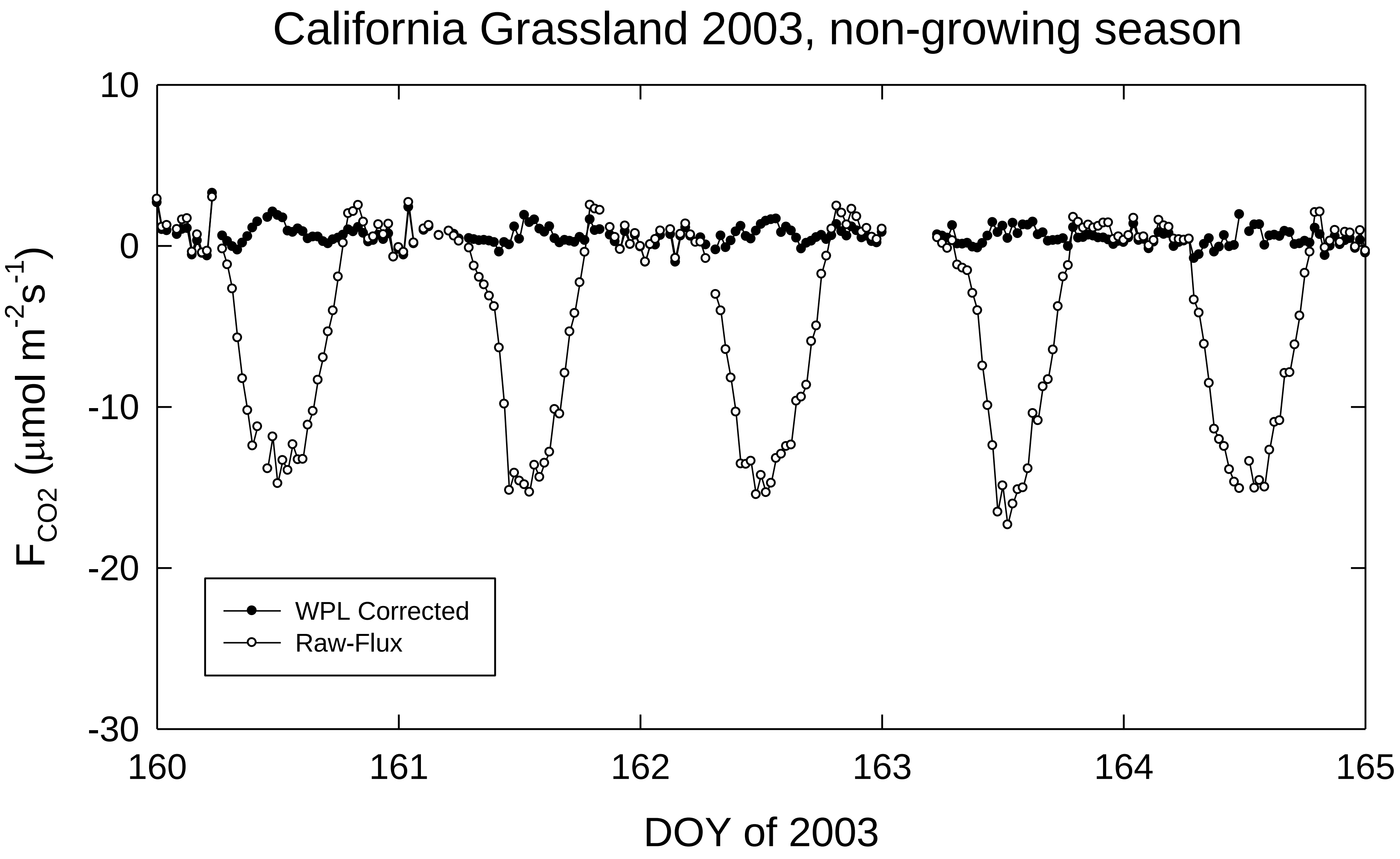
California grassland 2003, growing season



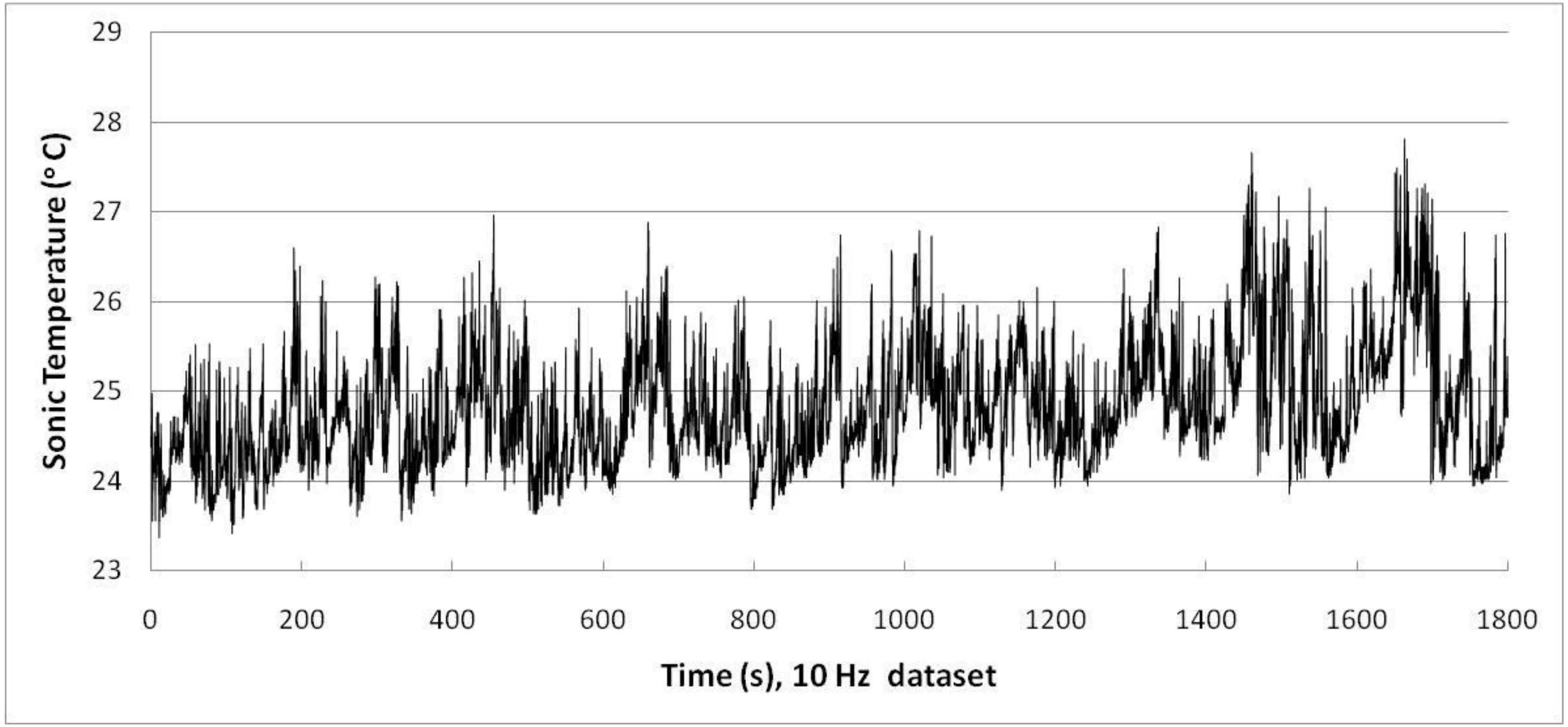
Magnitude of the density correction

Magnitude of the density correction



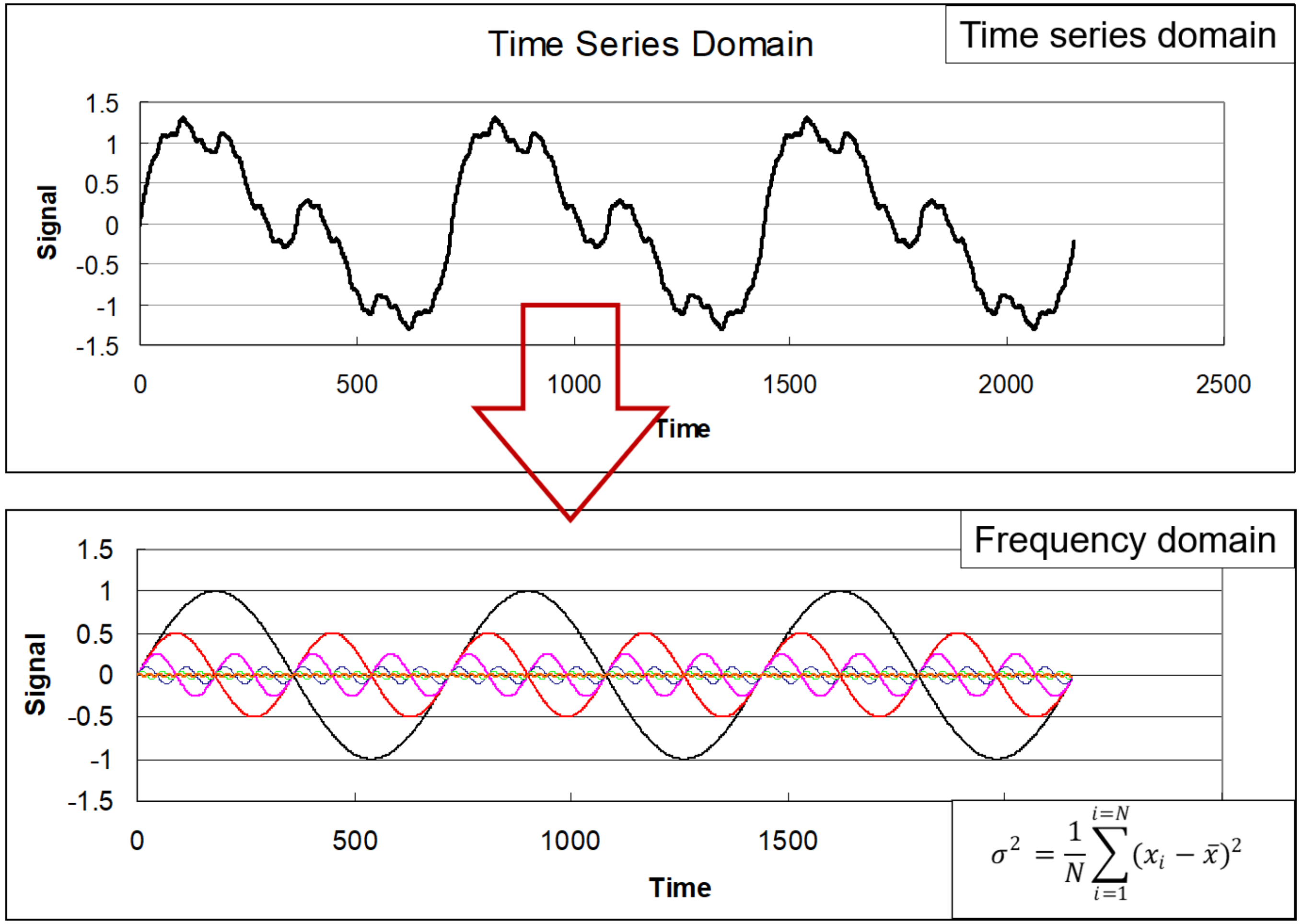

California Grassland 2003, non-growing season
10
0
-10
-20
-30
160
161
162
163
164
165
DOY of 2003
FCO2 (µmol m-2s-1)
WPL Corrected
Raw-Flux

Spectra Analysis



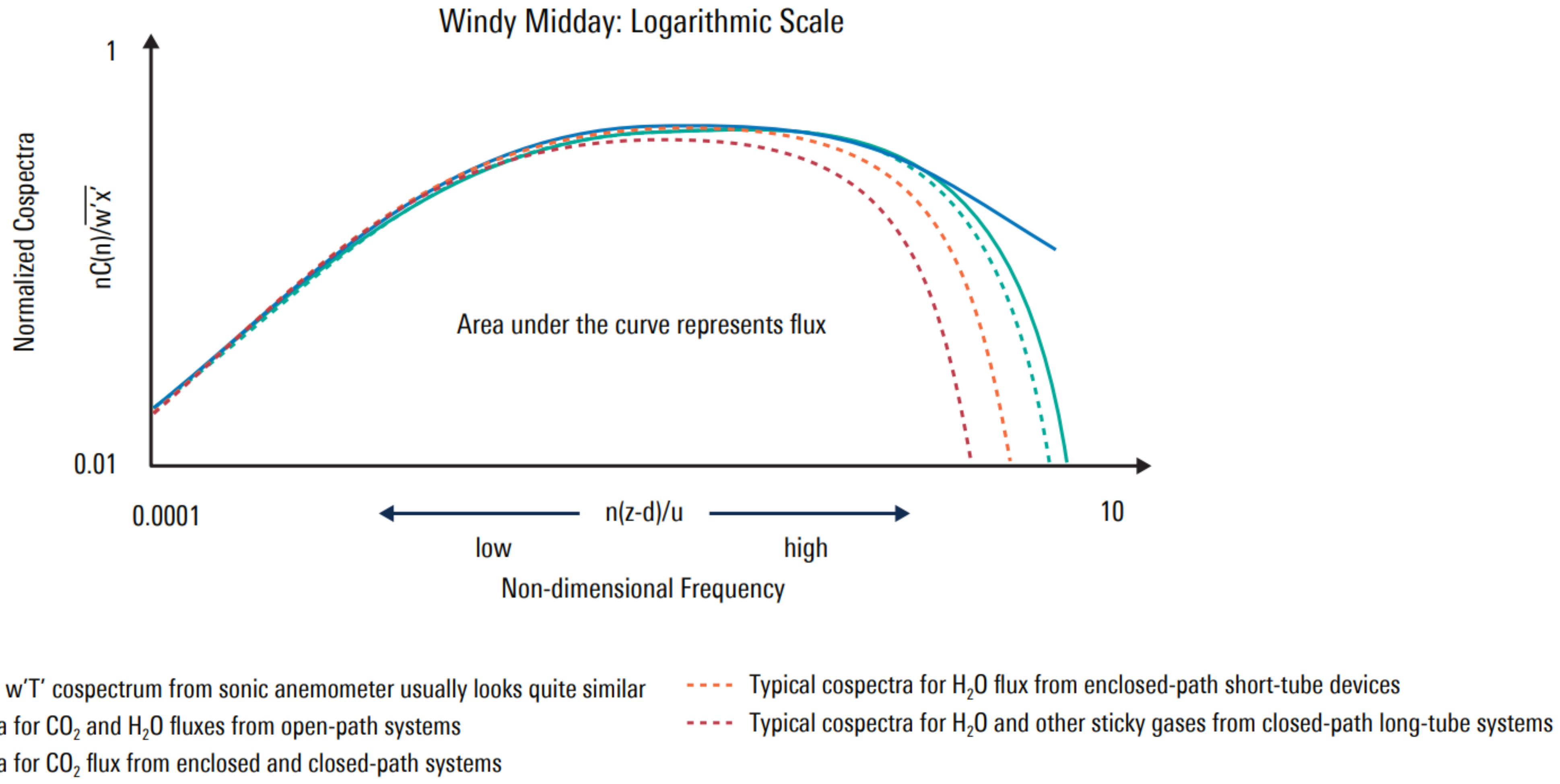
In the case of a discrete time series with a finite number of points, you can have only a finite number of sine and cosine terms to fit our points exactly.

Spectra Analysis

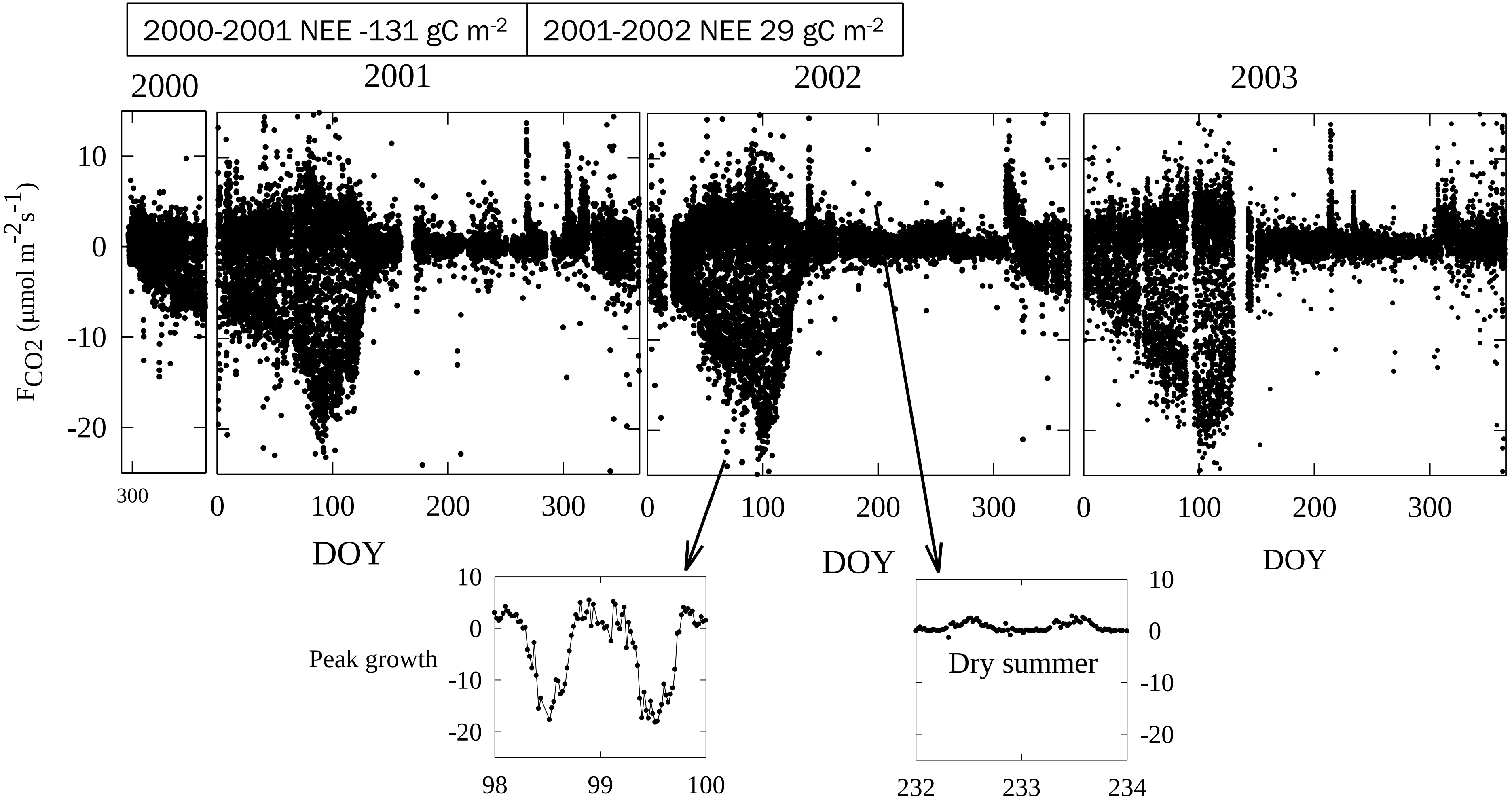


$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{i=N}(x_i - \bar{x})^2$$

Spectra Analysis: Open vs. Closed Path Analyzers



Example of long-term flux data (2000-2003)
California grassland



Xu and Baldocchi, 2004

Advantages of the EC Method over other methods

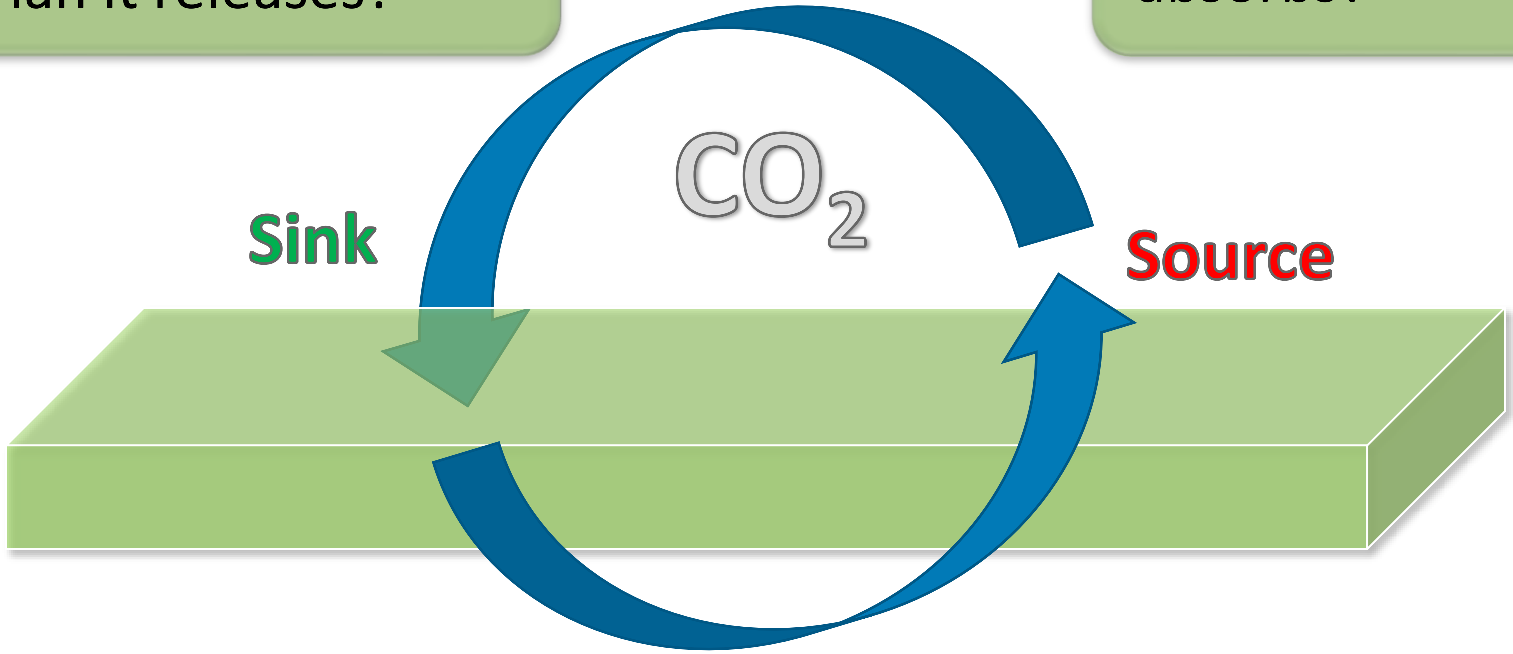
- direct measure of the flux density
- *in situ*
- No disturbance on the system
- Continuous
- Represents a large upwind area

EC Applications

Eddy covariance applications: Ecological research

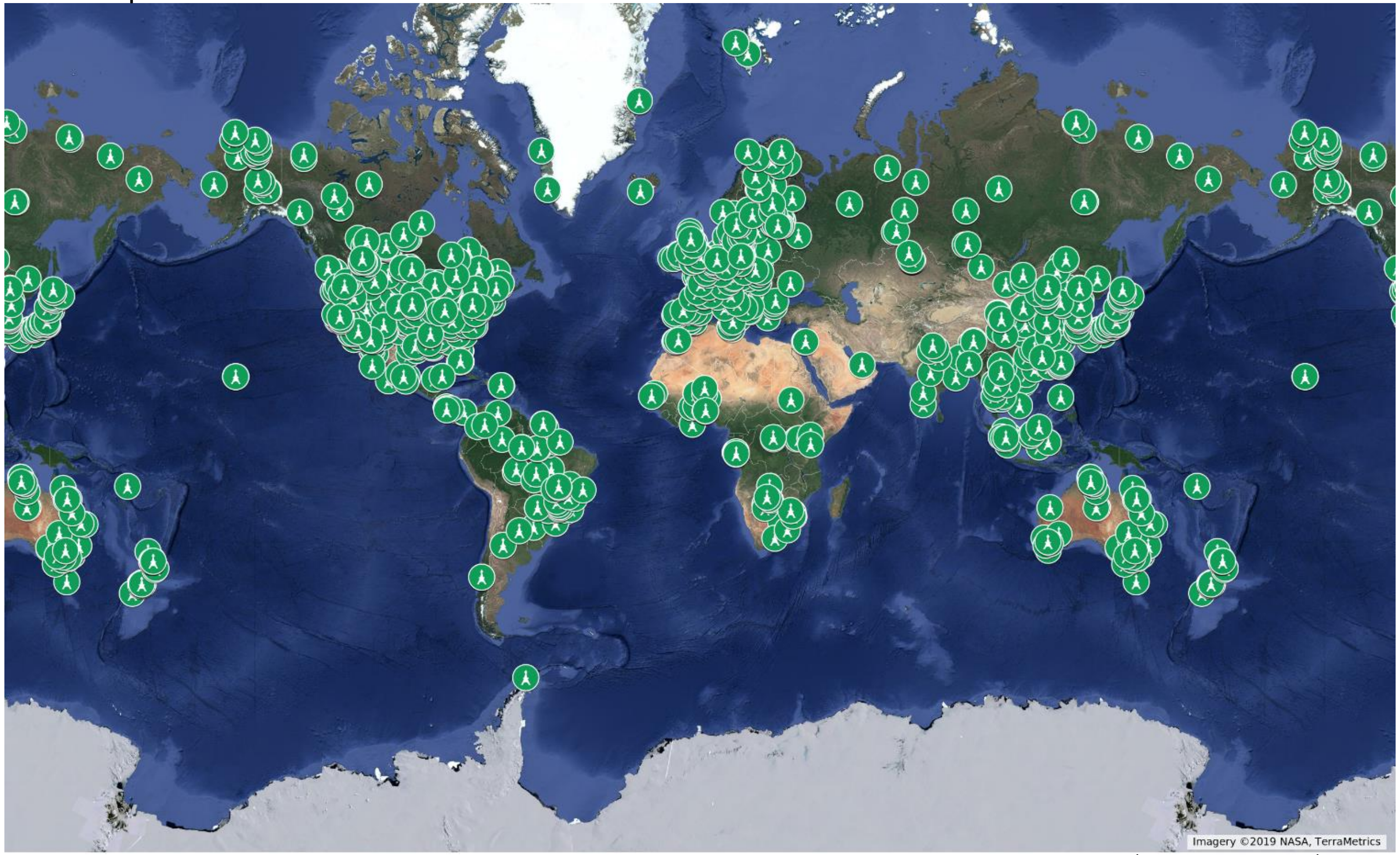
Does this Ecosystem ***absorb*** more carbon than it releases?

Or ***release*** more carbon than it absorbs?



Past and Present Eddy Covariance Measurement Locations

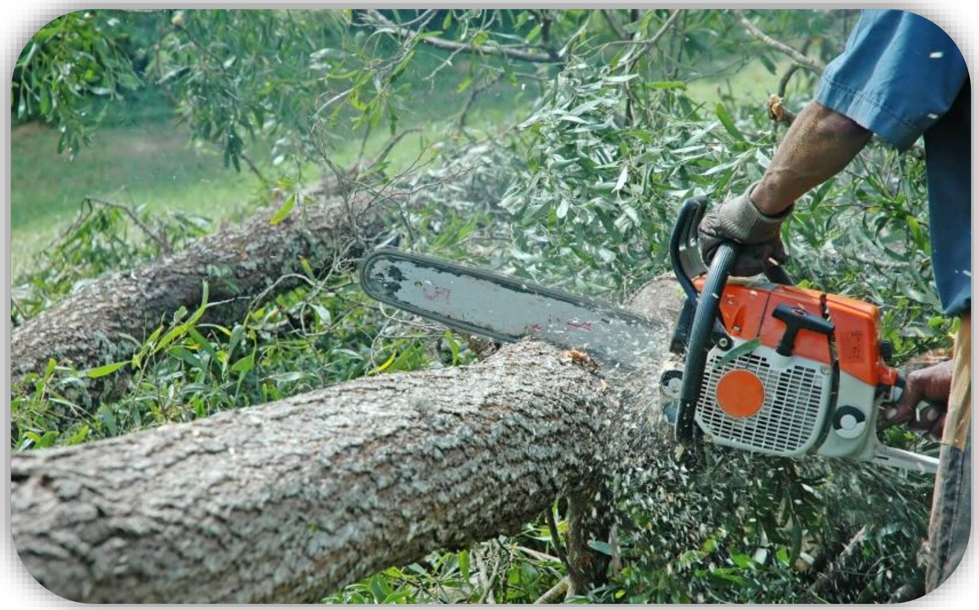
Past and present EC sites: 2029 Known discontinued EC sites: 608



George Burba, 2019, Illustrative Maps of Past and Present Eddy Covariance Measurement Locations: I. Early Update. DOI - 10.13140/RG.2.2.25992.67844/1

Agriculture

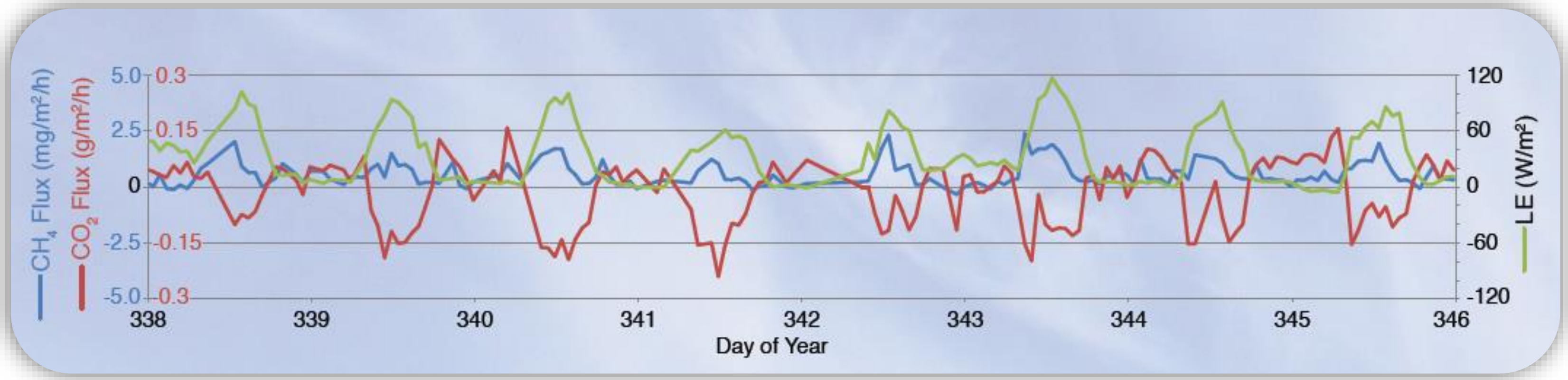
- Agricultural sciences
- Carbon Farming, sequestering atmospheric carbon into the soil
- Precision agriculture
- Water use and irrigation efficiency
- Biofuels



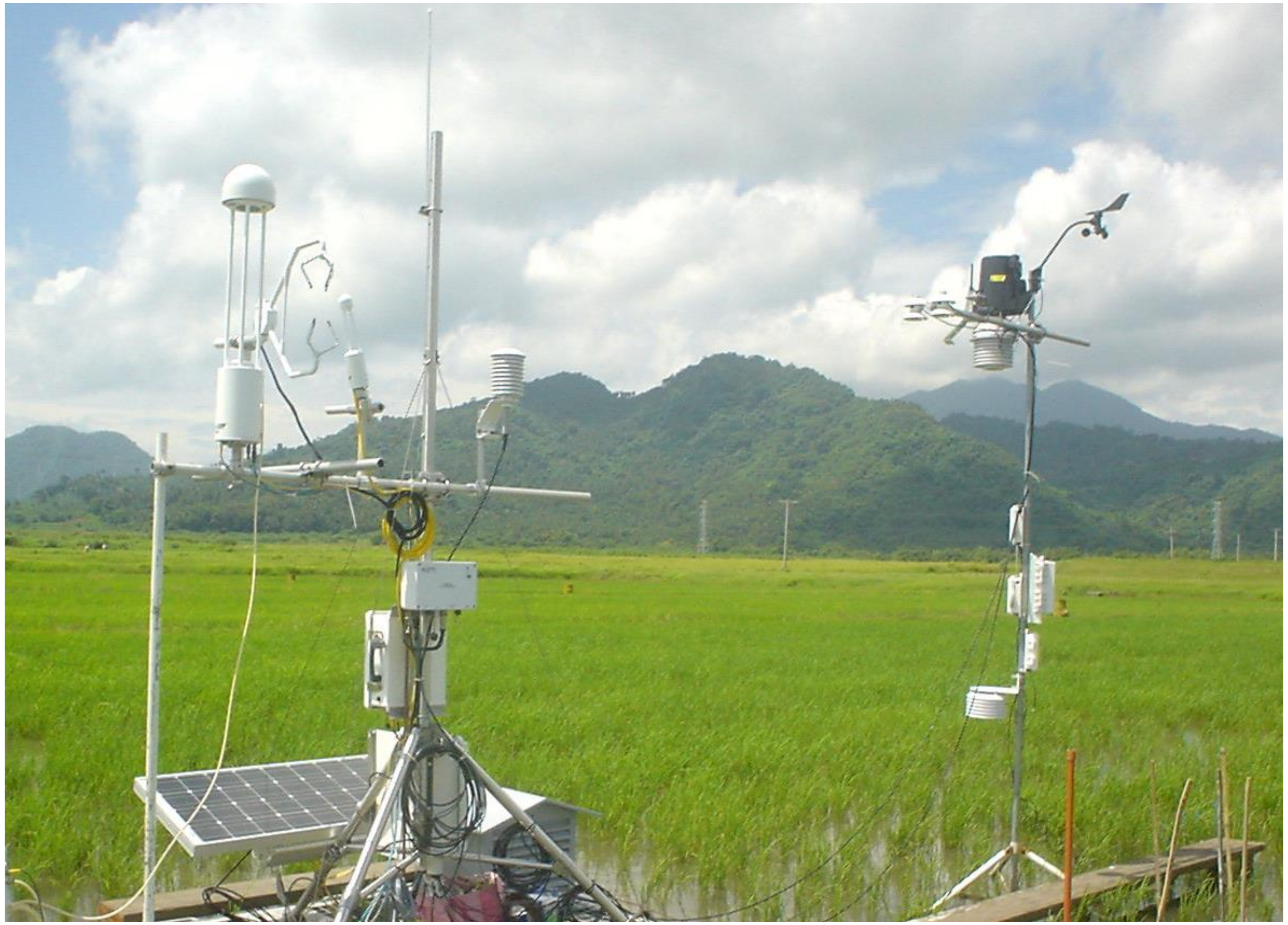
Land management, Deforestation

Law et al., 2004. Disturbance and climate effects on carbon stocks and fluxes across Western Oregon USA. *Global Change Biology* 10: 1429-1444.

Wetland research, CH_4 emissions, CO_2 and H_2O budgets



Rice field, CO_2, ET, and CH_4 flux



Mangrove research, CH_4 and CO_2 budgets

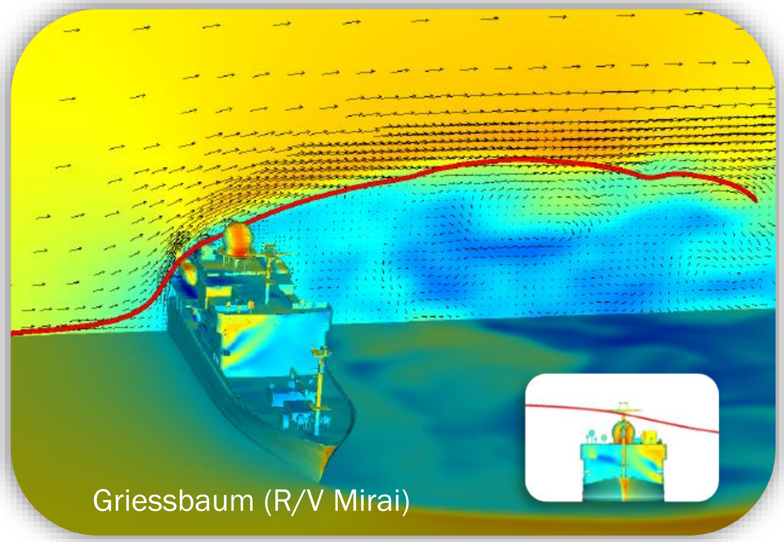
Mangrove ecosystem, Kenya, Africa

Geophysical Research Abstracts
Vol. 15, EGU2013-5346, 2013
EGU General Assembly 2013

Gas-phase carbon exchange between mangrove forests and the atmosphere

Mark Rayment

LI-COR



Oceanography

Miller S. D. 2010. Ship-based measurement of air-sea CO_2 exchange by eddy-covariance. *J of Geophy. Res.* 115:D02304, doi: 10.1029/2009JD012193.

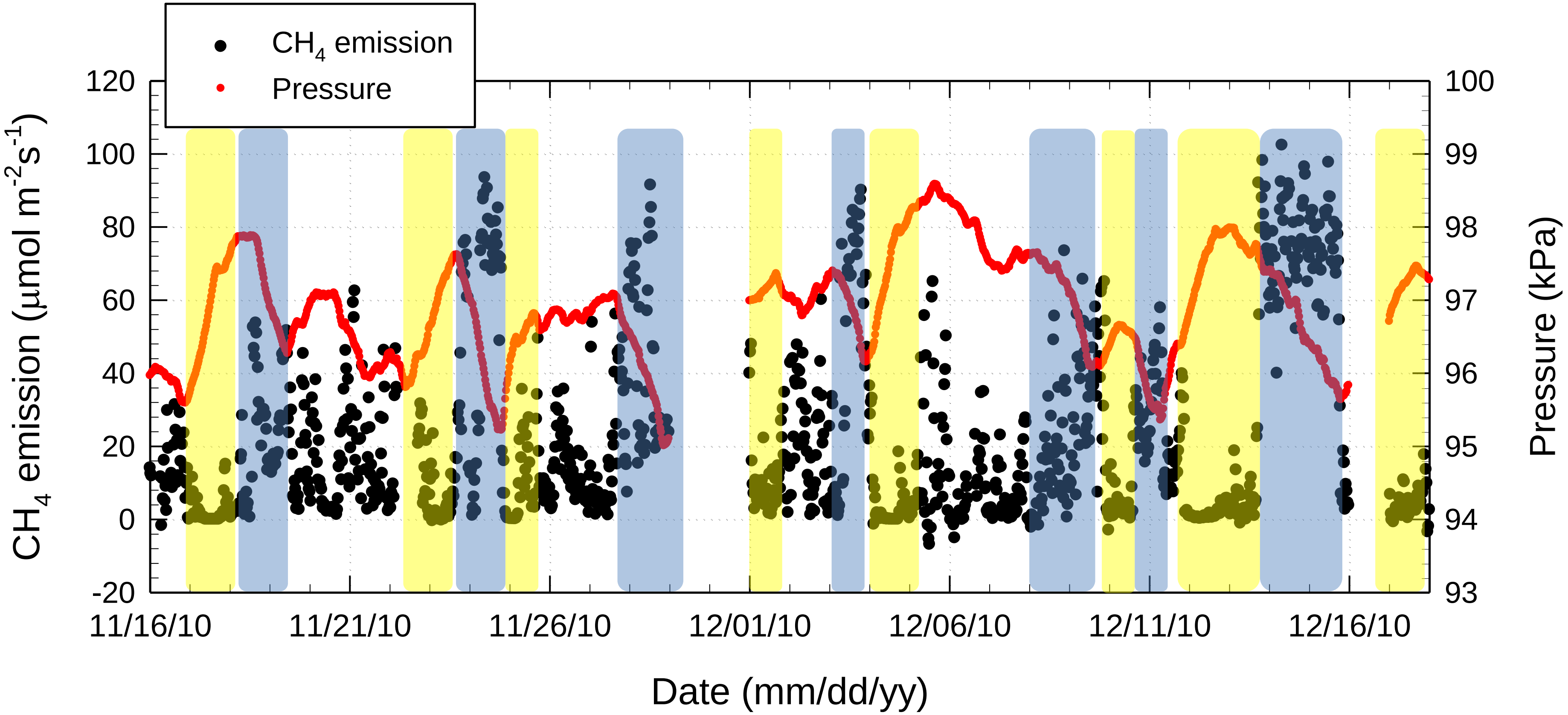
Water management

Water losses through **Evapotranspiration**?
- To investigate water rights.
- To protect endangered species.
- Agricultural Irrigation needs.
- Human demands for water.

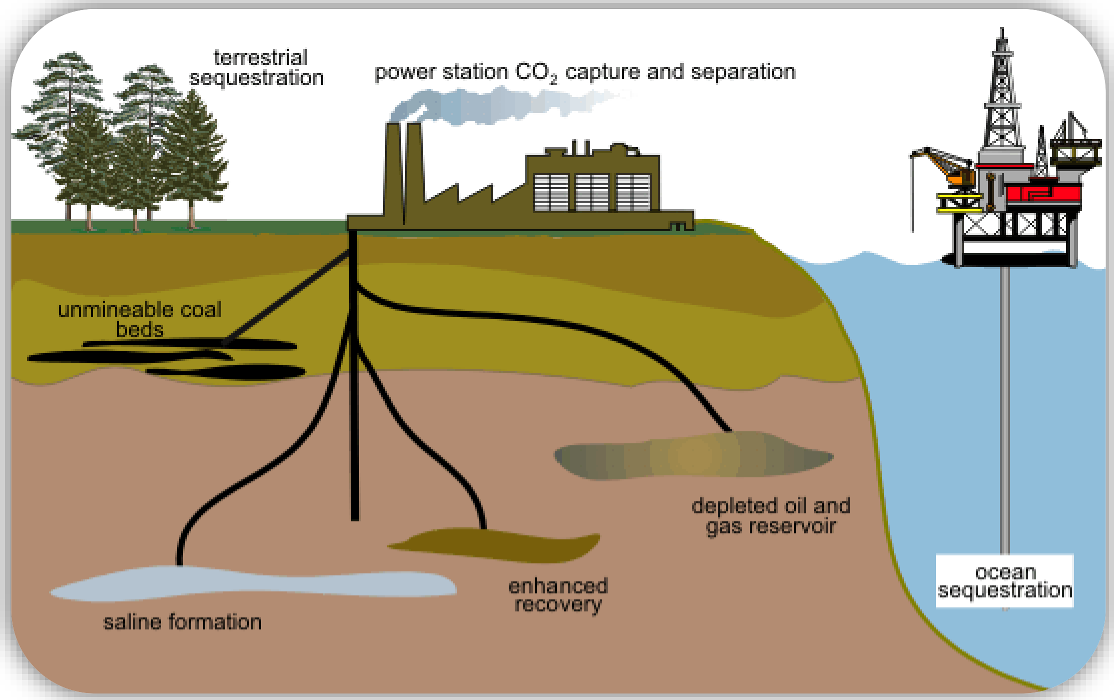
How much **Methane** is leaking out?

Landfill, CH_4 emissions and capture, etc.

Landfill CH_4 emission depends on changes in barometric pressure



Xu et al., 2014. Impact of Changes in Barometric Pressure on Landfill Methane Emission. *Global Biogeochemical Cycles*.



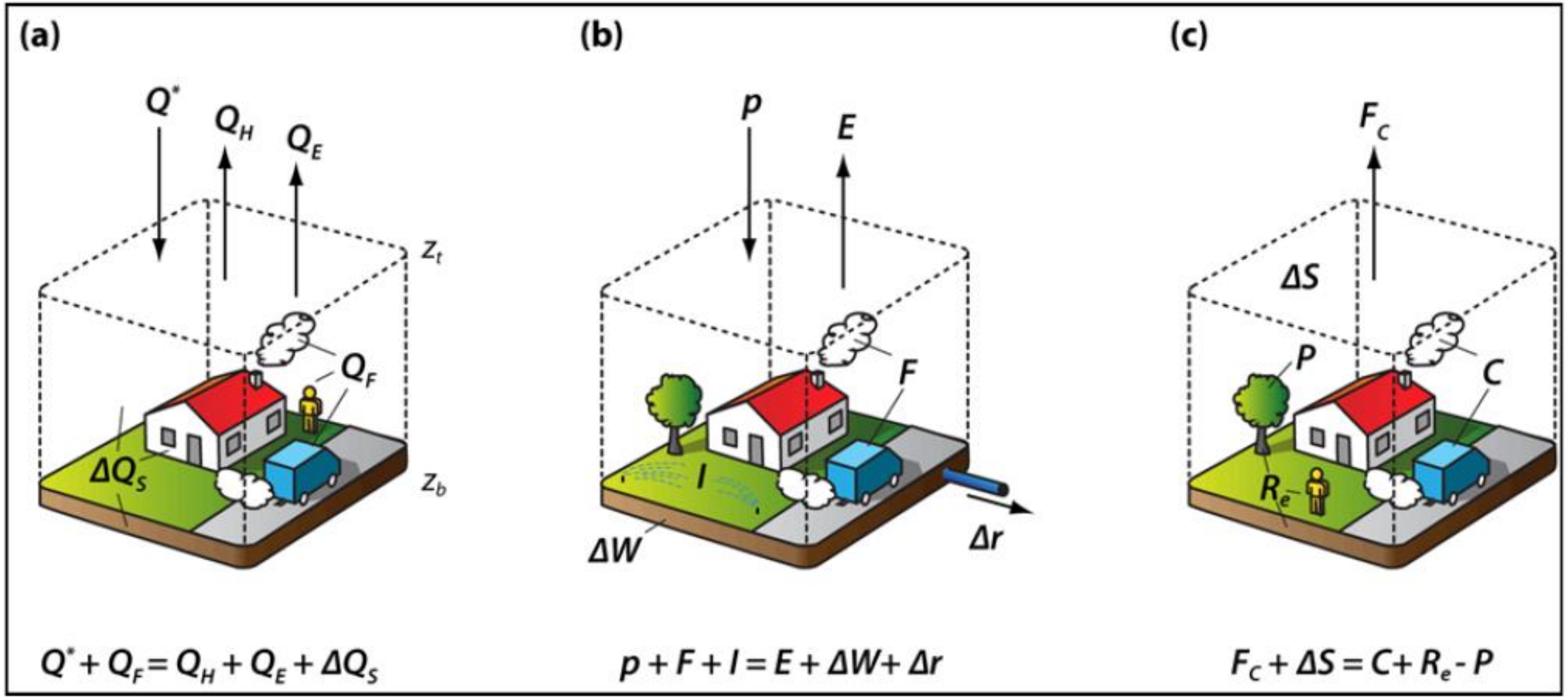
- Carbon capture & sequestration
- Carbon budget
- Leak detection

Eddy Covariance can be used for leak detection

Midwest Geological Sequestration Consortium Illinois Basin- Decatur Illinois Site. One million tons of CO_2 will be injected over a three-year period at a rate of 1,000 ton/day. The pure CO_2 will be captured from a nearby ethanol plant, then injected into the 1,500 ft thick Sandstone, at a depth of 6,000 to 7,000 ft.

Urban studies

Moriwaki R; Kanda M, 2004. Seasonal and diurnal fluxes of radiation, heat, water vapor, and carbon dioxide over a suburban area. *Journal of Applied Meteorology* (43), 1700-1710



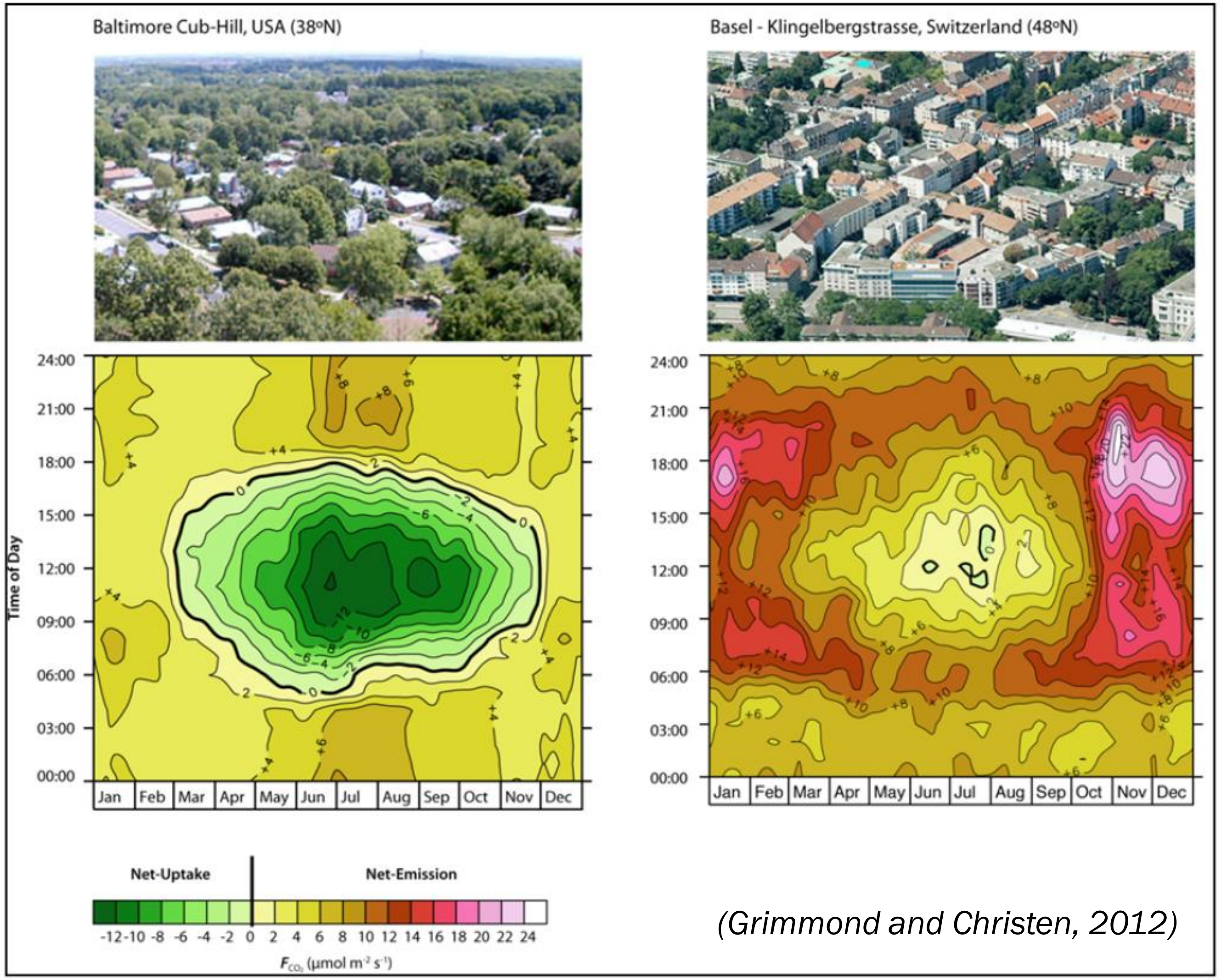
Q^*: net radiation
Q_F: heat from human activities
Q_H: sensible heat flux
Q_E: latent heat flux
ΔQ_s: storage term

P: precipitation
F: from combustion
I: irrigation
E: evaporation
ΔW: storage term
Δr: runoff

F_c: net CO_2 flux
Δs: storage term
C: combustion
R_e: respiration
P: photosynthesis

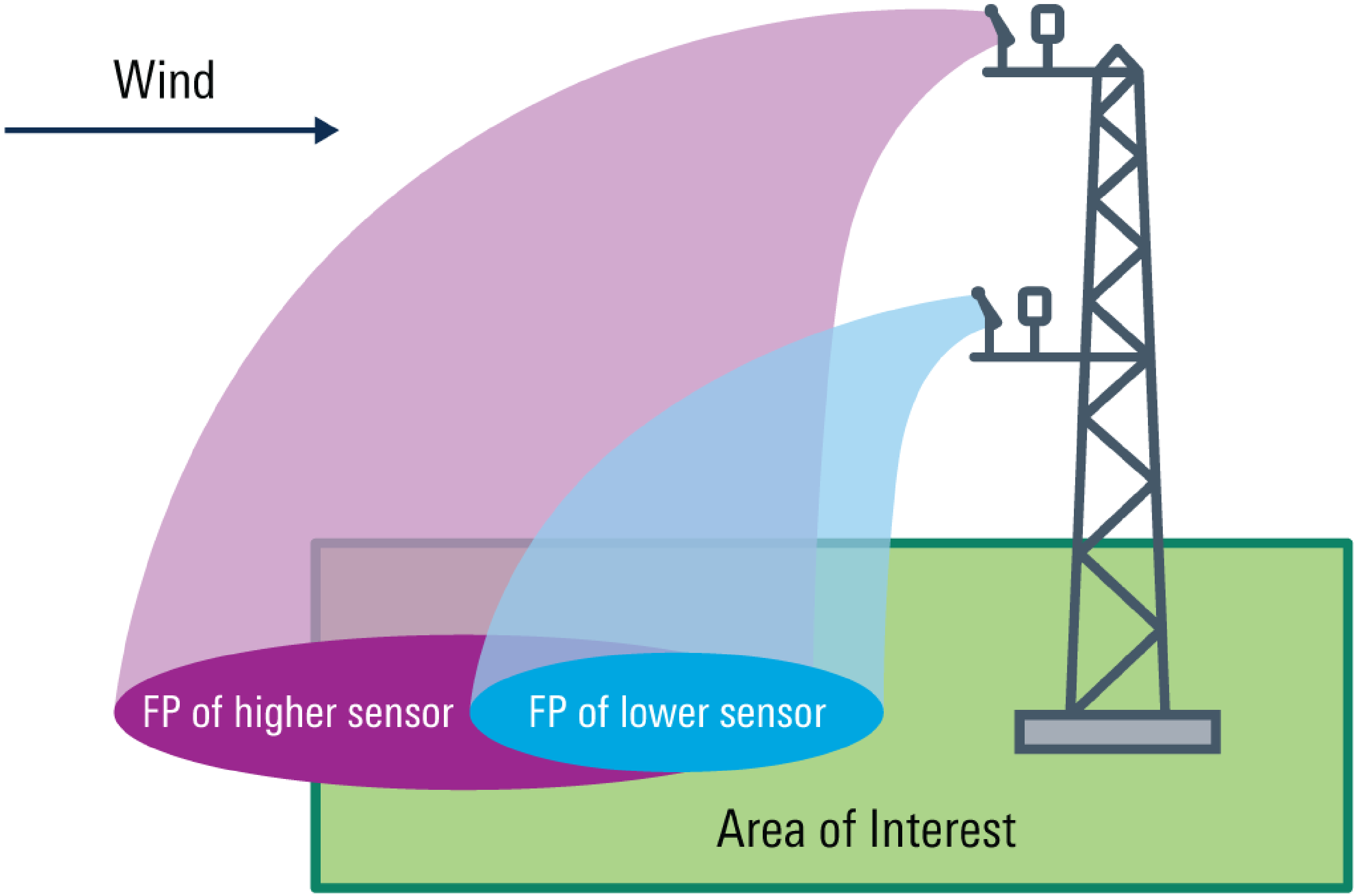
Feigenwinter et al., 2012

Urban CO_2 flux depends on vegetation cover



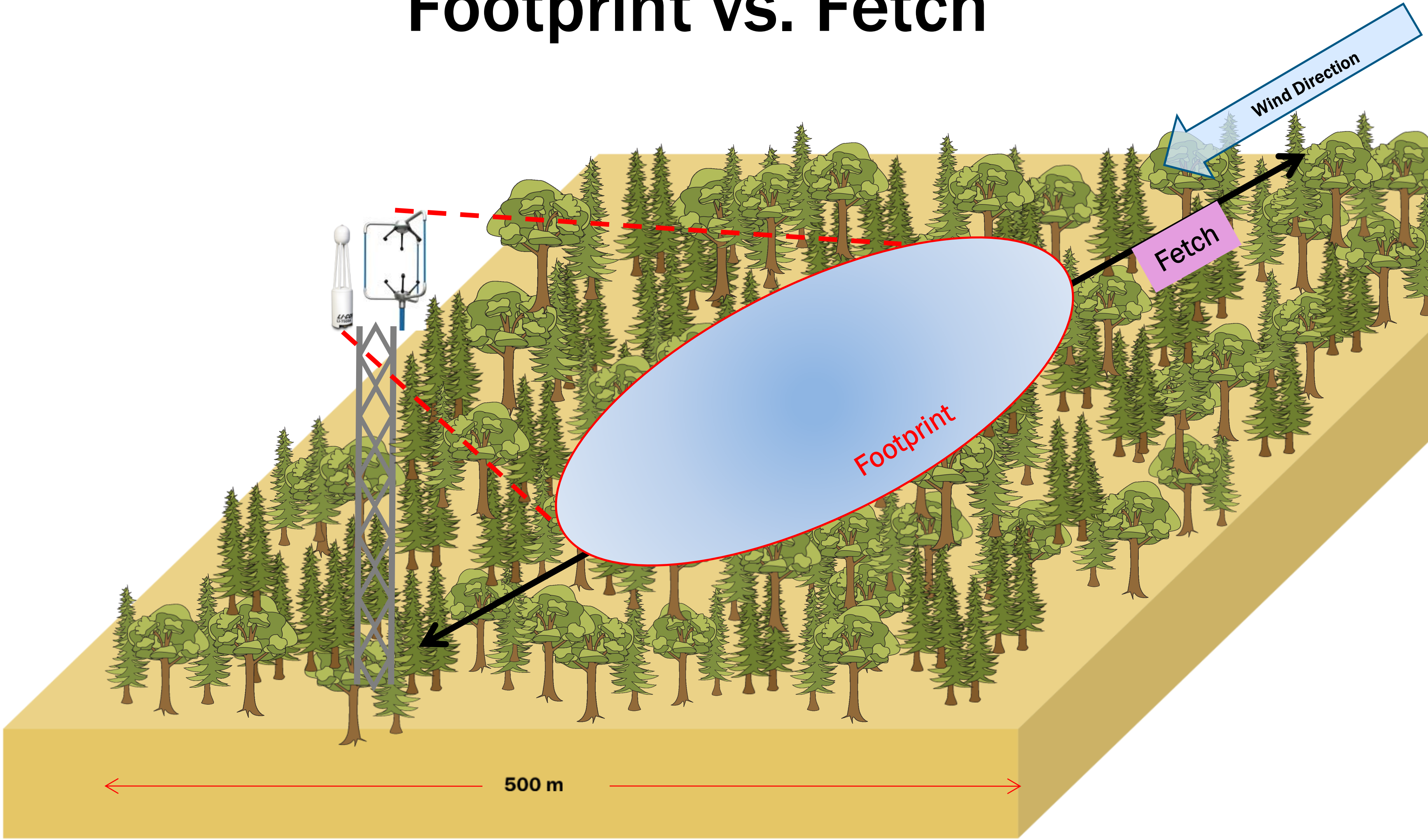
(Grimmond and Christen, 2012)

Location matters!



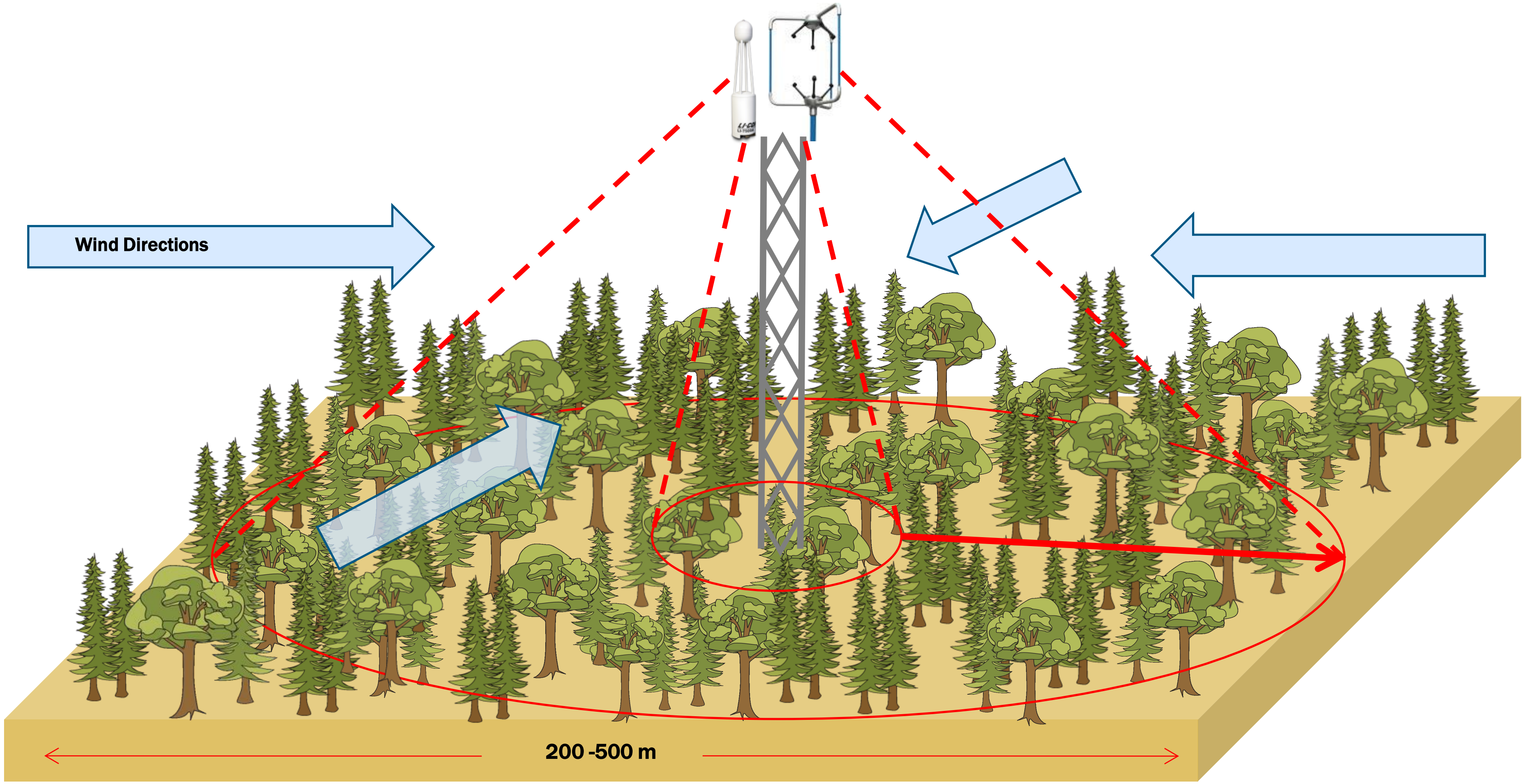
Tower will "see" fluxes from the upwind direction

Footprint vs. Fetch

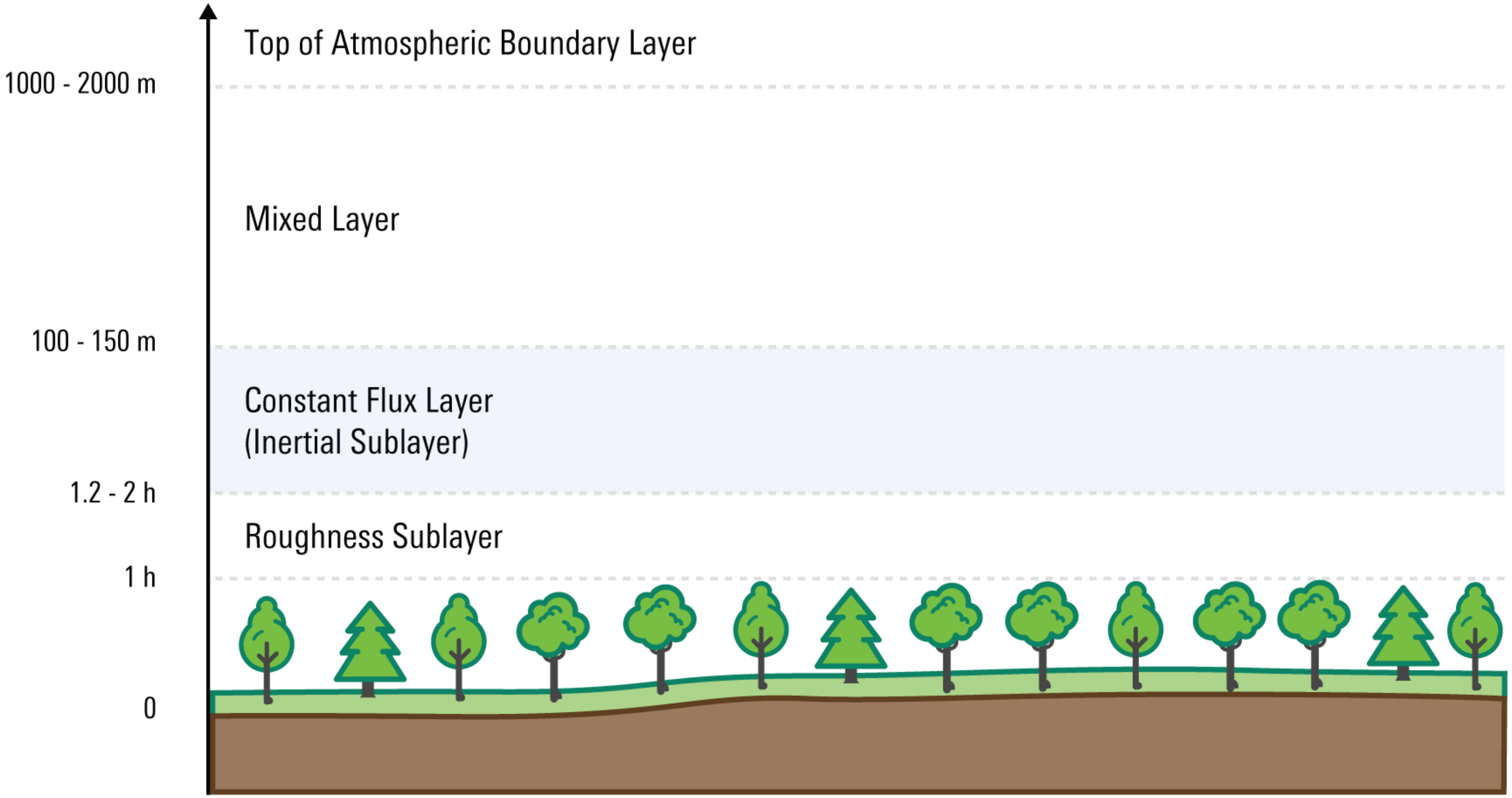


Footprint size varies also with atmospheric conditions

Omnidirectional Setup



Constant Flux Layer



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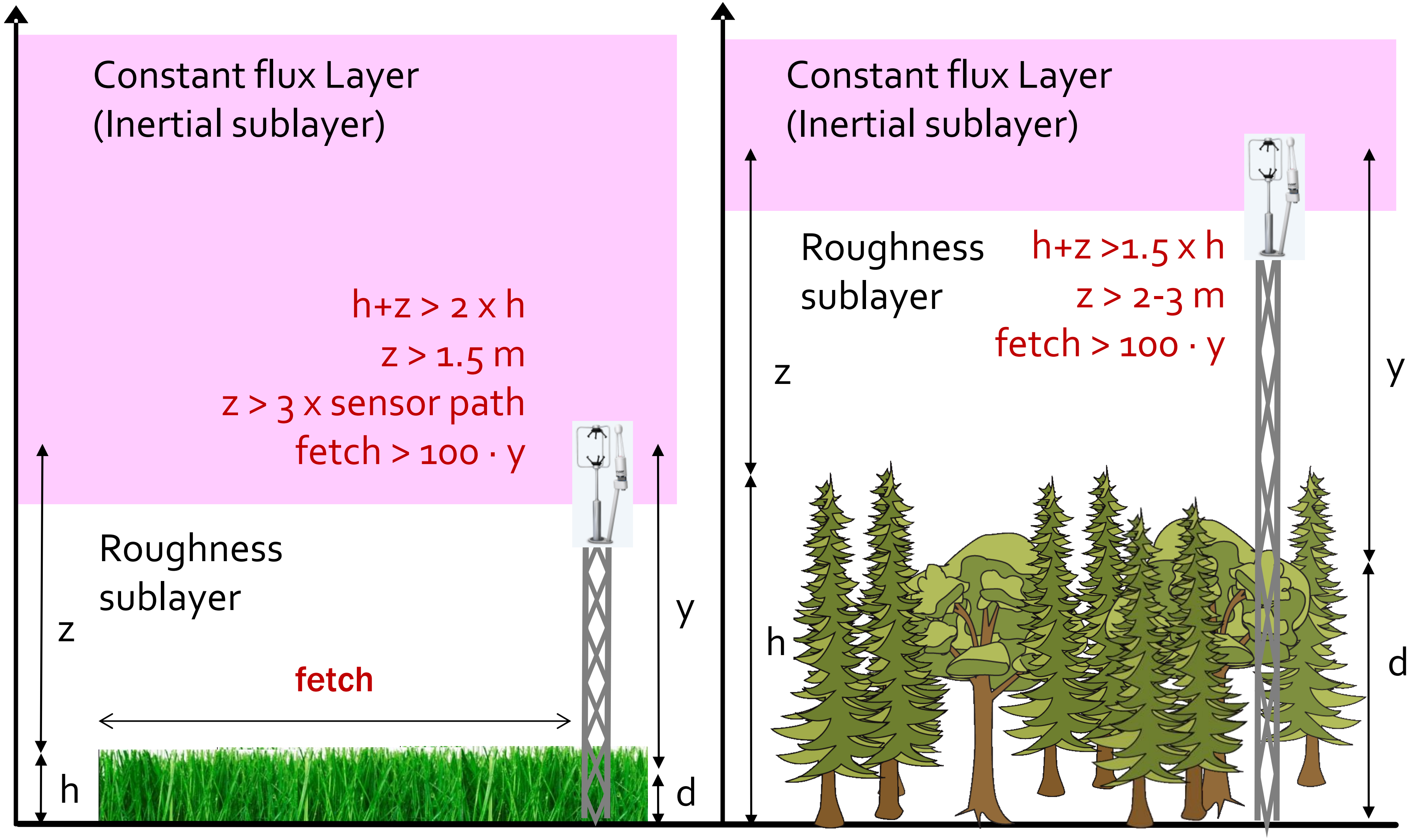
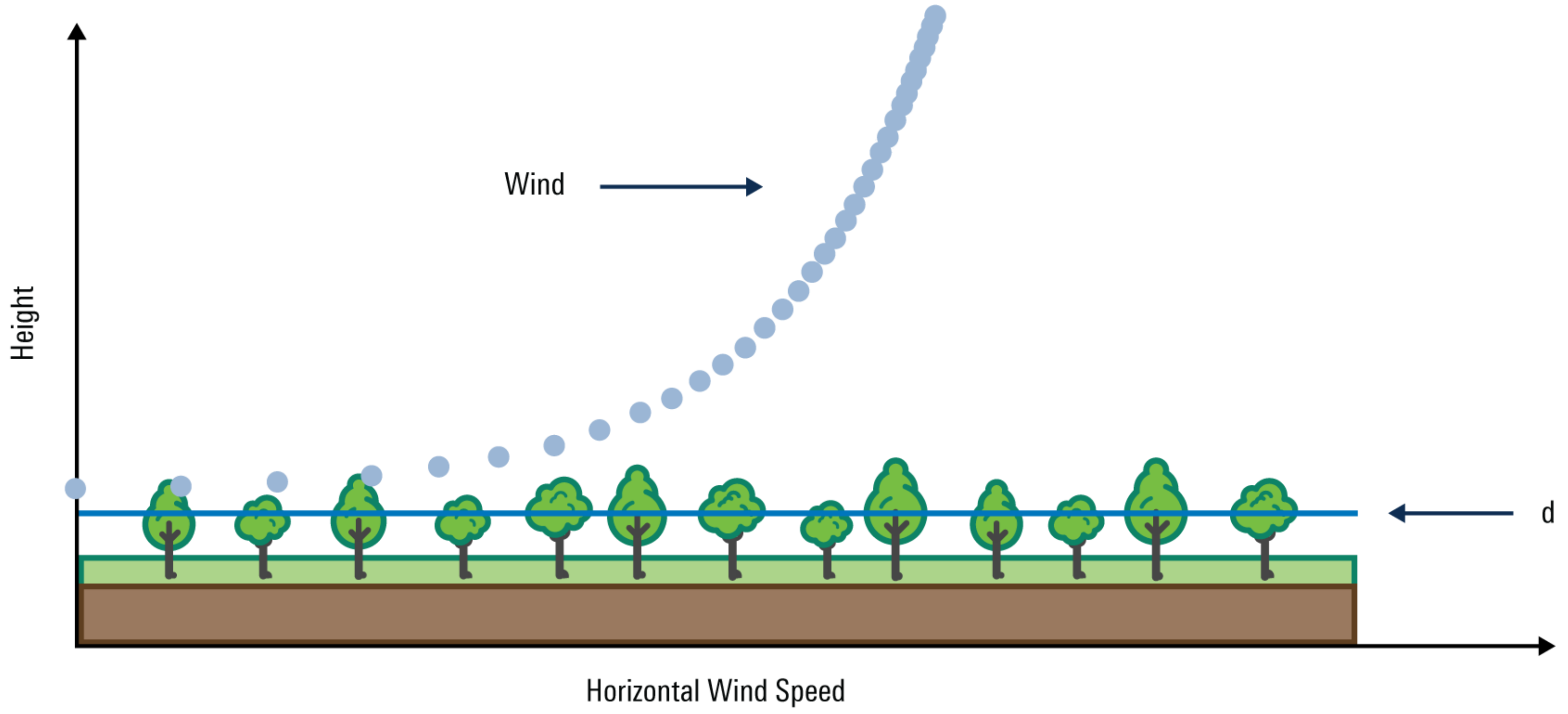
Rules-of-thumb: Instrument placement height



Short canopy (h), < 2-3 m

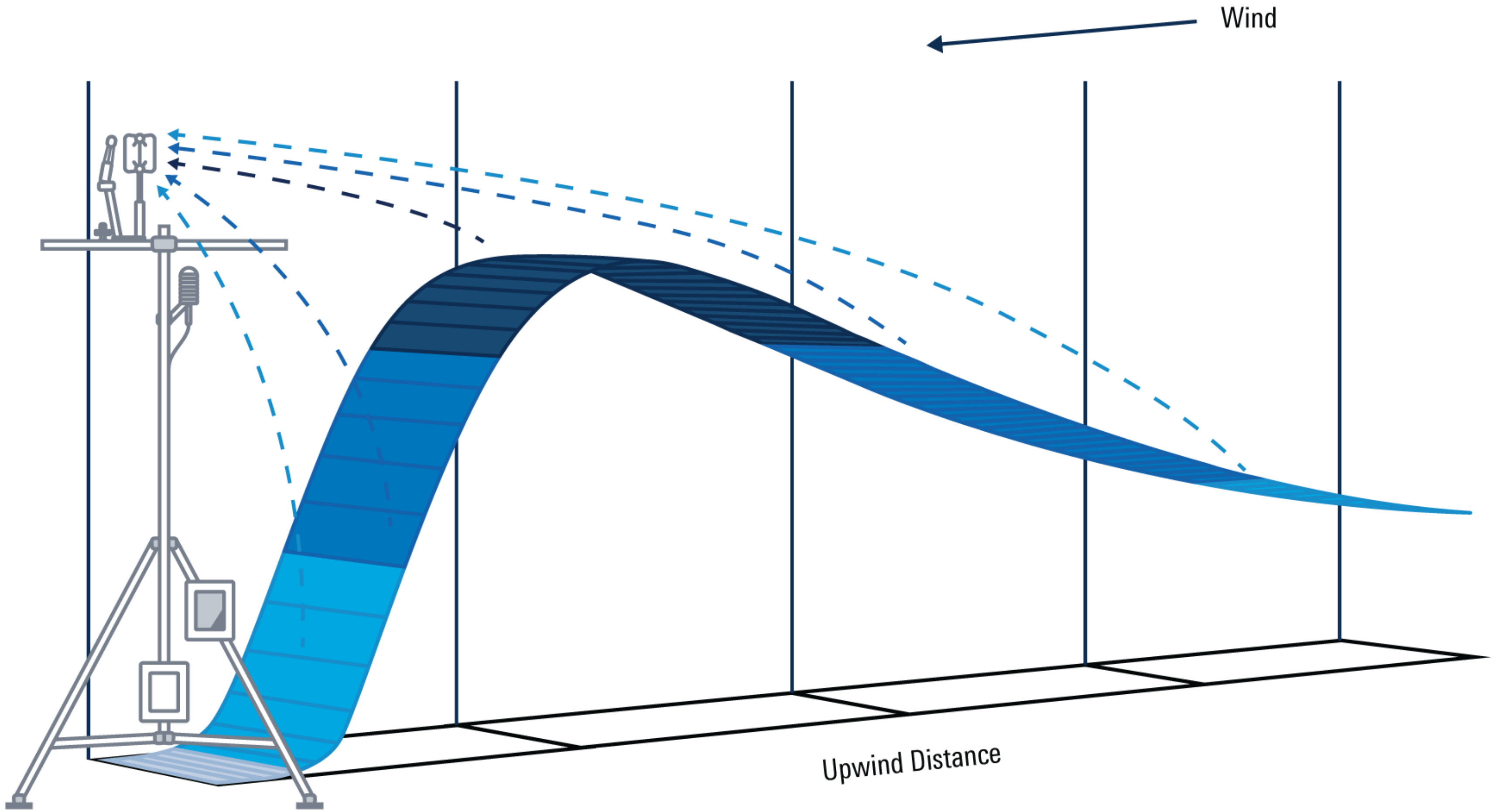
Tall canopy (h), > 2-3 m

Zero Plane Displacement Height (d)



d ≈ 0.67 to 0.8 x canopy height

Flux Contributions at up-wind distance from the EC system



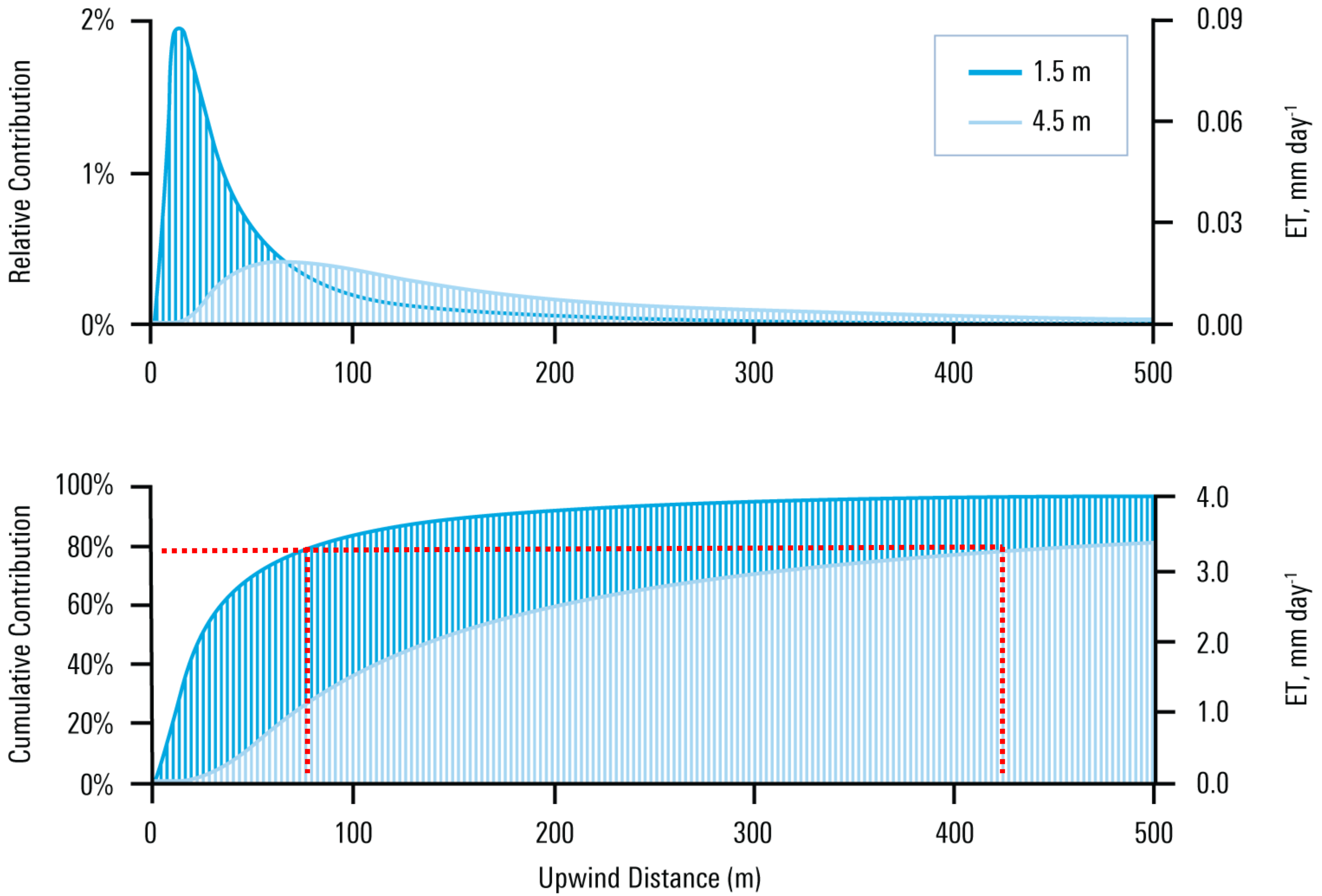
For near-neutral conditions:

$$CNF(x_L) = -\int_0^{x_L} \frac{U(z-d)}{u_* k x^2} e^{-\frac{U(z-d)}{u_* k x}} dx = e^{-\frac{U(z-d)}{u_* k x_L}}$$

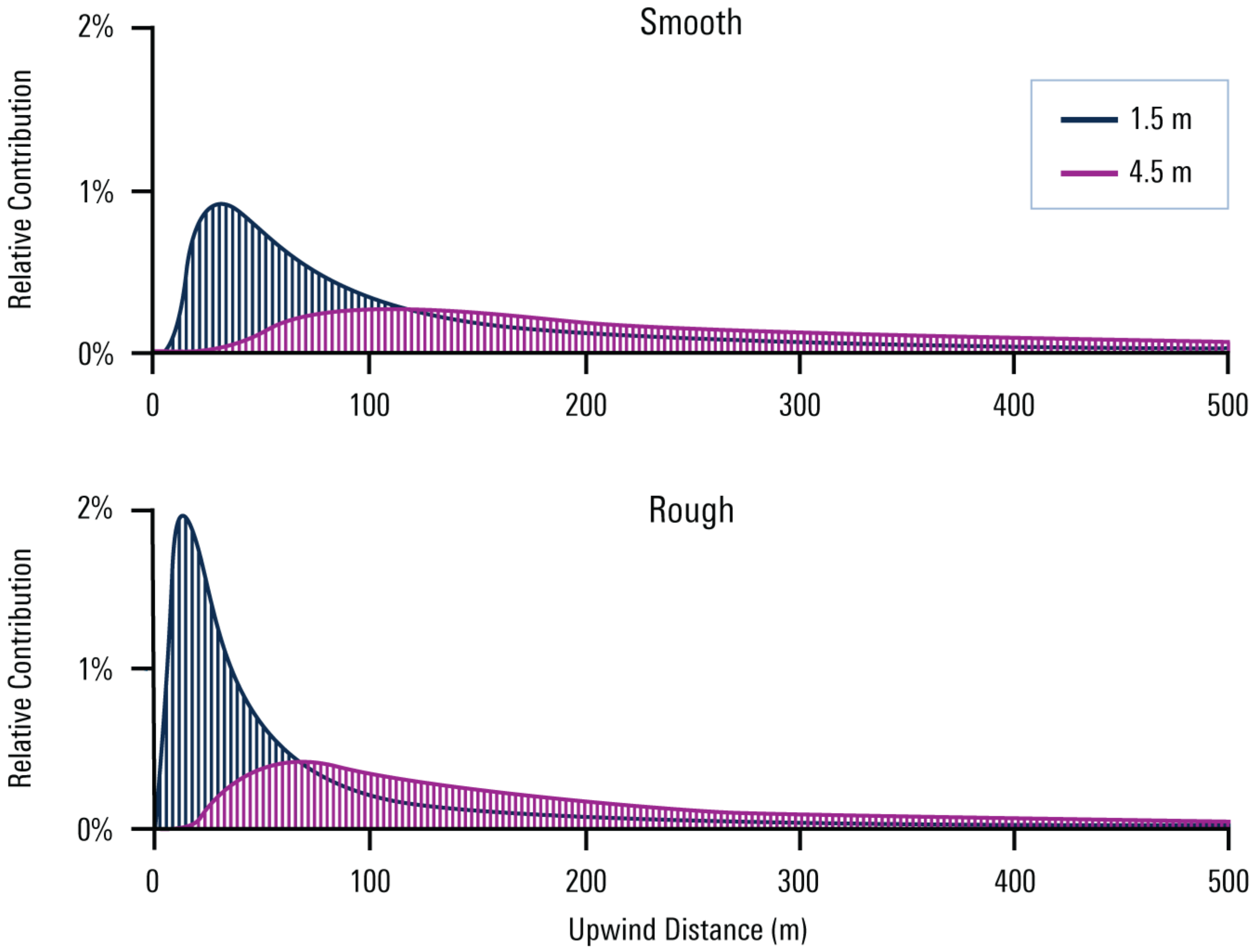
CNF is Cumulative Normalized contribution to Flux measurement, %
x_L is distance from the station, m
U is mean integrated wind speed, m s^{-1}
z is measurement height, m
u_* is friction velocity, m s^{-1}
d is zero plain displacement, m
k is von Karman constant (0.4)

Schuepp, P.H., Leclerc, M.Y., Macpherson, J.I., and R.L. Desjardins (1990)
'Footprint prediction of scalar fluxes from analytical solution of the diffusion equation'

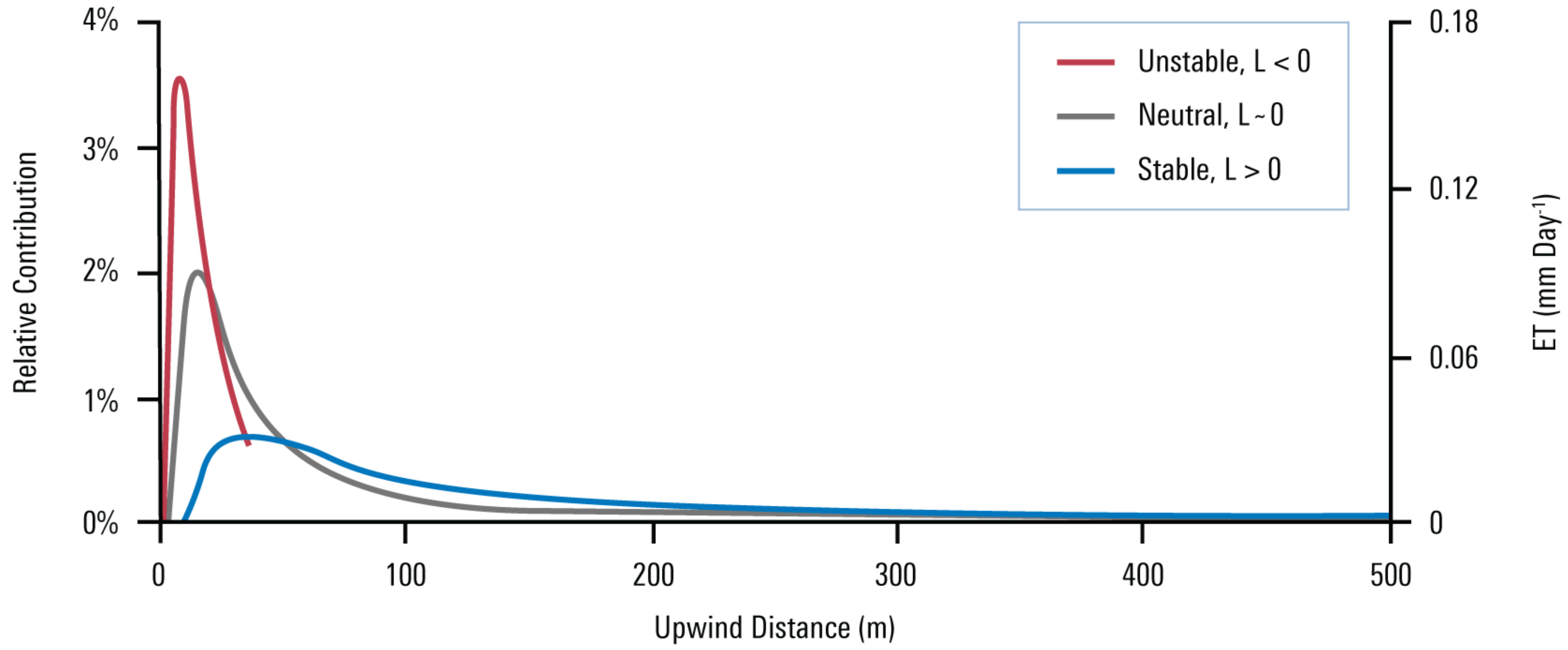
Measurement Height



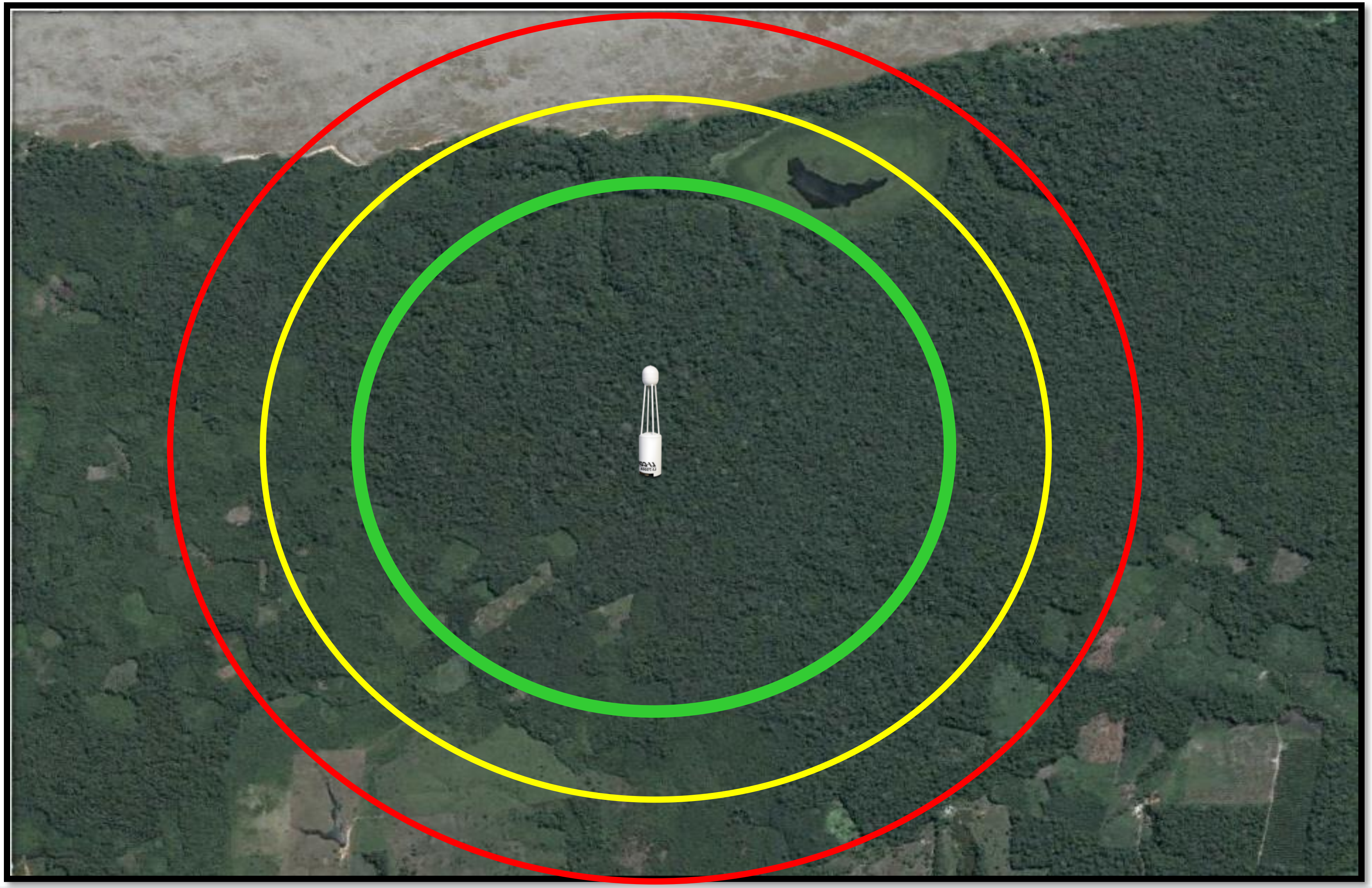
Surface Roughness



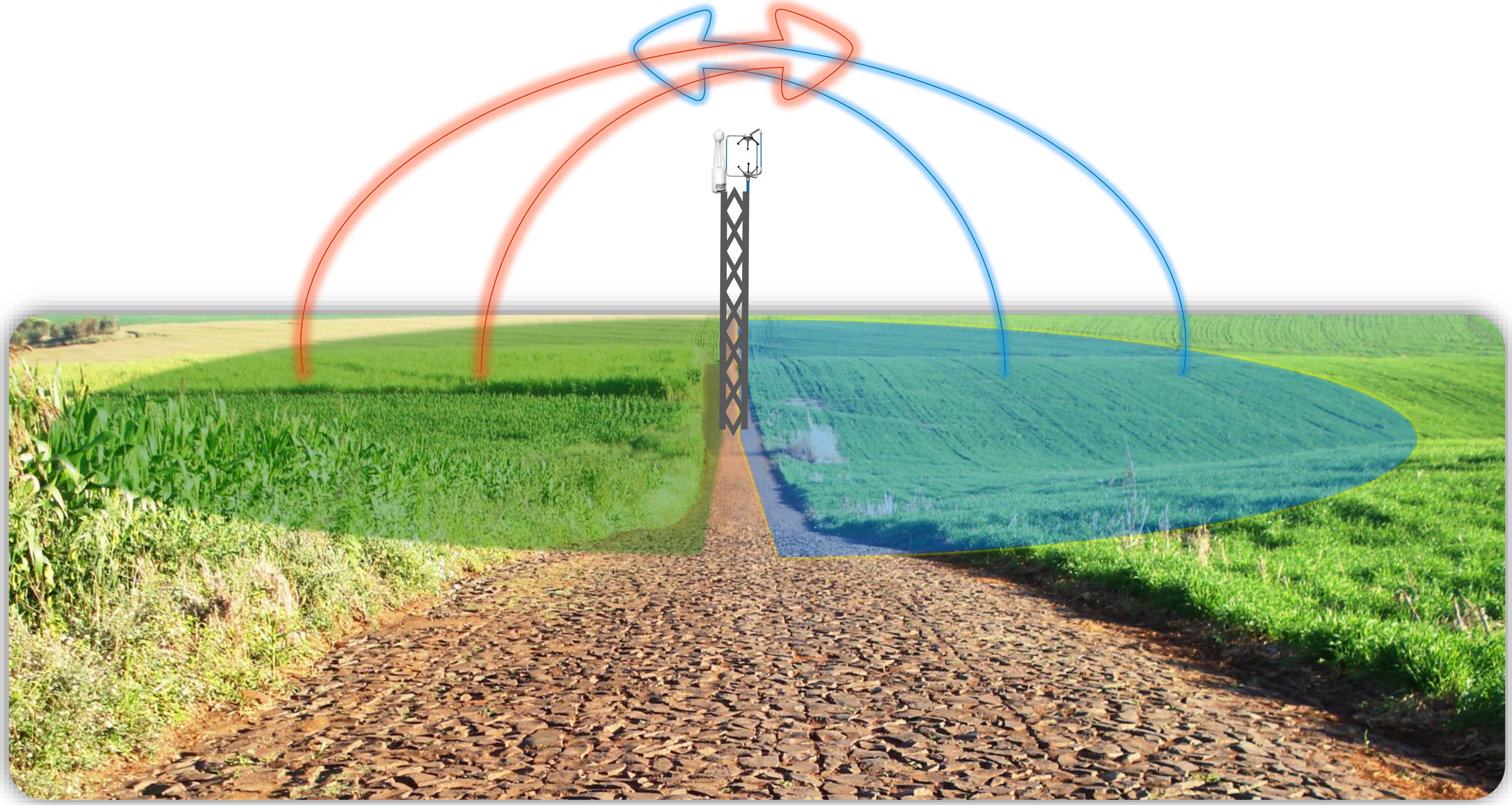
Thermal Stability



Fetch Requirement



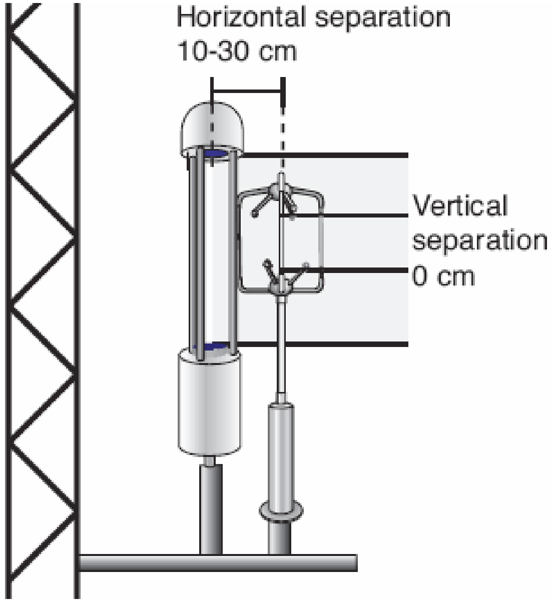
Tower will “see” fluxes from the upwind direction



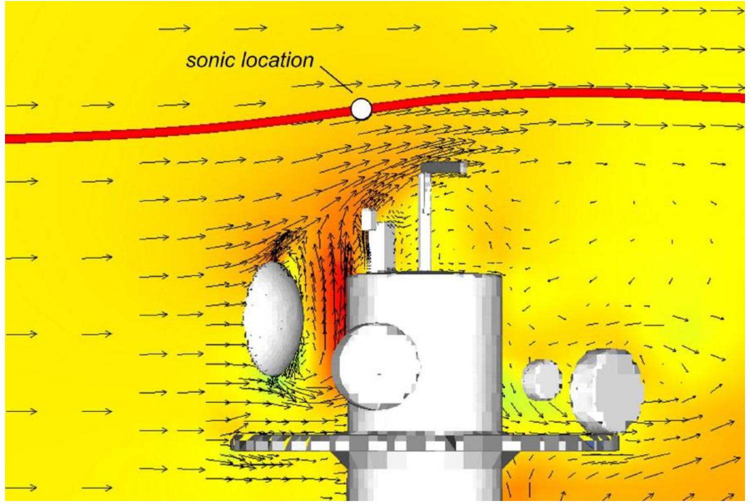

WIND

Arrangement of instruments on a tower

Sensor separation



Airflow distortion



Griessbaum and Schmidt (2009)

Münster, DE

- Each experimental site is different and requires unique treatment
- **Eddy Covariance is, to a large extent, a site-specific method**
- The entire process of experimental design, implementation and data processing should be tailor-made for specific purpose at specific site

During experiment design:

- establish purpose
- define variables
- select instruments
- decide on software
- finalize location
- develop maintenance plan

During implementation:

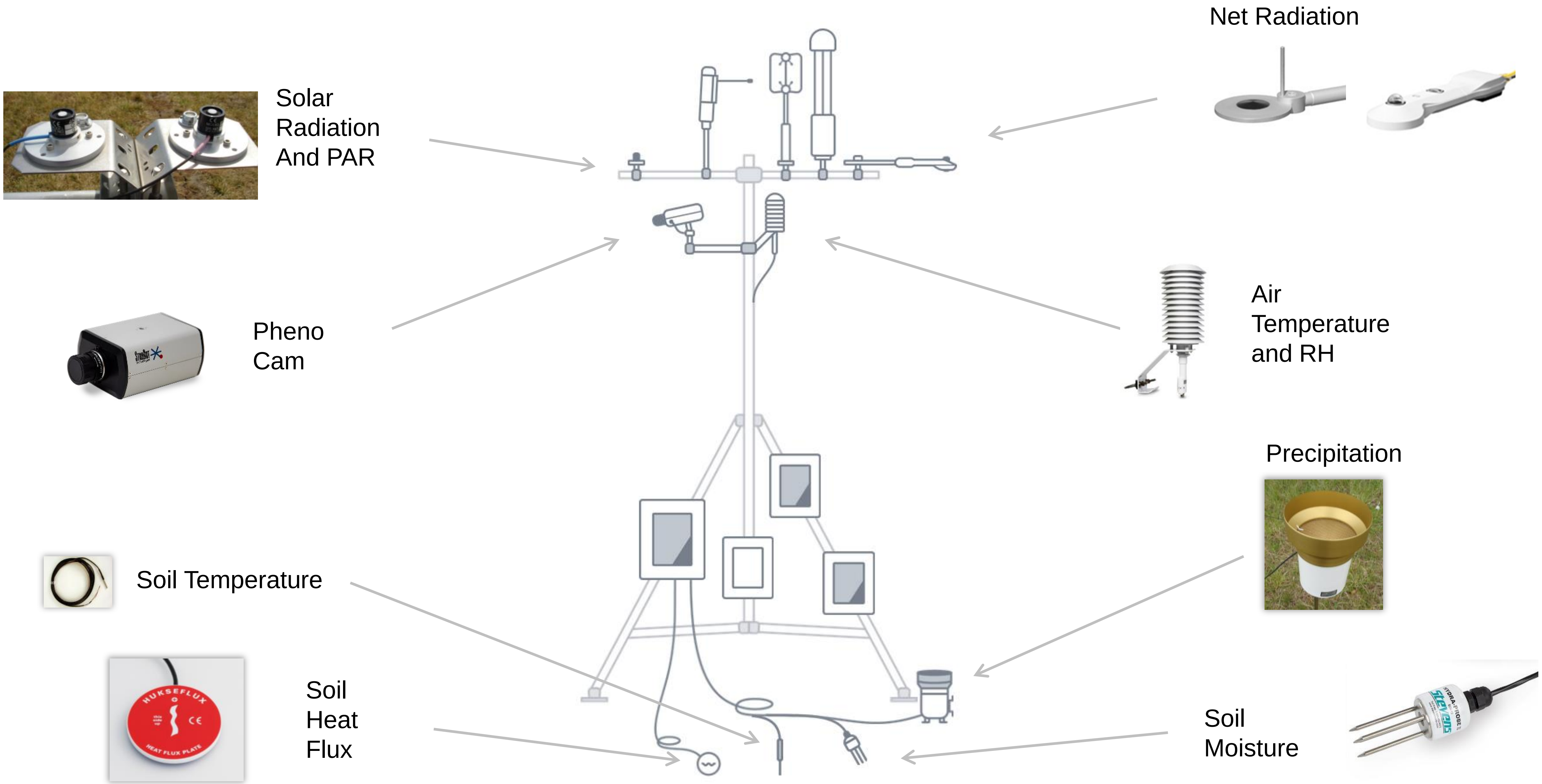
- place tower
- position instruments
- test data collection
- test data retrieval
- test processing with standard file
- **continuously keep up maintenance**

Biomet Sensors and Measurements

What are ‘Biomet’ Sensors?

- Sensors used for monitoring the environment (biological and meteorological).
- Typically measured once every 1-60 seconds

Biomet Measurements



Why collect Biomet measurements?

- Improved flux computation and corrections

  Quantities estimated from EC replaced by mean values

- Quality Assurance and Quality Checking (QA/QC)

  Energy Balance closure

- Gap filling, when instrumentation or power fails, low data quality

- Recording weather helps to explain site behavior

  Physical/biological environment has profound effects on surface-atmosphere exchange

Improving fluxes

Fluxes (e.g. over 30 min intervals) are calculated and corrected based on:

- Covariances: calculated from fast measurement, acquired at f > 5 Hz
- Mean quantities: averaged over the 30 min interval, calculated starting either from fast or slow measurements

$$F = \overline{\rho_a} \cdot \overline{w'c'}$$

Improving fluxes

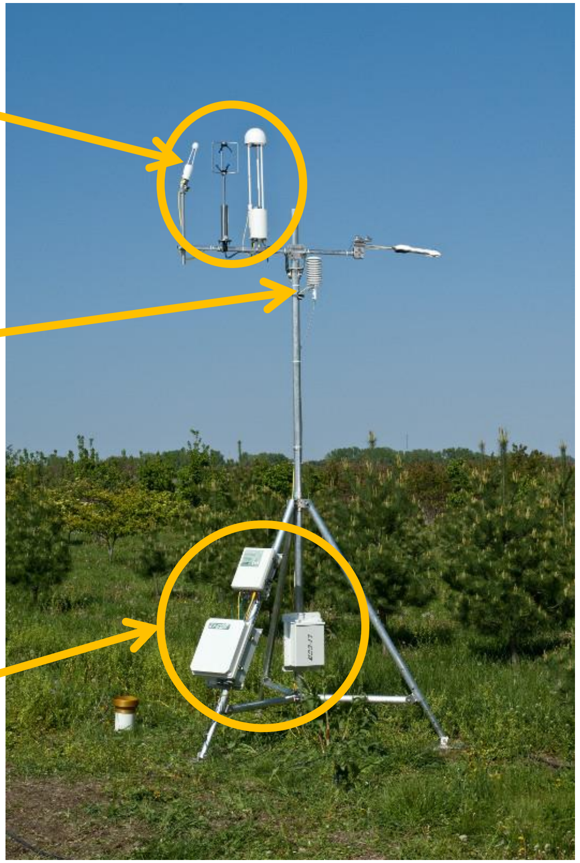
Average Ta and P are involved in various flux equations, for example:

- dry air density: $\rho_d = \frac{P}{R_d T_a} - \rho_w \frac{m_d}{m_w}$
- Gas flux: $F = \overline{\rho_d}\,\overline{w's'}$
- WPL term: $F = F_o + \mu \frac{E}{\rho_d} \frac{\rho_c}{1 + \mu \frac{\rho_w}{\rho_d}} + \frac{H}{\rho_c C_p} \frac{\rho_c}{T_a} + P_{term}$

Vaisala HMP155 Humidity and Temperature Probe with RM Young Radiation Shield

Improving fluxes

- Height where flux measurements are made.
- Measuring air temperature up here, and using this value in the flux calculations, can improve results.
- Height where the CO2/H2O analyzer measures temperature.



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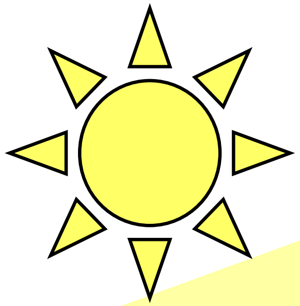
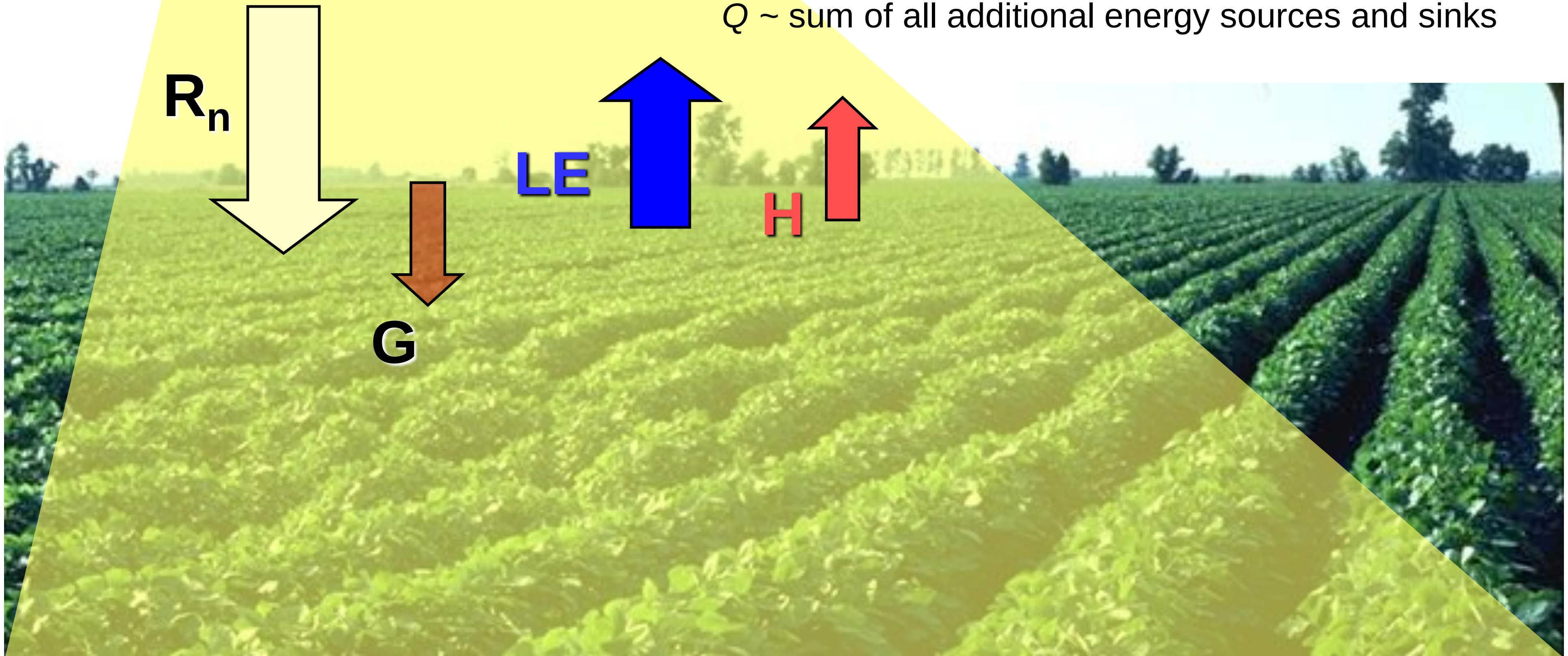
The Energy Budget (daytime)



$$R_n = H + LE + G + S + Q$$

All terms have units of (W m^2).

R_n ~ net radiation flux density
H ~ surface sensible heat flux density
LE ~ surface latent heat flux density
G ~ heat flux within the soil
S ~ rate of change of heat storage (air and biomass) between the soil surface and the level of the eddy covariance instrumentation
Q ~ sum of all additional energy sources and sinks

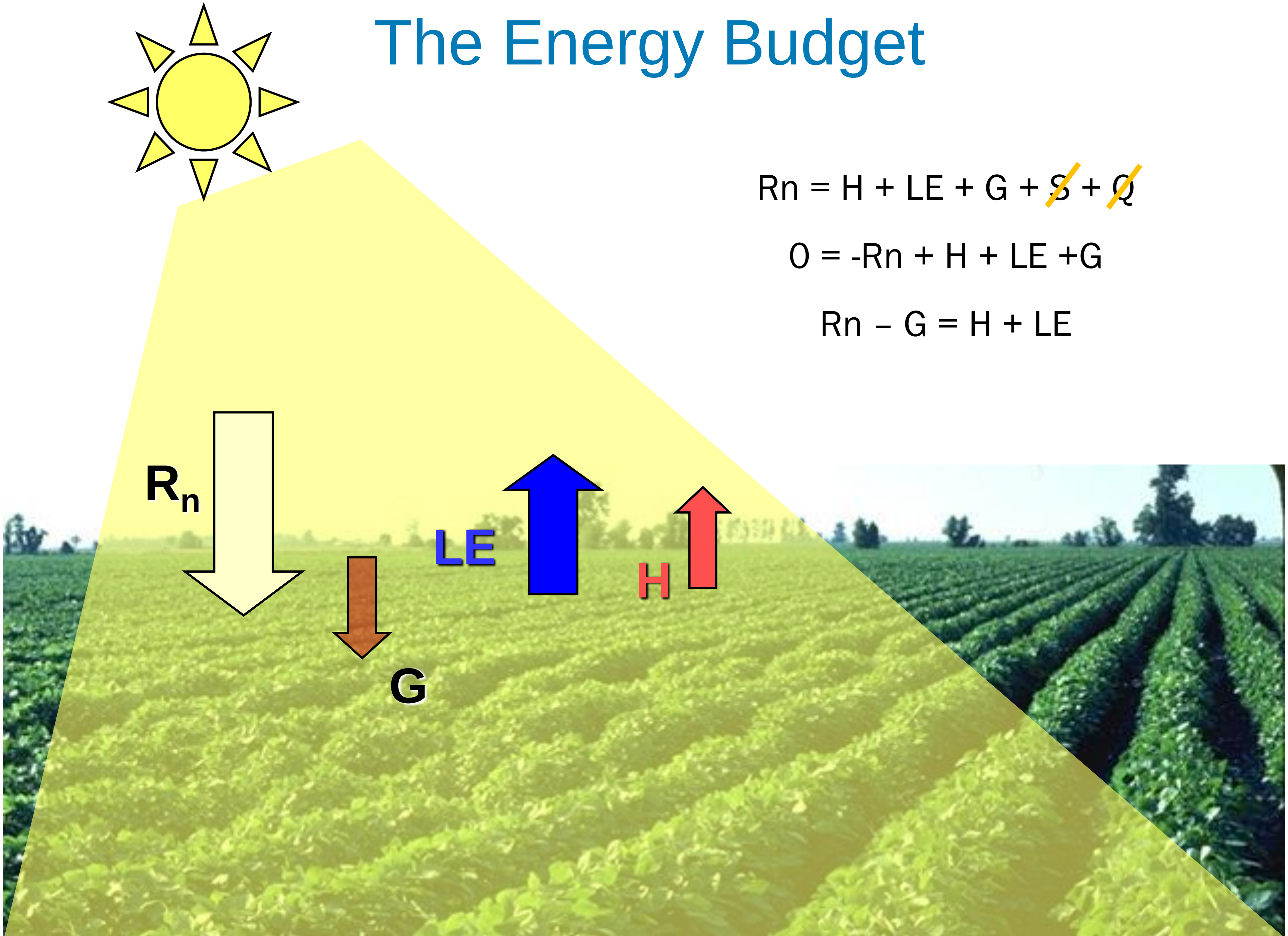


The Energy Budget

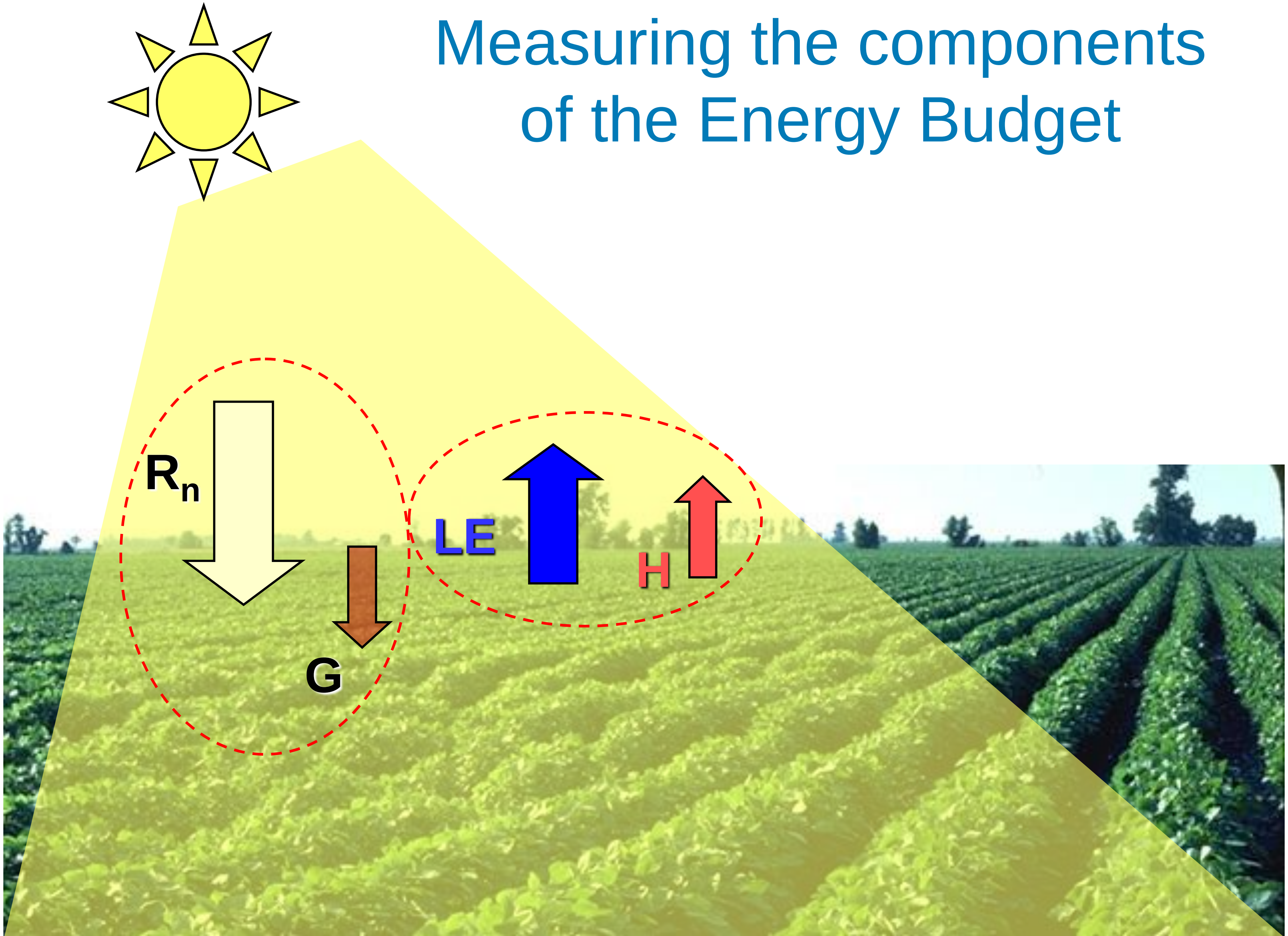
$$Rn = H + LE + G + \cancel{S} + \cancel{Q}$$

$$0 = -Rn + H + LE + G$$

$$Rn - G = H + LE$$

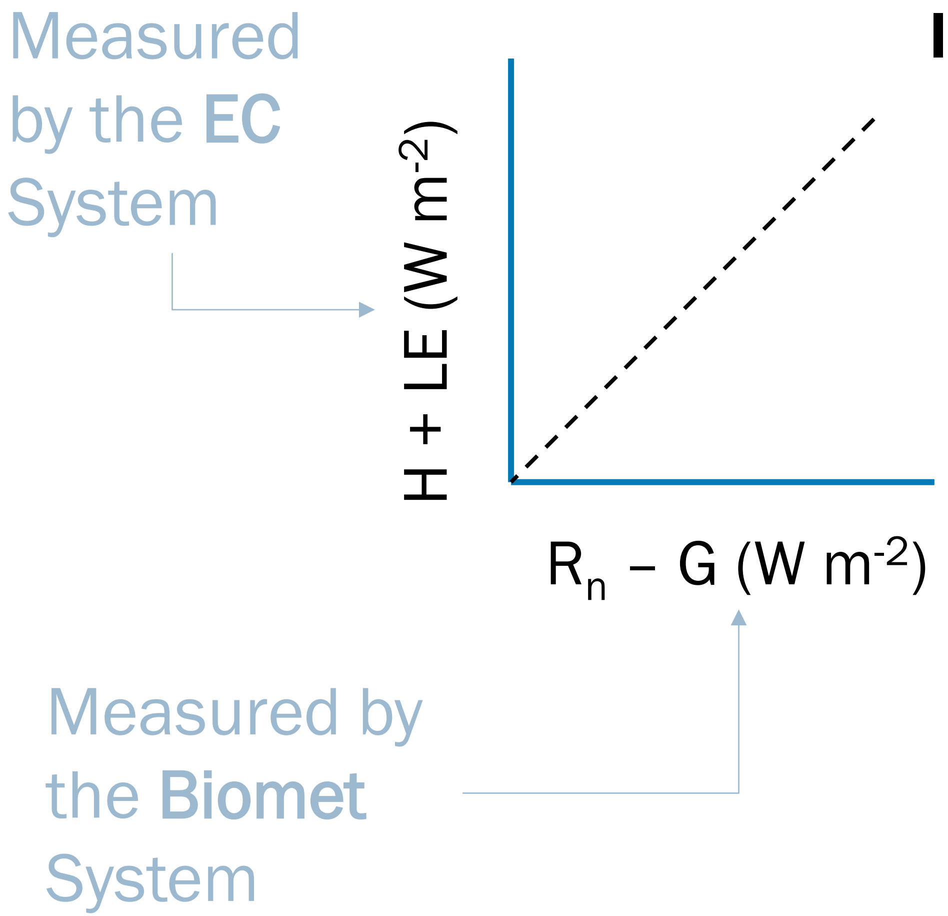


Measuring the components of the Energy Budget



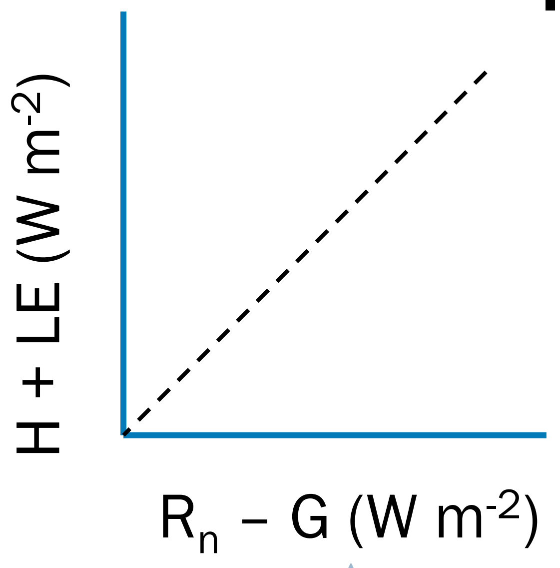
Checking for energy balance closure

Ideal closure is represented by a slope of 1 and an intercept of 0.



Checking for energy balance closure

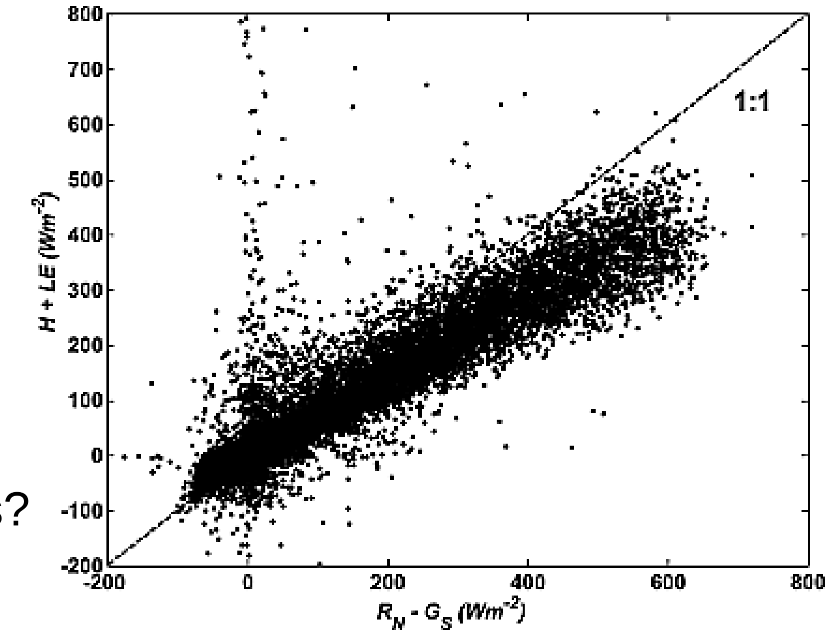
Measured by the **EC** System



Measured by the **Biomet** System

Ideal closure is represented by a slope of 1 and an intercept of 0.

Realistic (measured) closure



If not ideal:

- Sampling errors?
- Systematic biases?
- Neglected energy sinks?
- Other?

How Sampling could cause an imbalance

Cause of imbalance	Examples
Sampling	Source areas differ
Instrument bias	Net radiometer biased
Neglected energy sinks	Storage above soil heat plates
High/low frequency loss	Sensor separation/large eddies
Advection	Regional circulation

Wilson, K et al (2002). Energy balance closure at FLUXNET sites. Agricultural and Forest Meteorology

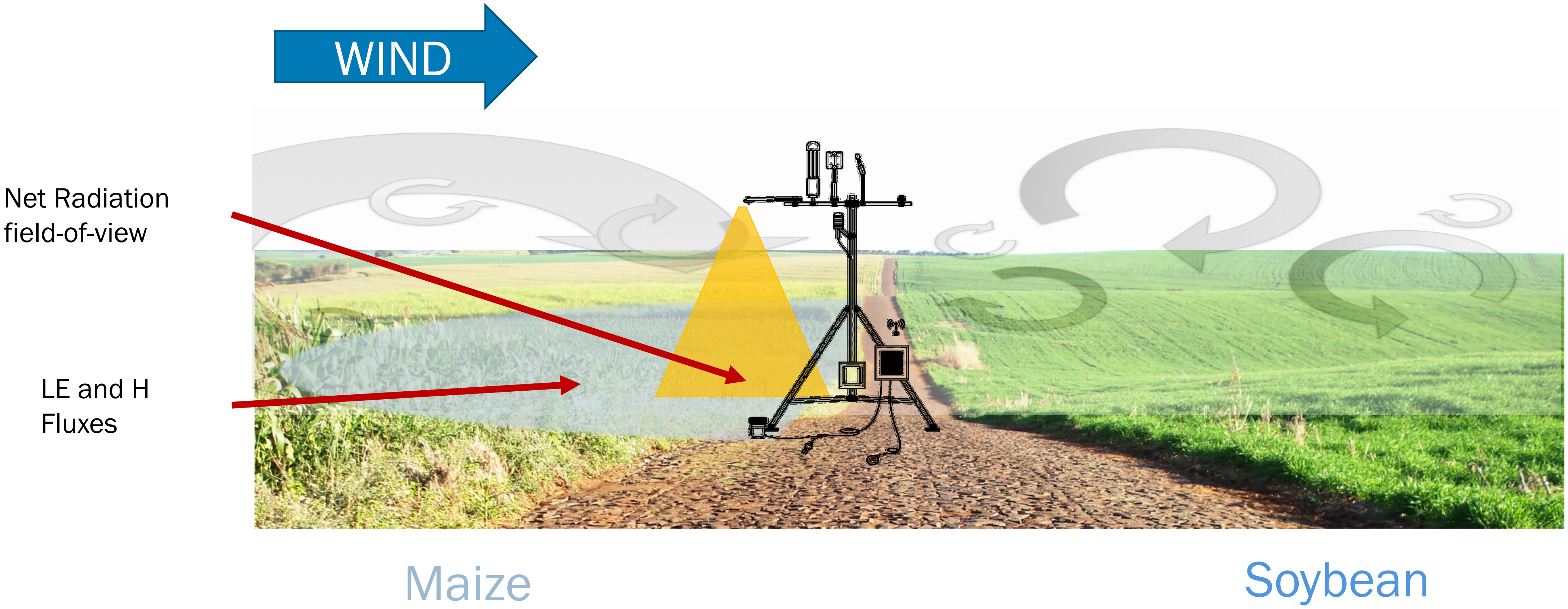
One EC System between two different plots

LE and H
Fluxes

Maize

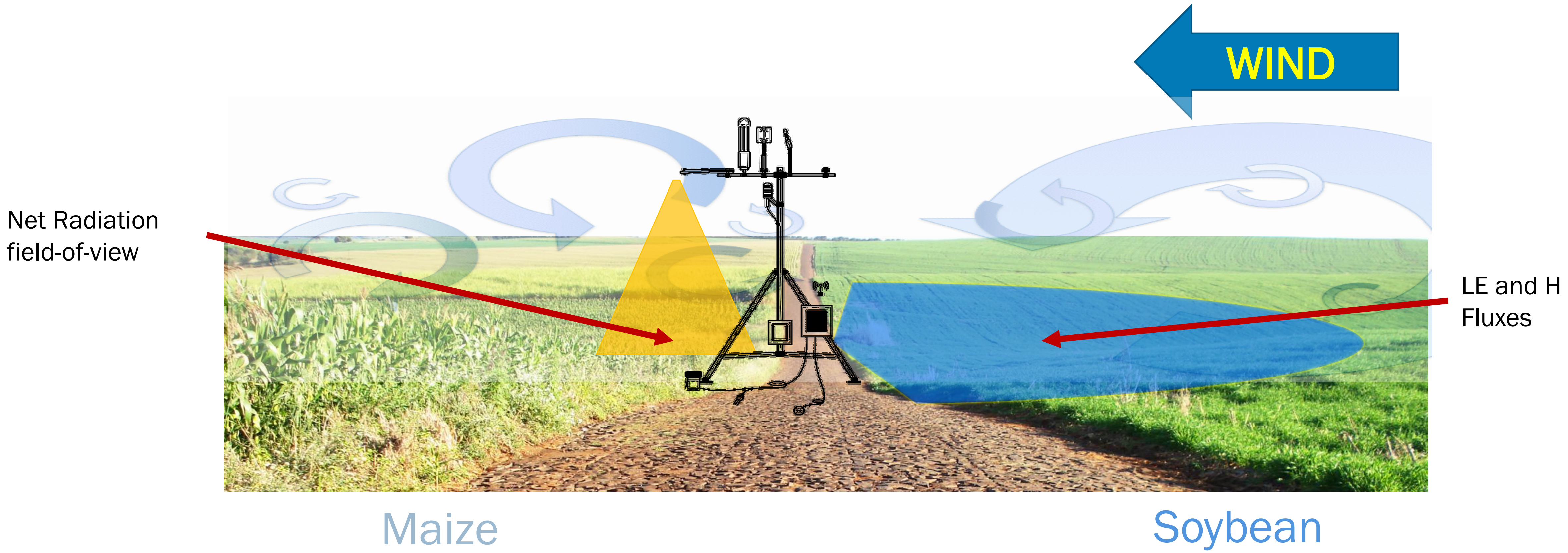
Soybean

When Source Areas are the same...



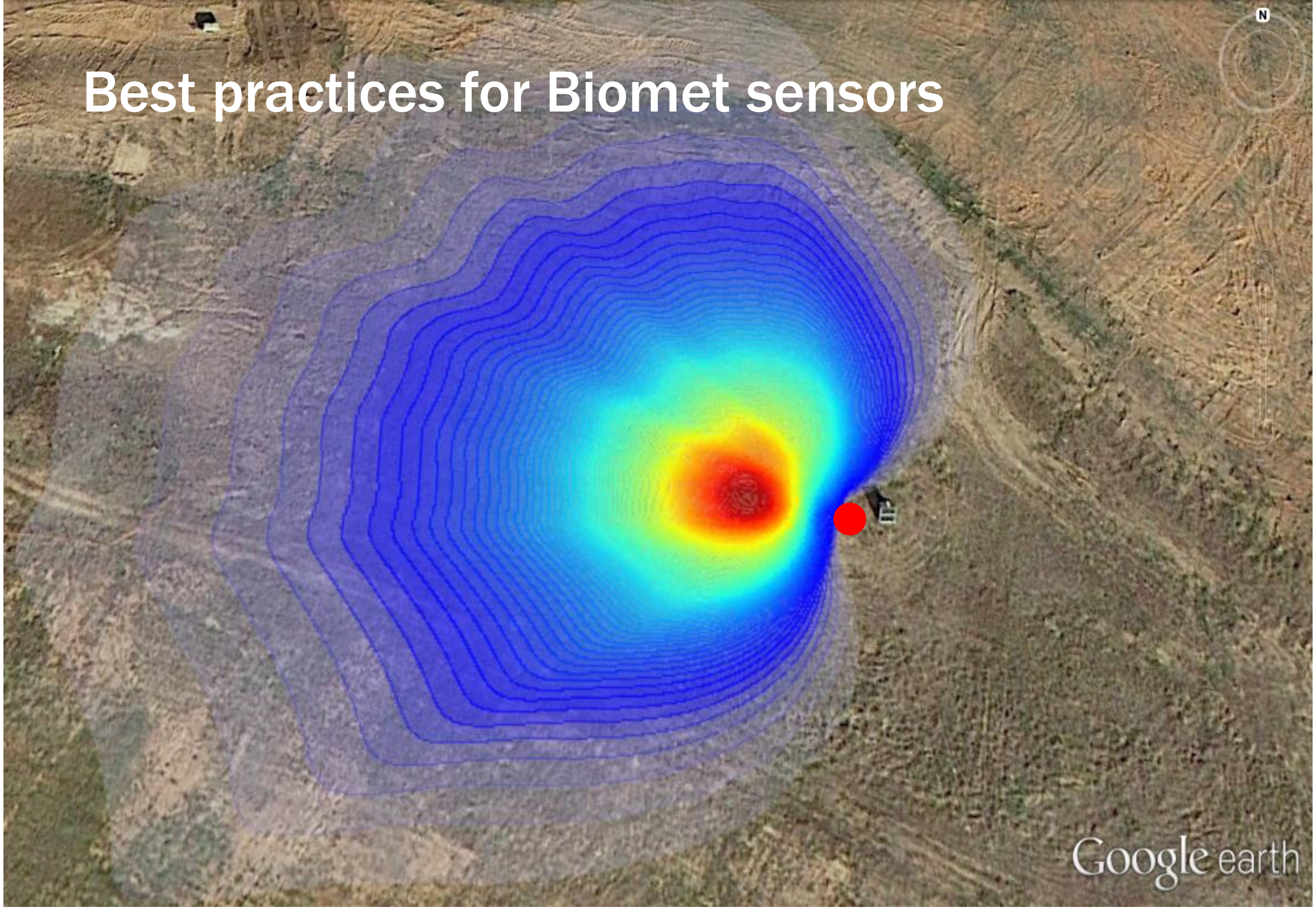
Energy measurements are from the same ecosystem

When Source Areas are different...



! Energy measurements are from the <u>different</u> ecosystems

Best practices for Biomet sensors



How Biases could cause an imbalance

Cause of imbalance	Examples
Sampling	Source areas differ
Instrument bias	Net radiometer biased
Neglected energy sinks	Storage above soil heat plates
High/low frequency loss	Sensor separation/large eddies
Advection	Regional circulation

Wilson, K et al (2002). Energy balance closure at FLUXNET sites. Agricultural and Forest Meteorology

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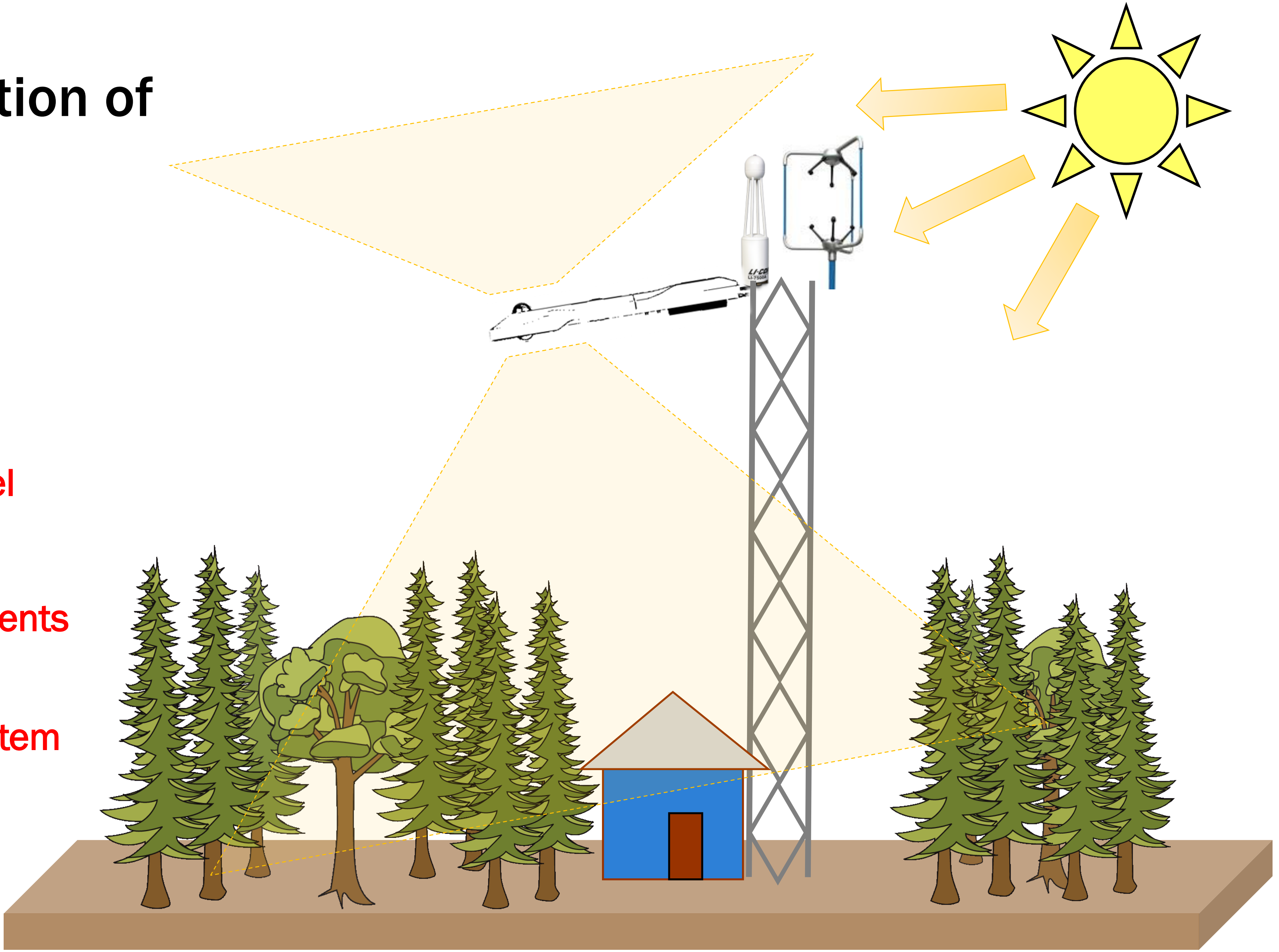
Instrument bias; improper installation of Net Radiometer



- ! Radiometer is not level
- ! Radiometer can be shaded by EC instruments
- ! Radiometer is not measuring the ecosystem
- ! Radiometer is measuring the tower

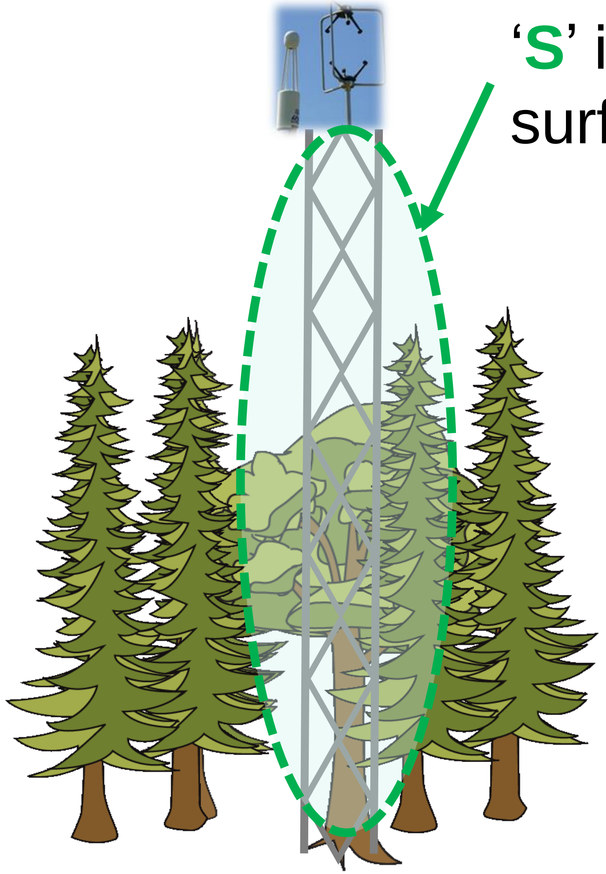
How neglecting energy sinks could cause an imbalance

Cause of imbalance	Examples
Sampling	Source areas differ
Instrument bias	Net radiometer biased
Neglected energy sinks	Storage above soil heat plates
High/low frequency loss	Sensor separation/large eddies
Advection	Regional circulation

Wilson, K et al (2002). Energy balance closure at FLUXNET sites. Agricultural and Forest Meteorology

Heat energy is stored in the (tall) canopy

For tall vegetation sites *(h* > 8m*)*



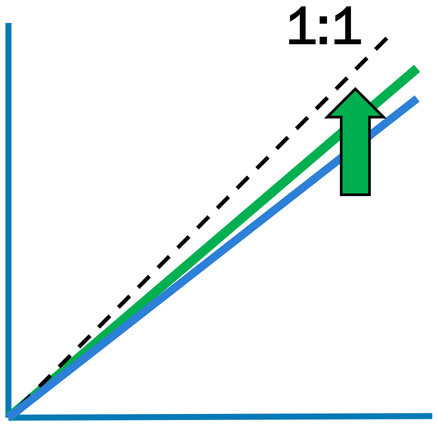
'**S**' is the rate of change of heat storage between the soil surface and the level of the eddy covariance instrumentation

*If we add '**S**' back into the Energy Balance Eqn:*

$$R_n = H + LE + G + \mathbf{S} + Q$$

$$R_n - G - \mathbf{S} \approx H + LE$$

Based on 26 site-years of data, including '**S**' for tall sites *increased* the slope by an average of **7%**



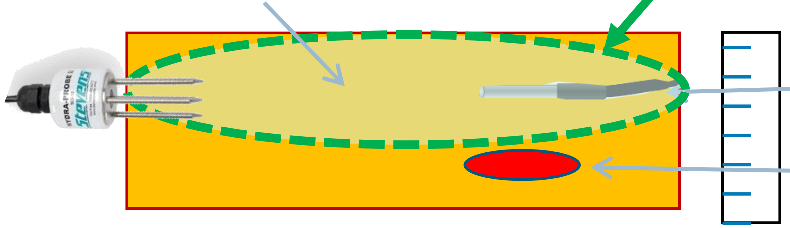
Tall forested sites should measure *S*.

Heat Energy is also stored in the Soil

We can estimate Heat Storage in the Soil (between Heat flux plates and surface)

Heat stored ‘**S**’ above heat flux plates can be estimated using information on soil properties, soil temperature, and moisture.

Soil Moisture



2.5 cm Soil Temperature

5.0 cm **Soil Heat Flux**

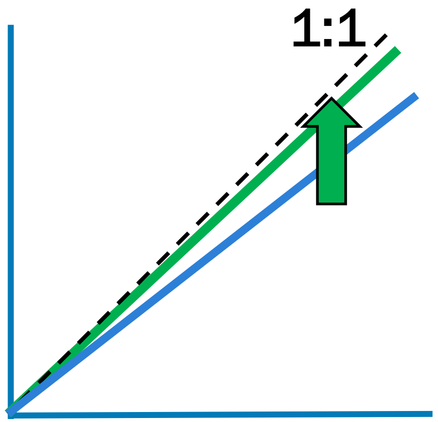
Soil Heat Flux at Surface = Measured Soil Heat Flux + Storage Term (S)

*If we add ‘**S**’ back into the Energy Balance Eqn:*

$R_n = H + LE + G + \mathbf{S} + Q$

$\Rightarrow R_n - G - \mathbf{S} \approx H + LE$

Including the soil heat storage ‘***S***’ *increases* the average slope by about **20%** for grasslands and agricultural sites



Short canopy sites should measure *S*.

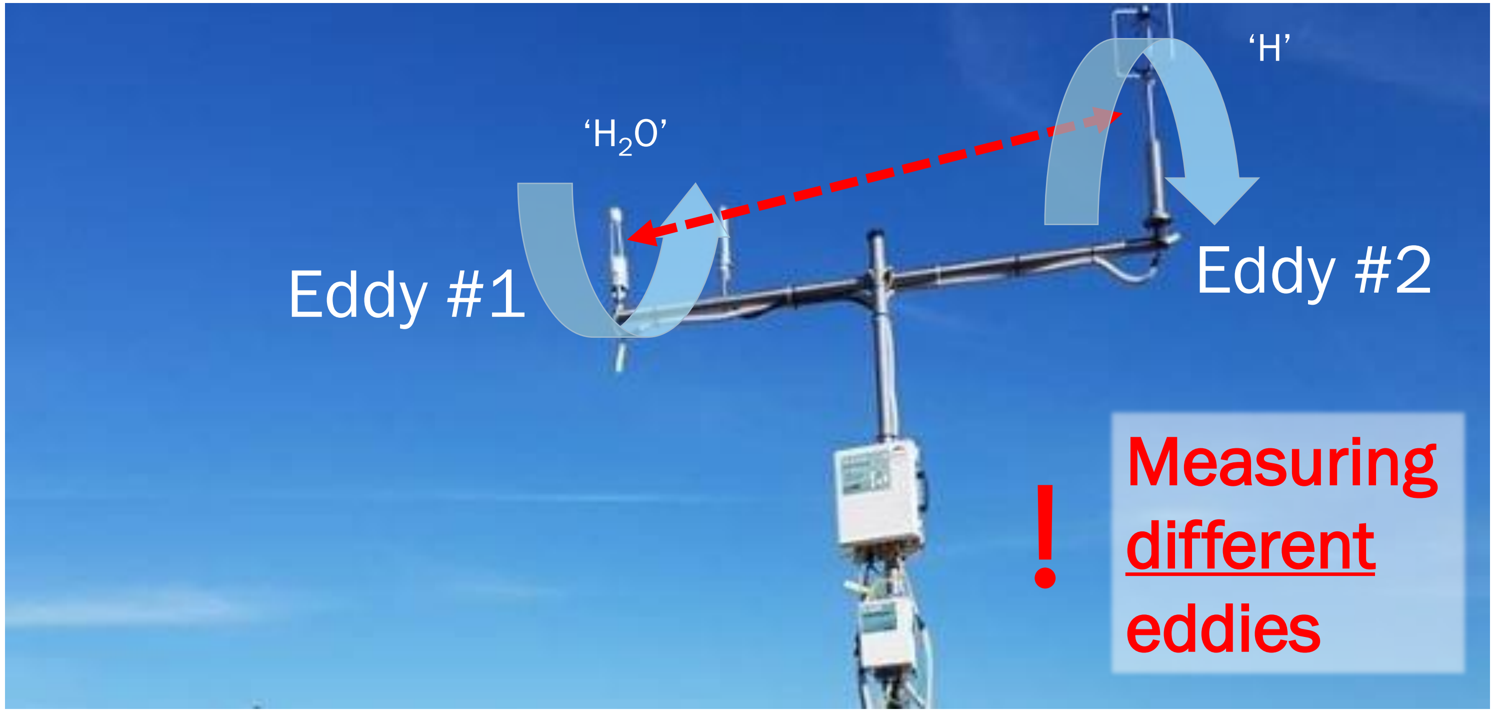
How losing high / low frequencies, and advection can cause an imbalance in the EB closure

Cause of imbalance	Examples
Sampling	Source areas differ
Instrument bias	Net radiometer biased
Neglected energy sinks	Storage above soil heat plates
High/low frequency loss	Sensor separation/large eddies
Advection	Regional circulation

Wilson, K et al (2002). Energy balance closure at FLUXNET sites. Agricultural and Forest Meteorology

Improper sensor separation can cause the loss of high frequency energy measurements

- If separation is too big, H and H_2O are not from the same eddy and covariance is lost, creating an energy imbalance



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Summary Energy Balance closure

- **Good closure is not necessarily a validation, bad closure is a definite problem** *Burba 2013*

- Energy balance closures cannot be used as a quality criteria for turbulent fluxes (Aubinet et al. 2000). This is because the influencing factors are so greatly different, wrong conclusions are possible. In comparison with similar experiments, energy balance can give only a rough criterion about the accuracy of the fluxes. *Foken 2008*

Other Closure checks

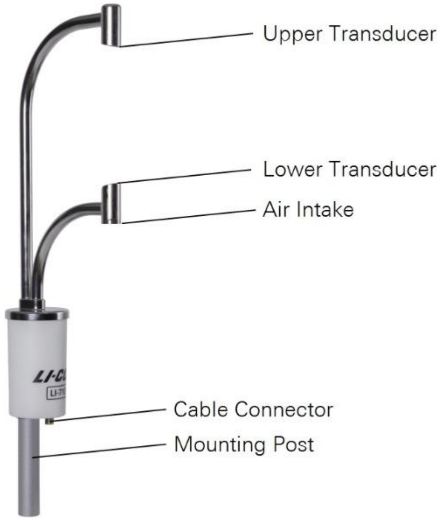
Carbon Closure

- Long-term biomass accumulation, compare to cumulated EC measurements

Other Closure checks

Hydrological balance

- Rain = **LE** + Runoff + Percolation + Storage



LI-710 Evapotranspiration Sensor

Water Node

Why collect Biomet measurements?

- Improved flux computation and corrections
  Quantities estimated from EC replaced by mean values
- Quality Assurance and Quality Checking (QA/QC)
  Energy Balance closure
- Gap filling, when instrumentation or power fails, low data quality
- Recording weather helps to explain site behavior
  Physical/biological environment has profound effects on surface-atmosphere exchange

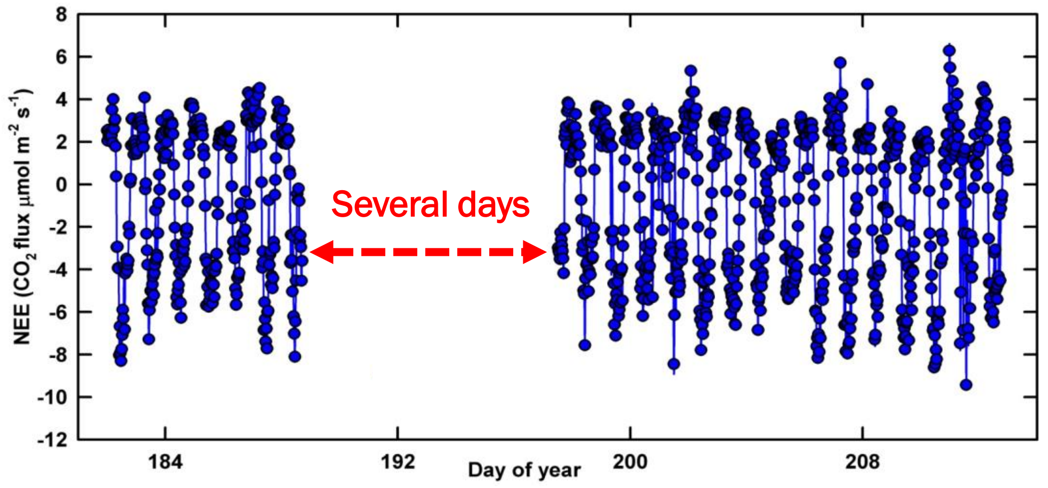
Gapfilling

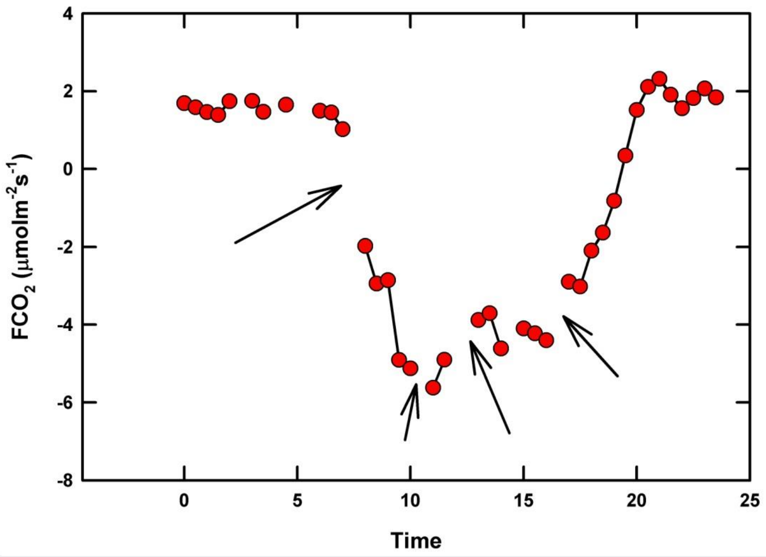
Gaps occur due to:

- Power supply issues
- Sensor failures
- Data flagged
- Spikes in data due to rain events
- Data flagged for low U*

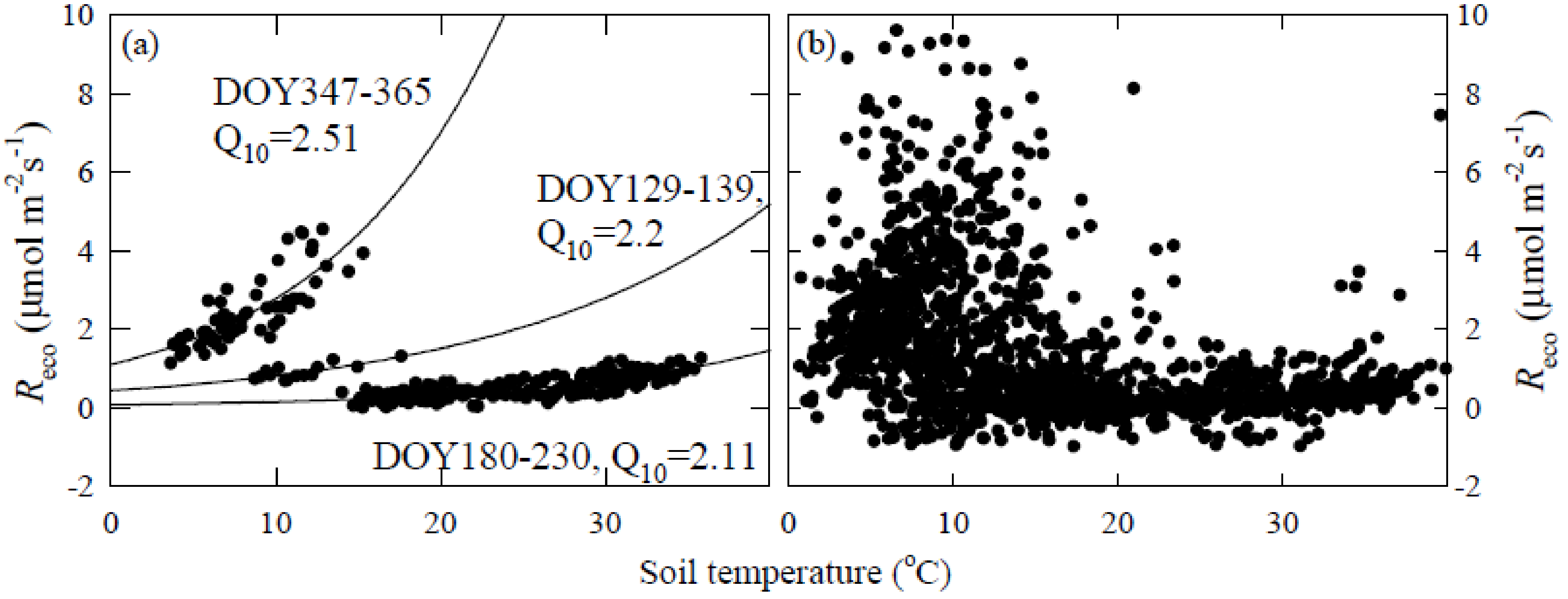
➢Small gaps: interpolation techniques

➢Large gaps: other techniques





Example, gap filling using Soil Temperature as a driver for Ecosystem Respiration

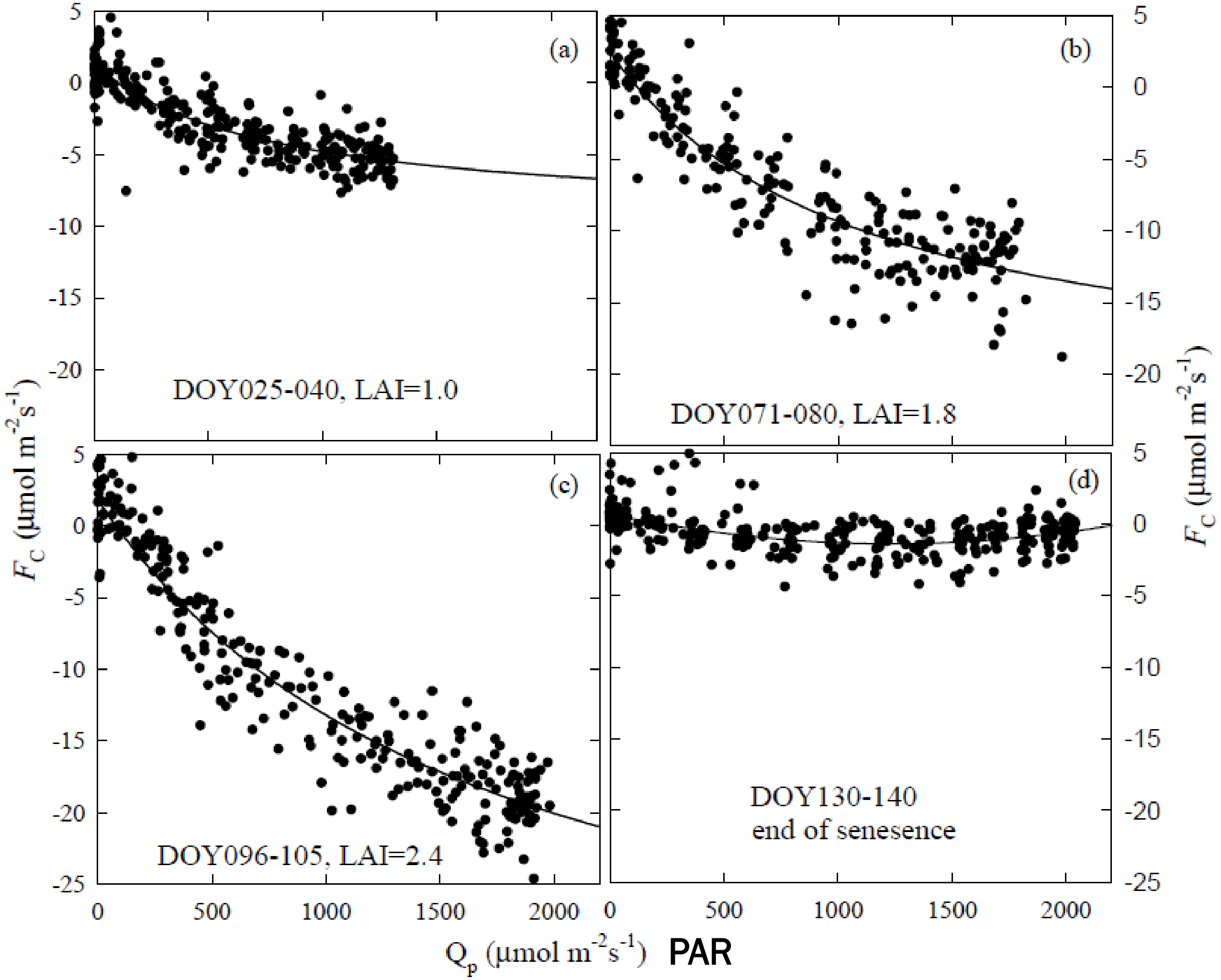


$$F_c = b_0 \exp(bT_{soil})$$

$$Q_{10} = \exp(10b)$$

Seasonal relationships between *Soil Temperature* and *Ecosystem Respiration*

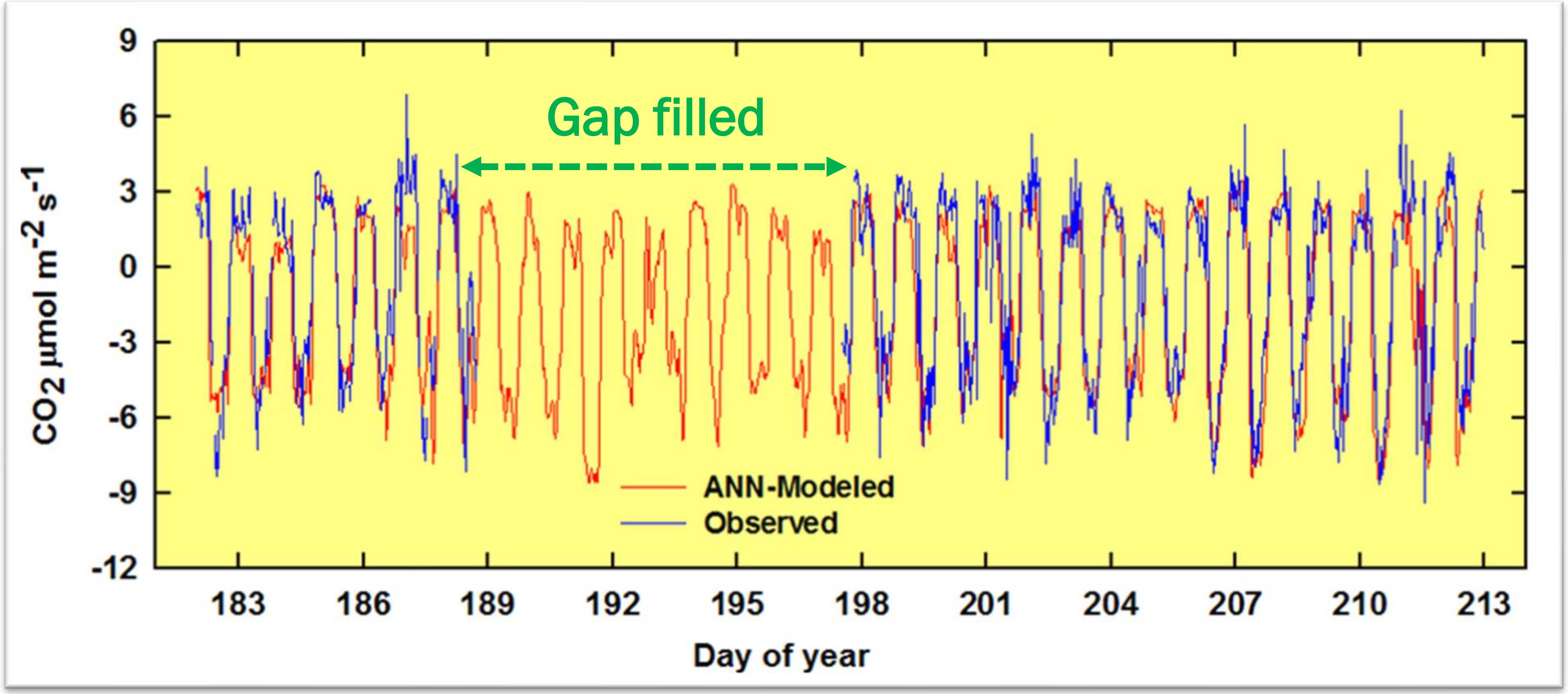
Example, gap filling using PAR as a driver for FCO_2



$$F_c = \frac{F_{max}\alpha PAR}{\alpha PAR + F_{max}} + R_{eco}$$

Seasonal relationships between *PAR* and *CO_2 flux*

Gapfilling – Artificial Neuronal Networks



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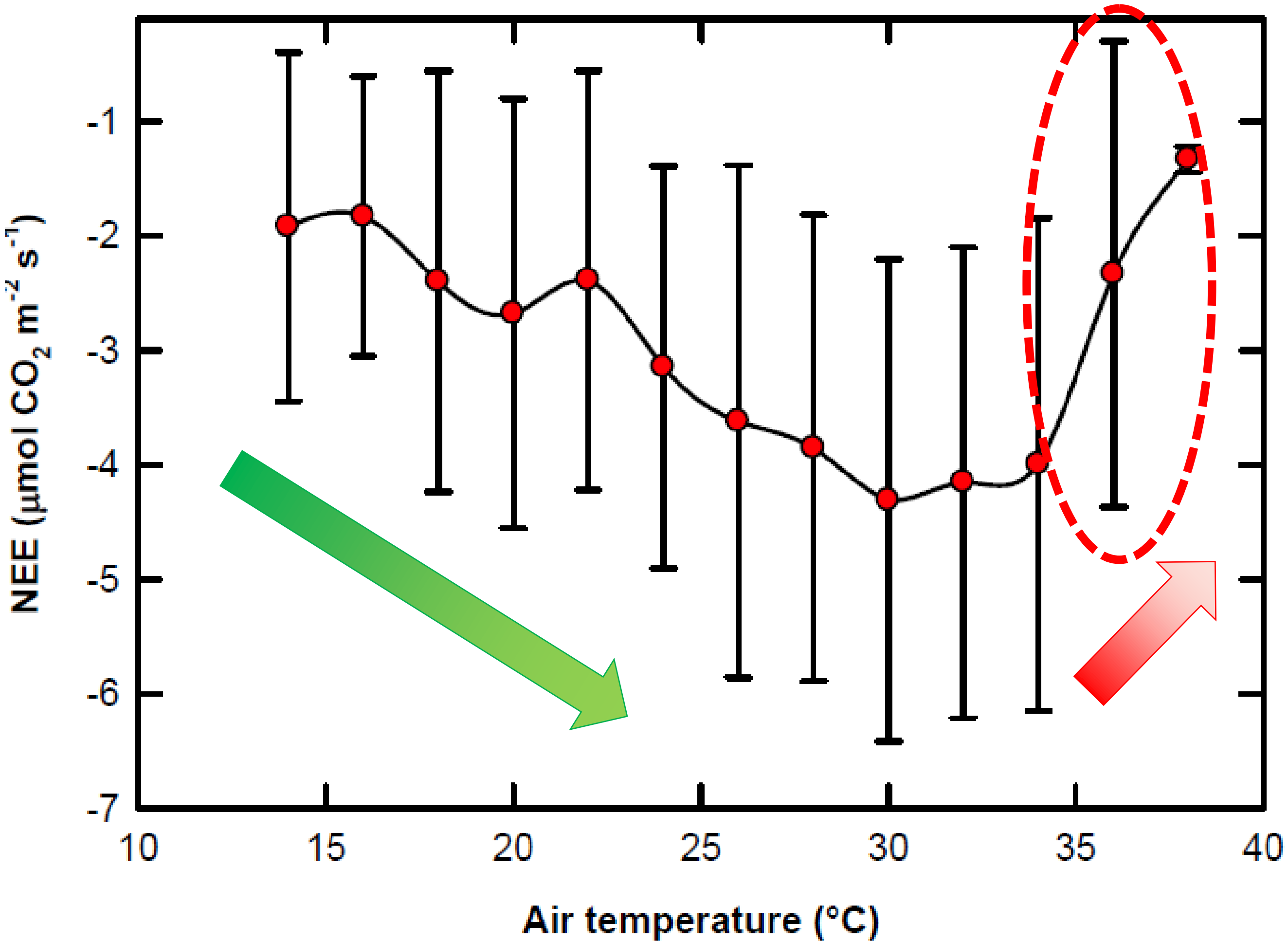
Example, how air temperature can affect fluxes

- We can see that air temperature can be a driver for fluxes



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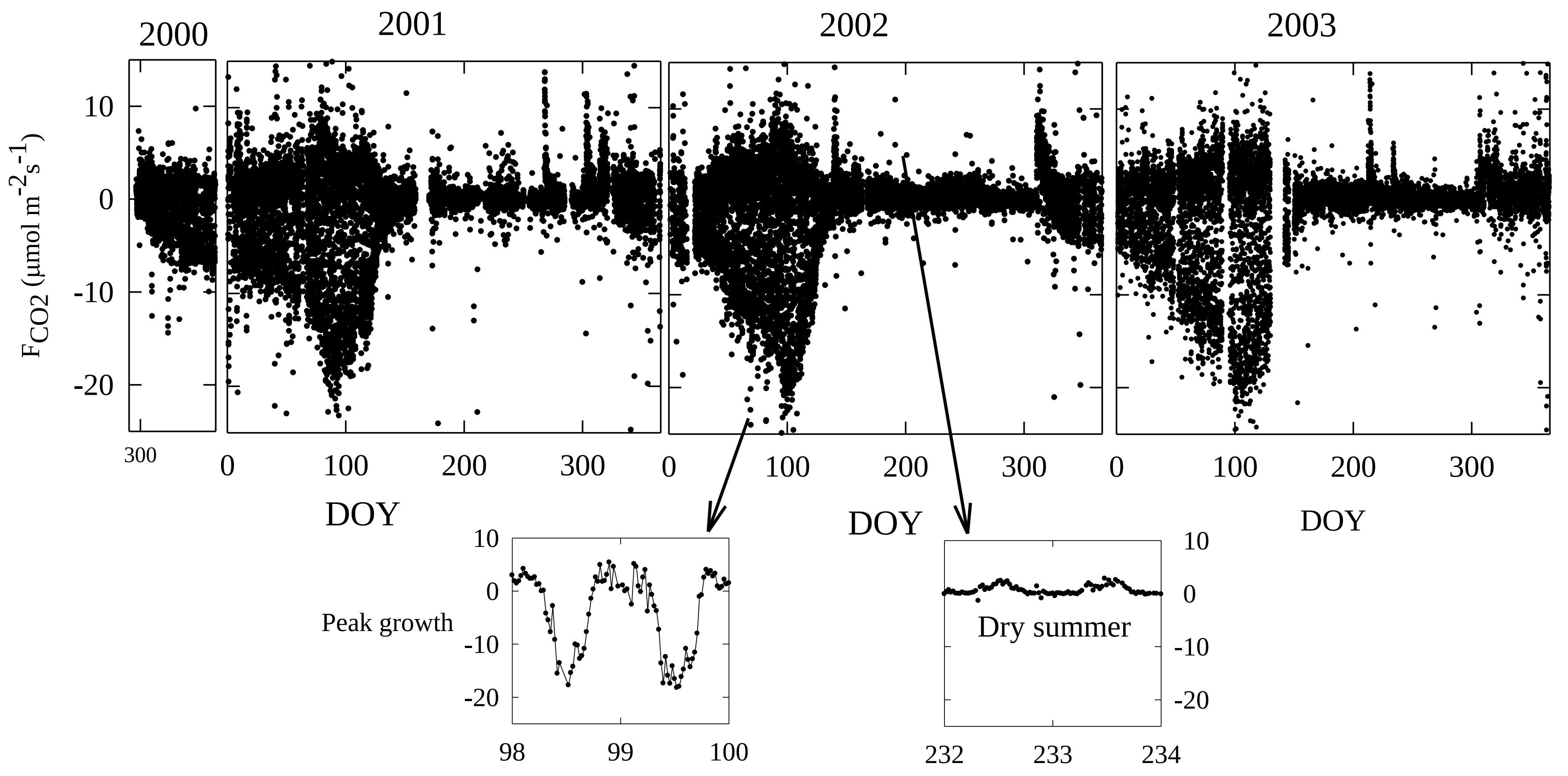
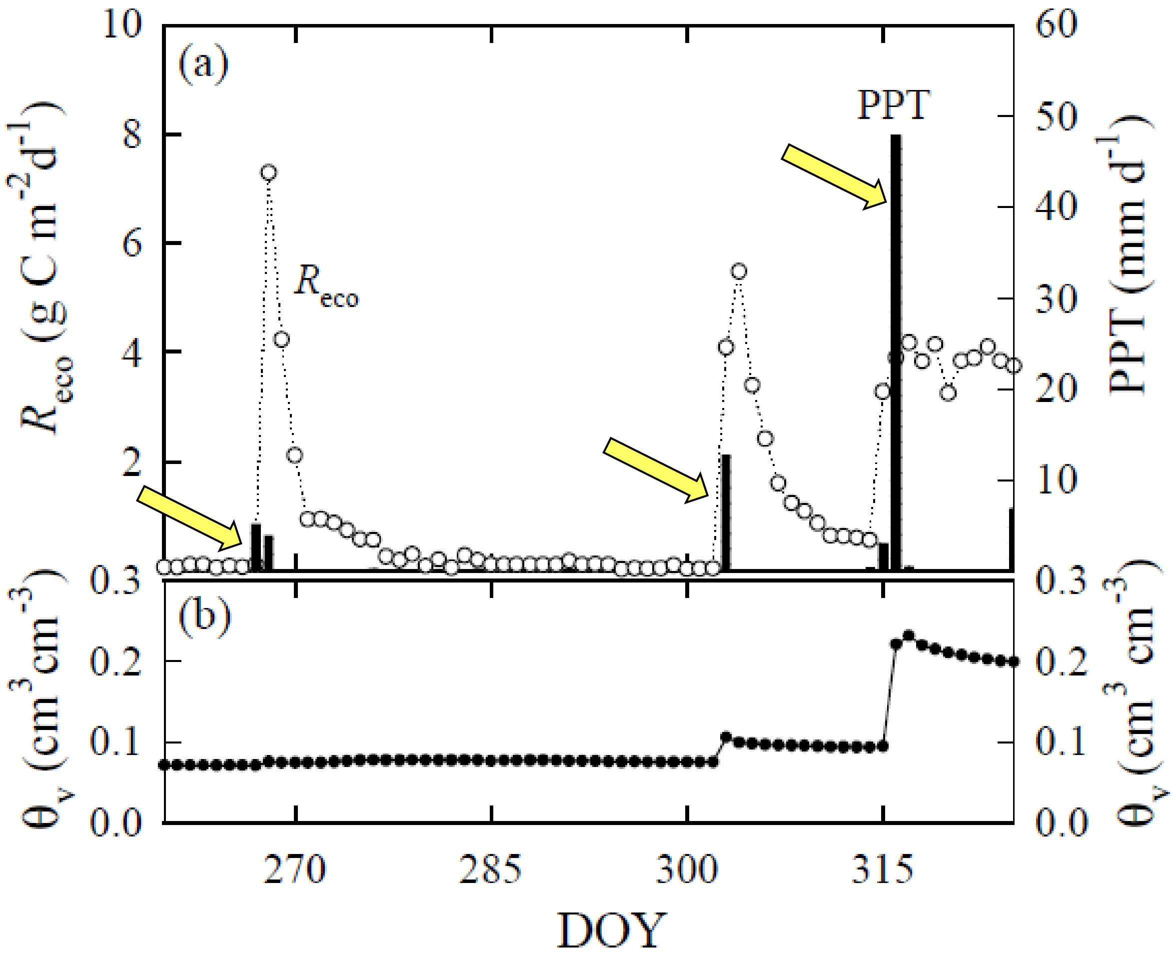
Example of long-term flux data - California grassland

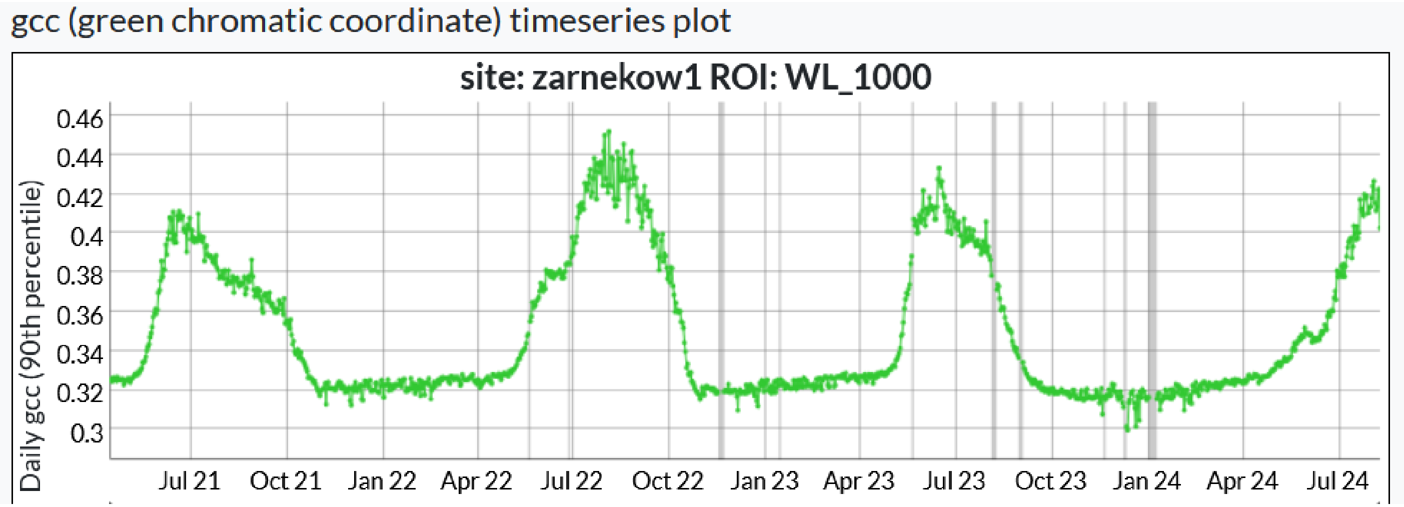


Example of long-term flux data - California grassland

Rain events affect Soil Moisture and Ecosystem Respiration rates



Phenocam – Network

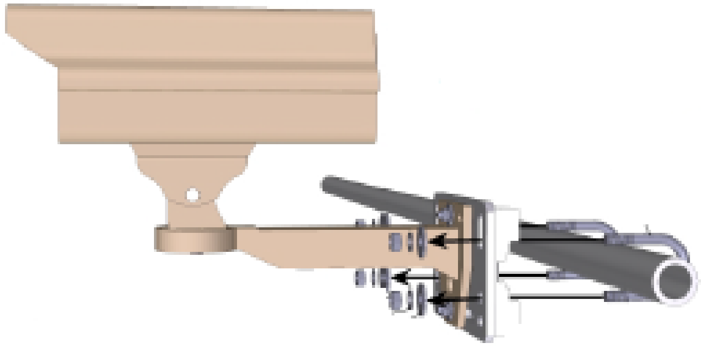


StarDot:
- NetCam SC
- StarDot Live2 (new!)

Interface: Ethernet
Power requirements: 12 VDC

Phenocam –Installation

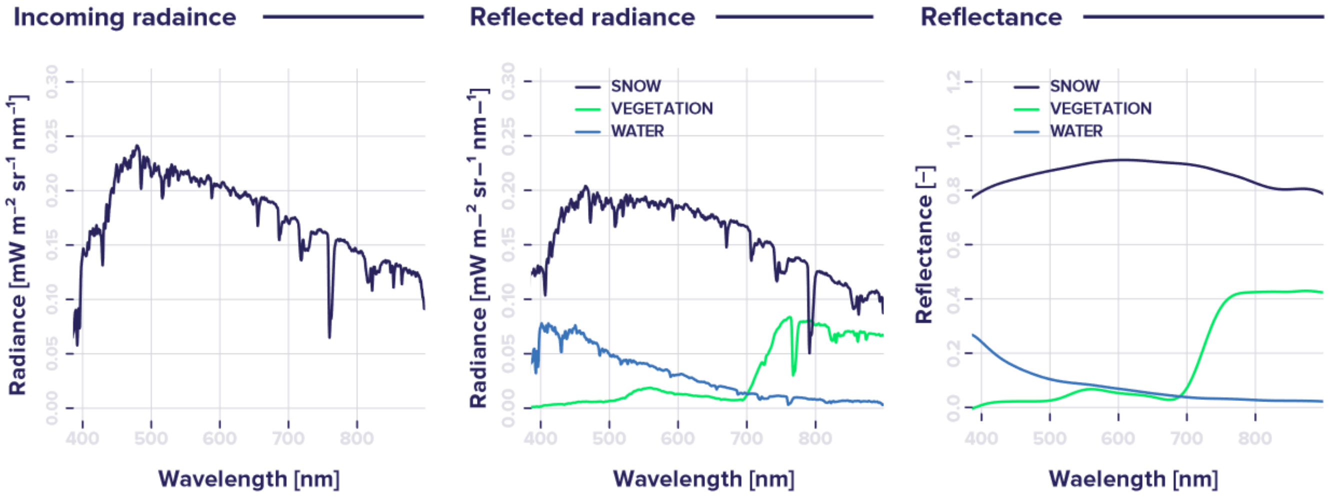
- Direct the camera to the North (on northern hemisphere) to avoid lens flare and shadowing.
- Mount the camera at a height of 5 to 10 meters above the canopy.
- The image should capture about 20% sky and 80% canopy. Be sure to include the horizon in the image.
- Mount the camera securely to prevent movement.



RoX and FloX

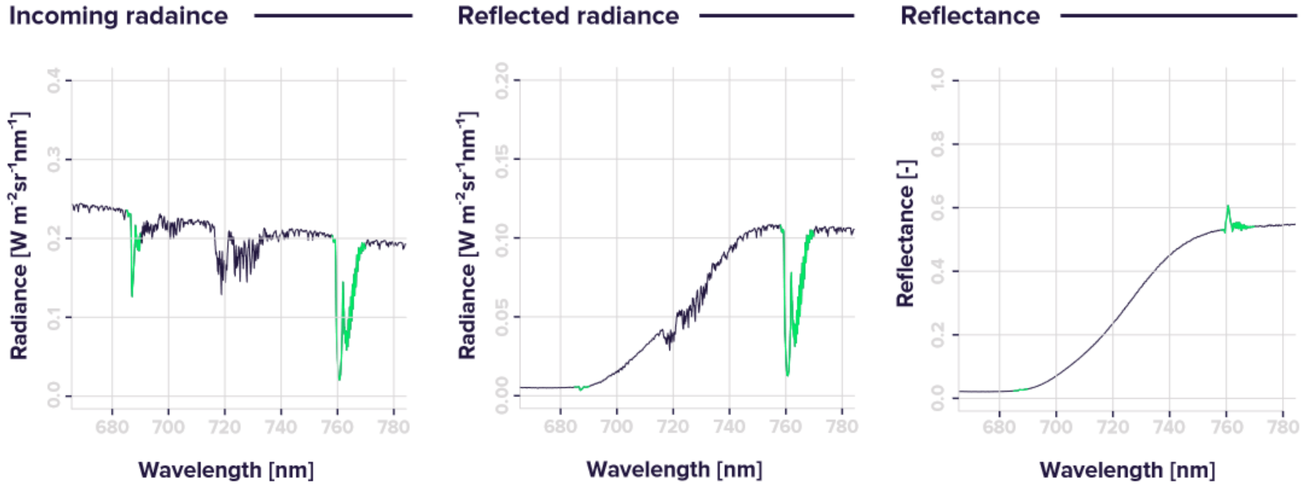
RoX – The Reflectance Box

Spec: 400-950 nm, SSI 0.65 nm, FWHM 1.5 nm, in 180°, refl. 25°



FloX – The Fluorescence Box

Spec1: 650-800 nm, SSI 0.17 nm, FWHM 0.3 nm, in 180°, refl. 25°
Spec2: 400-950 nm, SSI 0.65 nm, FWHM 1.5 nm, in 180°, refl. 25°

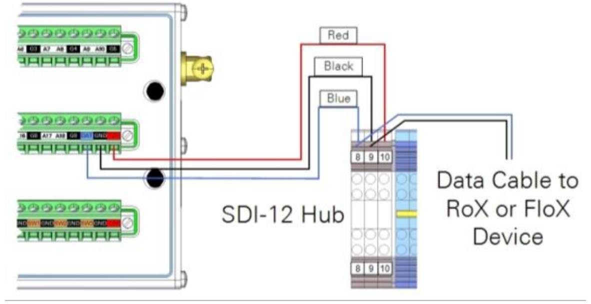


HYPERSPECTRAL DEVICES

DAQM Integration via SDI-12

SDI-12 integration

DAqM

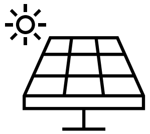


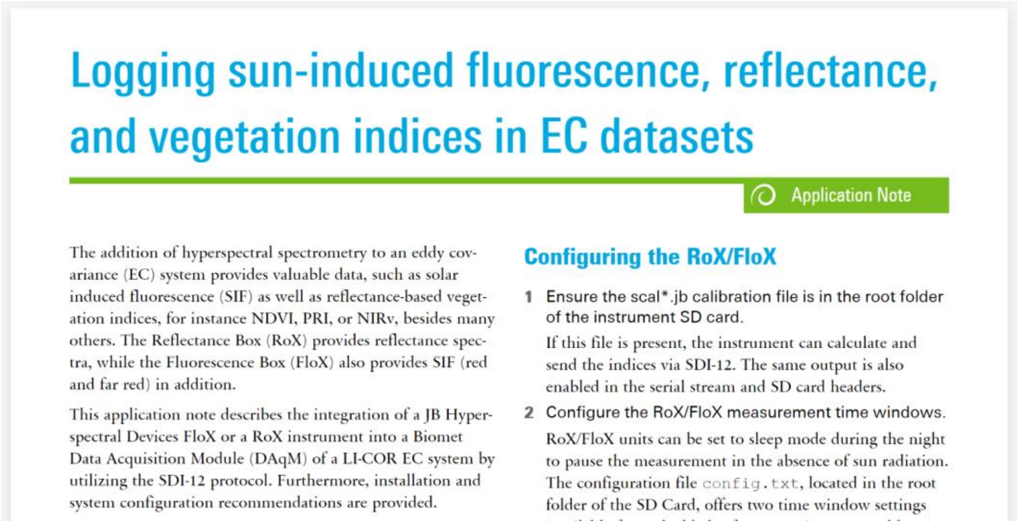
FloX

RoX

Table 1. RoX and FloX specifications[3].

	RoX	FloX
Power Requirements	10 to 14 VDC, 15 W	10 to 14 VDC, 60 W[1]
Weight	3 kg	18 kg
Fiber Length[2]	1x/1x, 7 meters	2x/2x, 7 meters
Internal Memory	32 GB SD card (24 months of raw data)	32 GB SD card (12 months of raw data)





Logging sun-induced fluorescence, reflectance, and vegetation indices in EC datasets

Application Note

The addition of hyperspectral spectrometry to an eddy covariance (EC) system provides valuable data, such as solar induced fluorescence (SIF) as well as reflectance-based vegetation indices, for instance NDVI, PRI, or NIRv, besides many others. The Reflectance Box (RoX) provides reflectance spectra, while the Fluorescence Box (FloX) also provides SIF (red and far red) in addition.

This application note describes the integration of a JB Hyperspectral Devices FloX or a RoX instrument into a Biomet Data Acquisition Module (DAqM) of a LI-COR EC system by utilizing the SDI-12 protocol. Furthermore, installation and system configuration recommendations are provided.

Configuring the RoX/FloX

1. Ensure the scal*.jb calibration file is in the root folder of the instrument SD card.

   If this file is present, the instrument can calculate and send the indices via SDI-12. The same output is also enabled in the serial stream and SD card headers.

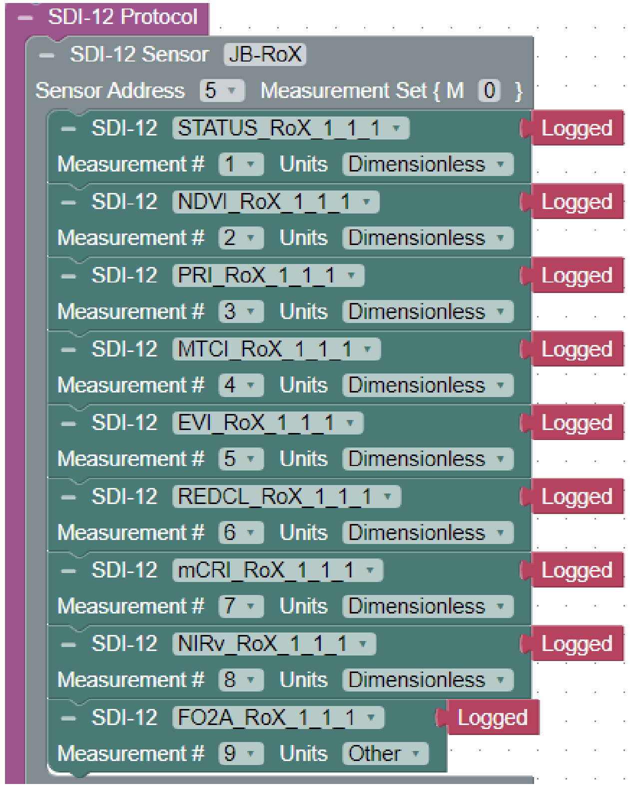
2. Configure the RoX/FloX measurement time windows.

   RoX/FloX units can be set to sleep mode during the night to pause the measurement in the absence of sun radiation. The configuration file `config.txt`, located in the root folder of the SD Card, offers two time window settings

LI-COR

RoX and FloX output via SDI-12

DAQM Code



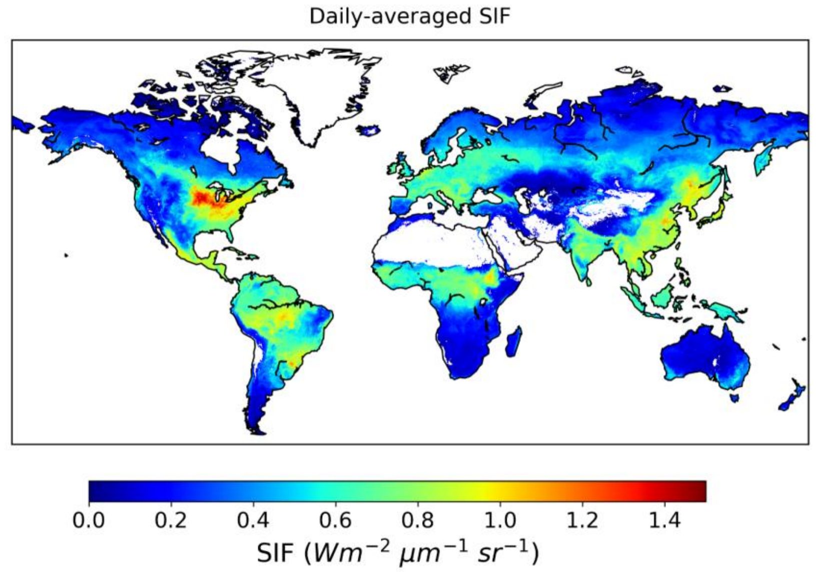
SDI-12	Name	Wavelengths	FWHM	Formula
1	STATUS	n/a	n/a	temperature+humidity+errors+voltage
2	NDVI	800;670	10;10	(a-b)/(a+b)
3	PRI	531;570	2;2	(a-b)/(a+b)
4	MTCI	754;709;681	7;10;7	(a-b)/(b+c)
5	EVI	800;670;480	10;10;10	2.5*(a-b)/(a+6*b-7.5*c+1)
6	RedCL	785;725	15;5	a/b-1
7	mCRI	510;725;785	5;5;15	c/(a-b)
8	NRIv	L800	40	NDVI * L800
9	FO2A	O2A	n/a	3FLD

FO2A (SIF) only available from FloX; FWHM: full width at half maximum
Requires reprocessing for publication grade results

JB-Hyperspectral Devices Integration

Field based measurements of sun-induced-fluorescence (SIF) and vegetation indices

- SIF and vegetation indices research topics include:
    - Ecosystem research: diurnal and seasonal dynamics of GPP, water deficit, heat effects, biomass/canopy density
    - Plant health/research: bacterial/fungal infection, stress detection, herbicide effects, nitrogen deficit, phenotyping
    - Plant damage prediction before manifestation
- Provide ground-truth for satellite-based SIF, such as for the FELX mission
- Flux networks (Fluxnet, Ameriflux, ICOS, NEON, …) started to intergrade ground-based SIF measurements, measurement protocols are being developed



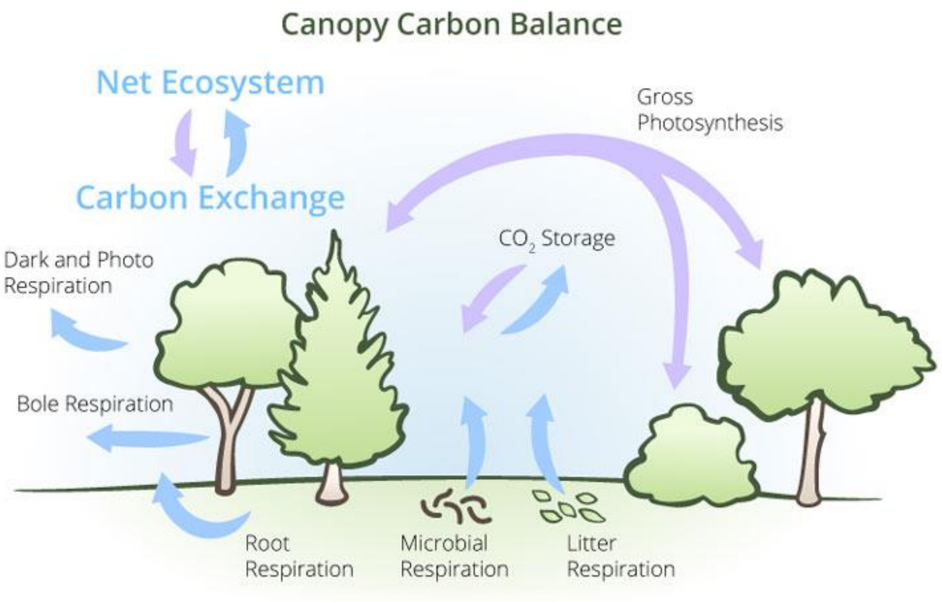
Daily-corrected SIF at 740 nm for August 2015. The highest SIF values during this time period were observed in agricultural sectors in the Northern Hemisphere

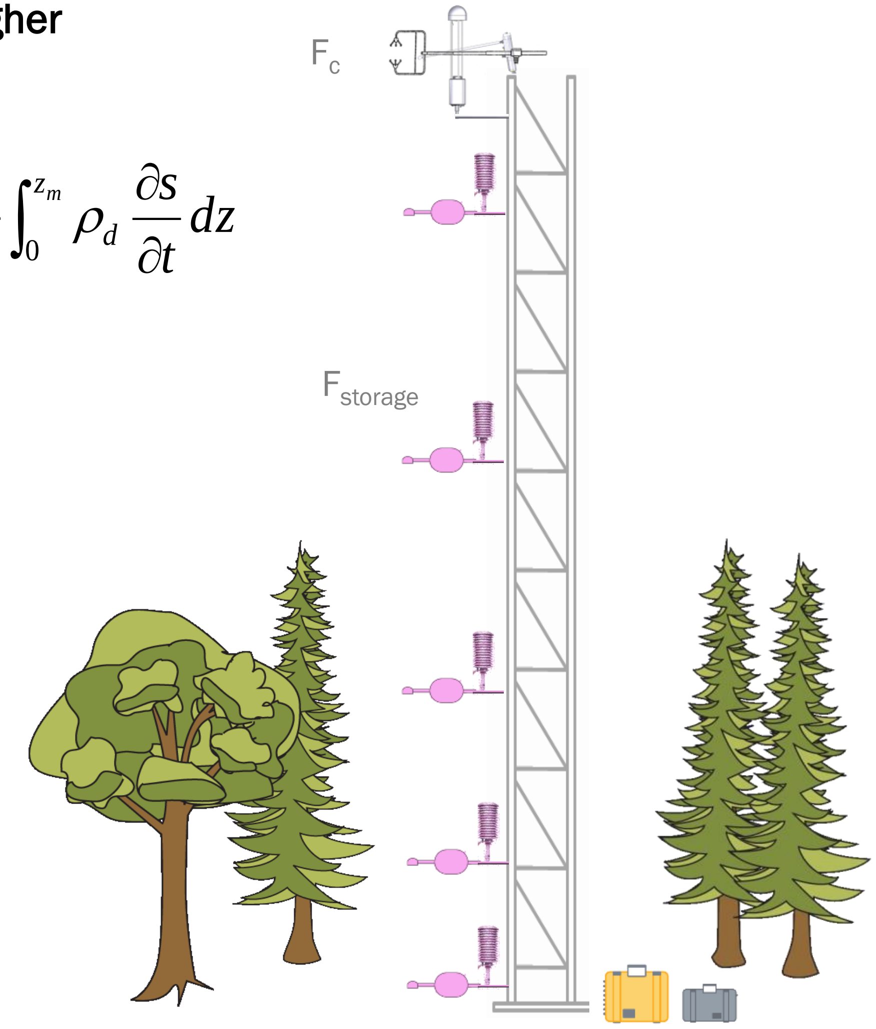
Atmospheric Profiling System with LI-8250 Multiplexer

Storage Flux - CO_2 / CH_4 / N_2O

ICOS: Atmospheric storage flux measurements are mandatory for **EC systems higher than 4 m above ground.**

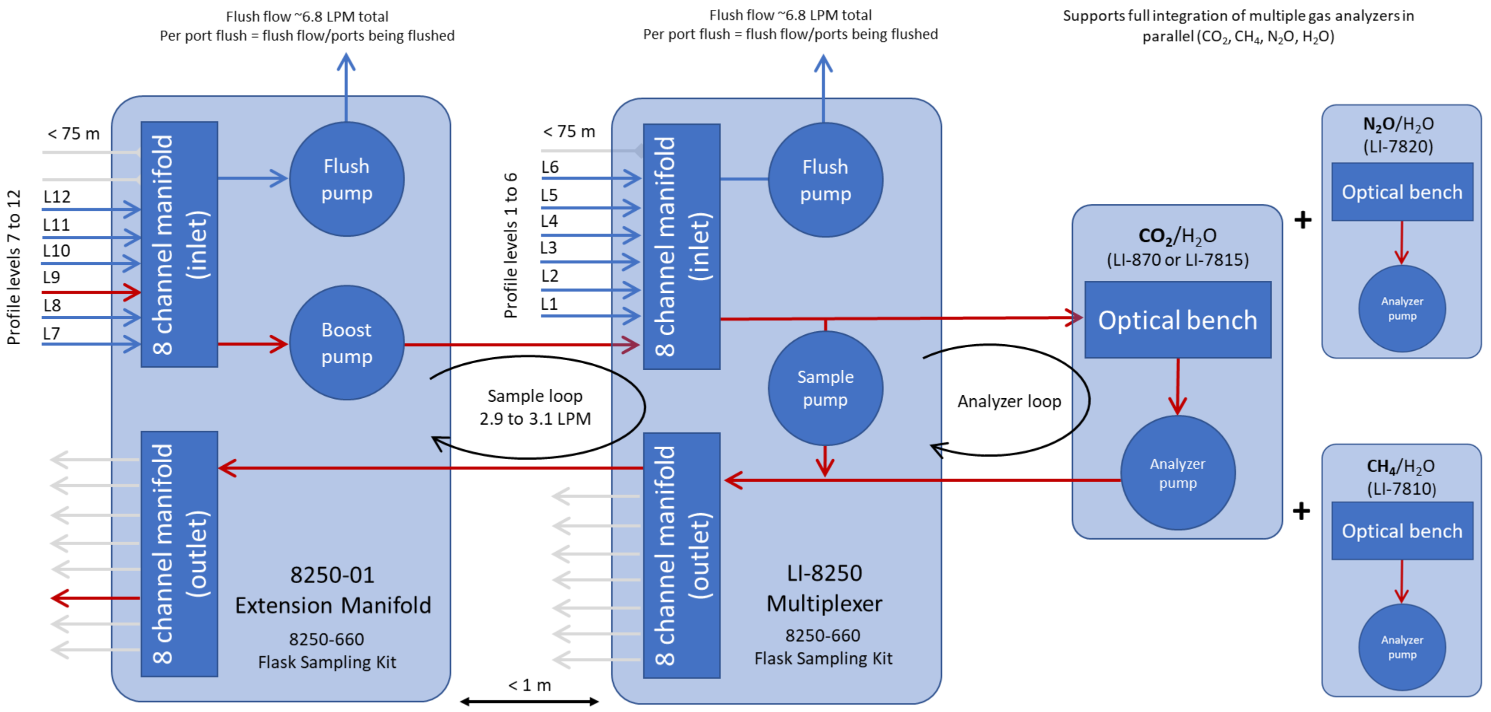
$$F_{ecosys} = F_c + F_{storage} = F_c + \int_0^{z_m} \rho_d \frac{\partial s}{\partial t} dz$$





Atmospheric Profiling System with LI-8250 Multiplexer

12 Level Atmospheric Profile



Mixed System – Profile and Soil Flux in one System

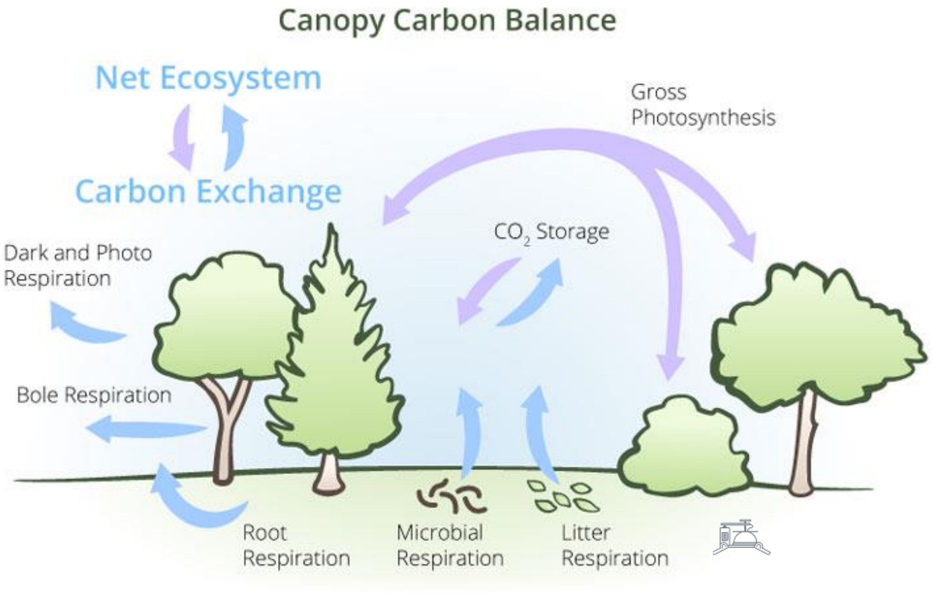
Add Soil Flux Measurement to Profile Measurement

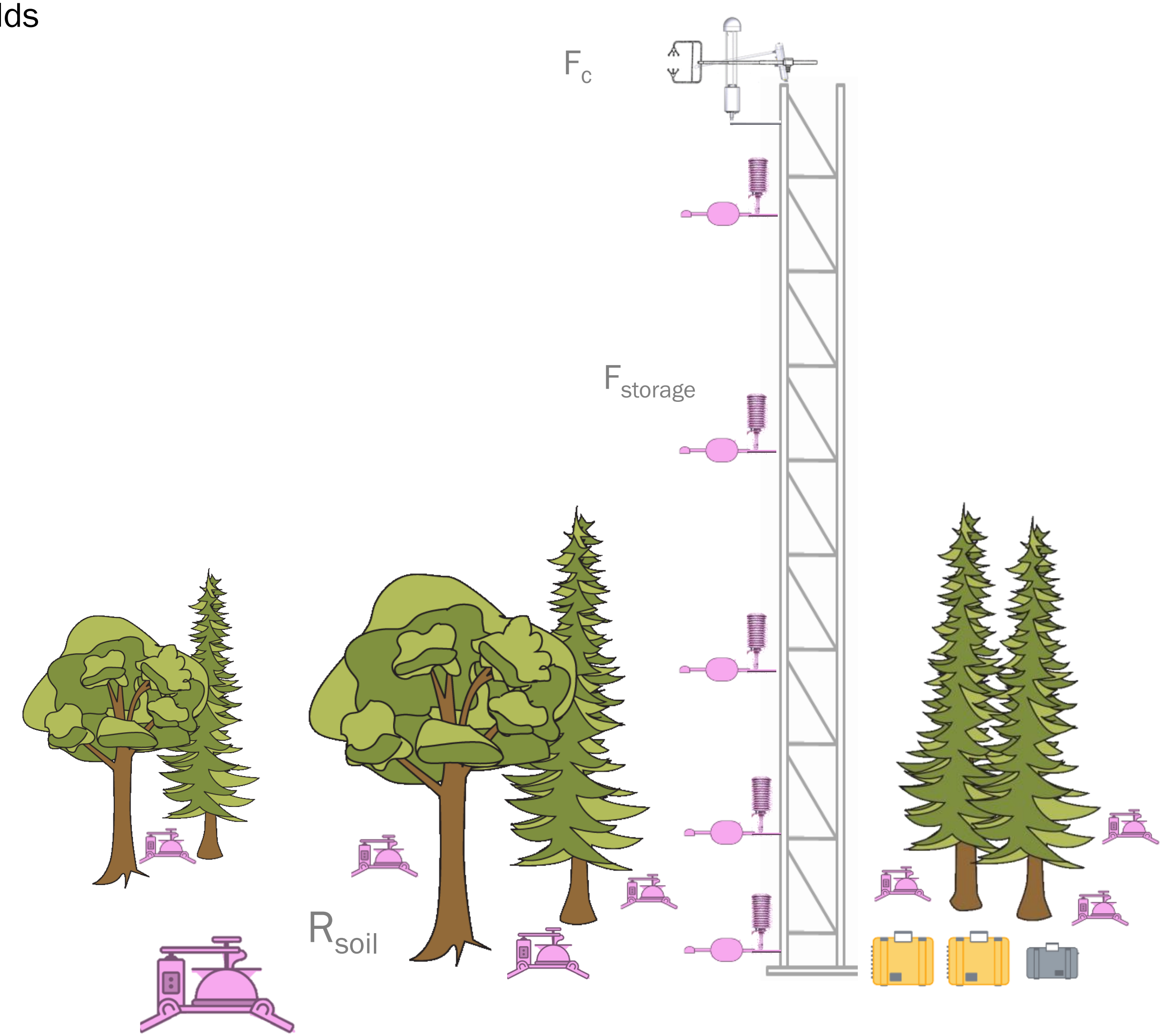
$F_{ecosys} = F_c + F_{storage}$

Recommended to connect **chambers** and **profile** tubes on different manifolds (multiplexer + extension manifold/s)

Example of a 30 min measurement schedule (1x mux + 2x ext. manifold):

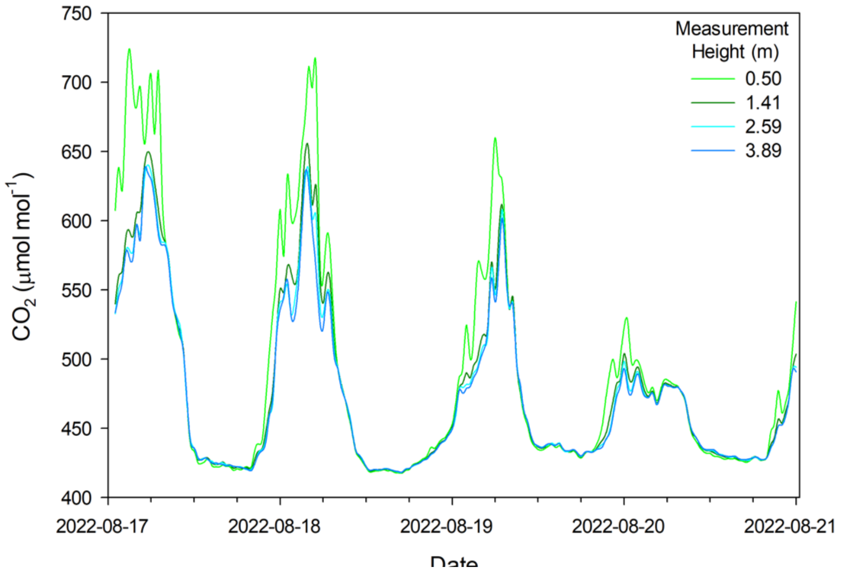
EC flux interval (30 min)
12x profile level -> 3 min
8x Long term chamber, each 3 min -> 24 min

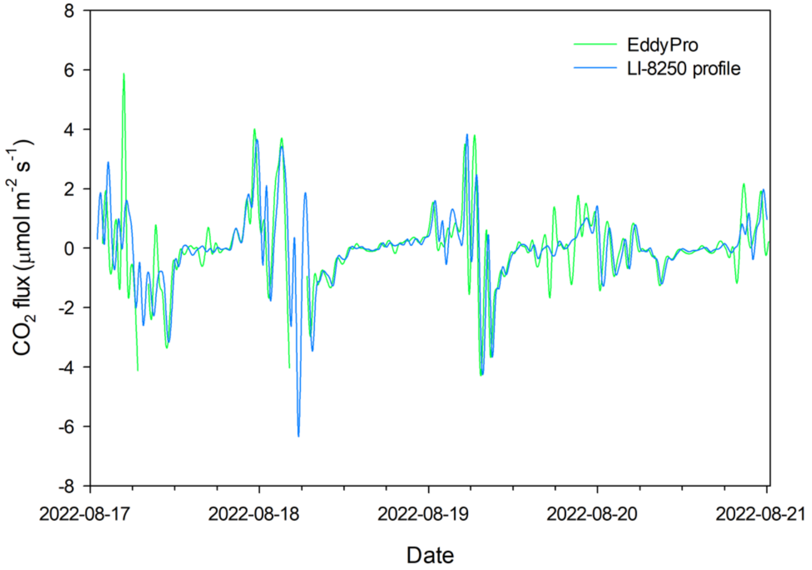




Atmospheric Profiling System with LI-8250 Multiplexer

CO_2 Storage Flux - Example setup at LI-COR experimental station, Lincoln NE





Buffered intake, rain cap and 3l buffer volume

Atmospheric profile measurements with the LI-8250 multiplexer system

Application Note

Contents

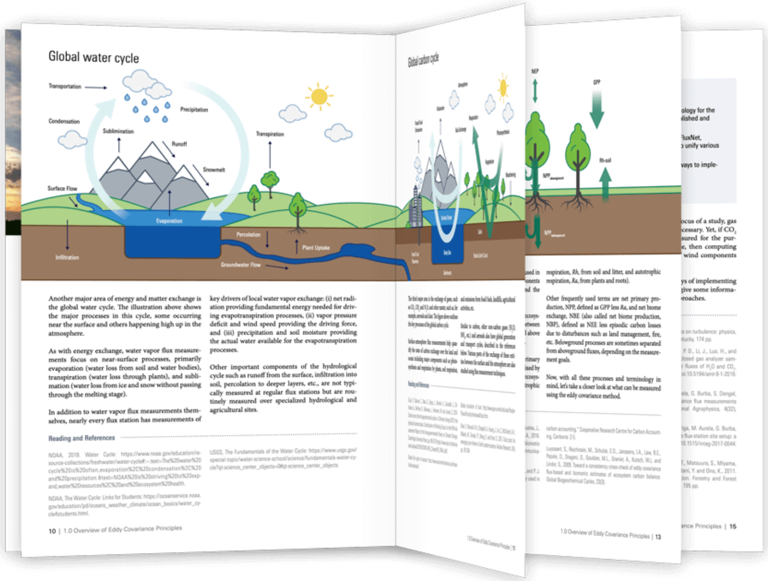
Sampling density, heights, and hardware selection 1
Purging profile intakes between measurements 1
Intake tubing 2
Buffer volumes 3
Air temperature 3
Installing the flask kit in the inlet-purge configuration . 3
Software configuration for profile measurements 7
Unlocking SoilFluxPro's secret level 9
An example profile system using buffered intakes 10
References 12

fall between 1.5 and 2 times the height of the plant canopy that the system is deployed in.

$$n = h_m{}^a \qquad 1$$

The parameter a has a recommended default value of 2/3, but may be adjusted depending on canopy characteristics. For canopies where vegetation density is highly uniform with respect to height this value may be reduced to as little as 0.5. For more complicated, less uniform canopies values up to 0.75 may be used.

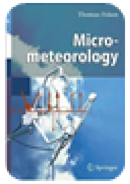
Basic reading for non-micrometeorologists and beginners:



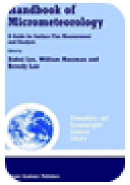
https://www.licor.com/env/products/eddy_covariance/ec-book

A more advanced reading for both non- and micrometeorologists:

EC: A Practical Guide to Measurement and Data Analysis, 2012. By M. Aubinet, T. Vesala, D. Papale *et al.* (Eds.)



Micrometeorology, 2008. By T. Foken. Springer-Verlag.



Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis, 2008. By X. Lee; W. Massman; B. Law (Eds.). Springer-Verlag.


Thank you