Ecosystem Gas Exchange: The Eddy Covariance Method

Liukang Xu

Outline

1. Basic eddy covariance (EC) theory
2. Examples of long-term flux measurements
3. GAP-filling
4. $GPP=R_{eco}-NEE$
5. Advantages of EC, and its disadvantages

Definition of variance and covariance

$x_1, x_2, x_3, x_4 \ldots\ldots\ldots\ldots x_n$

$y_1, y_2, y_3, y_4 \ldots\ldots\ldots\ldots y_n$

$\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2$ variance, 方差

$\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y}) = \overline{x'y'}$ covariance, 协方差

Terminology and units for gas flux

CO_2 flux: μmol 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}
(ET): mm hr^{-1}, mm day^{-1}

CH_4 flux: nmol m^{-2} s^{-1}

N_2O flux: nmol m^{-2} s^{-1}

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): $LE = \lambda E$ ($W\ m^{-2}$)
(*E is water vapor flux)*

Soil heat flux (G): $W\ m^{-2}$

LI-COR®

Vertical profile for environmental variables

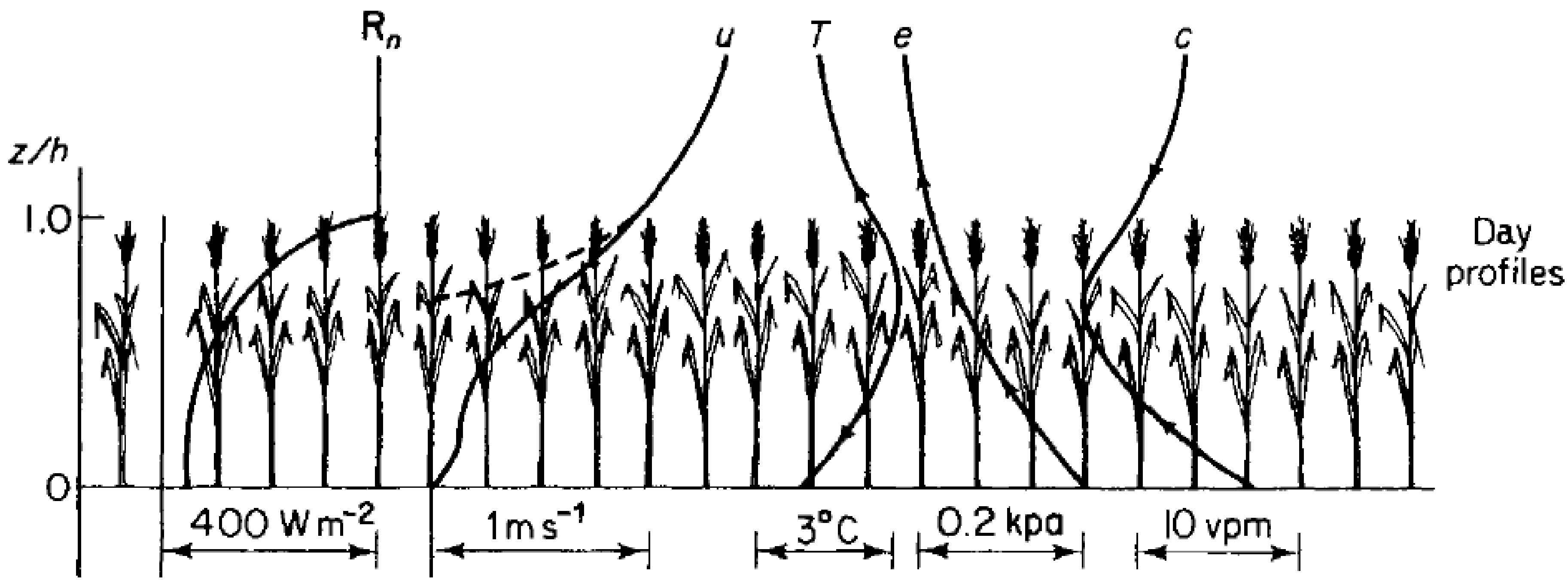
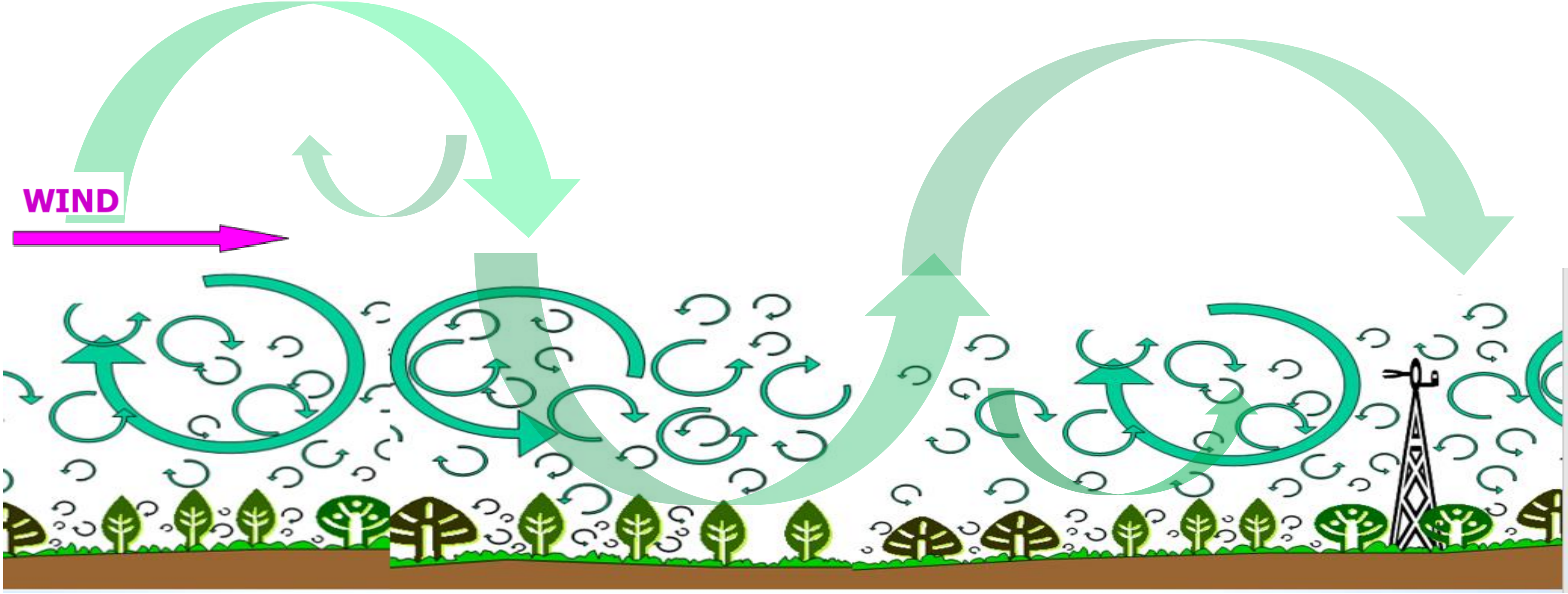
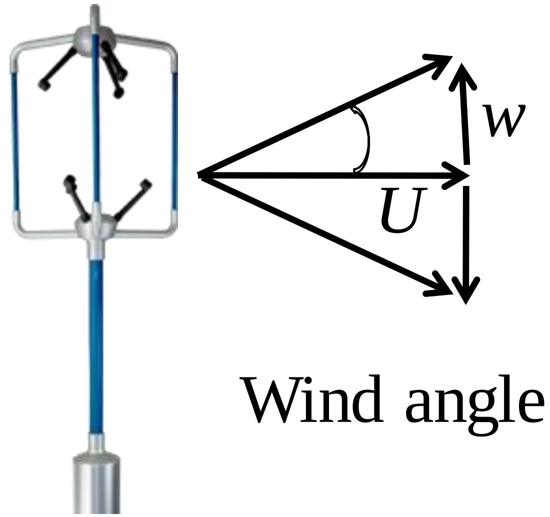


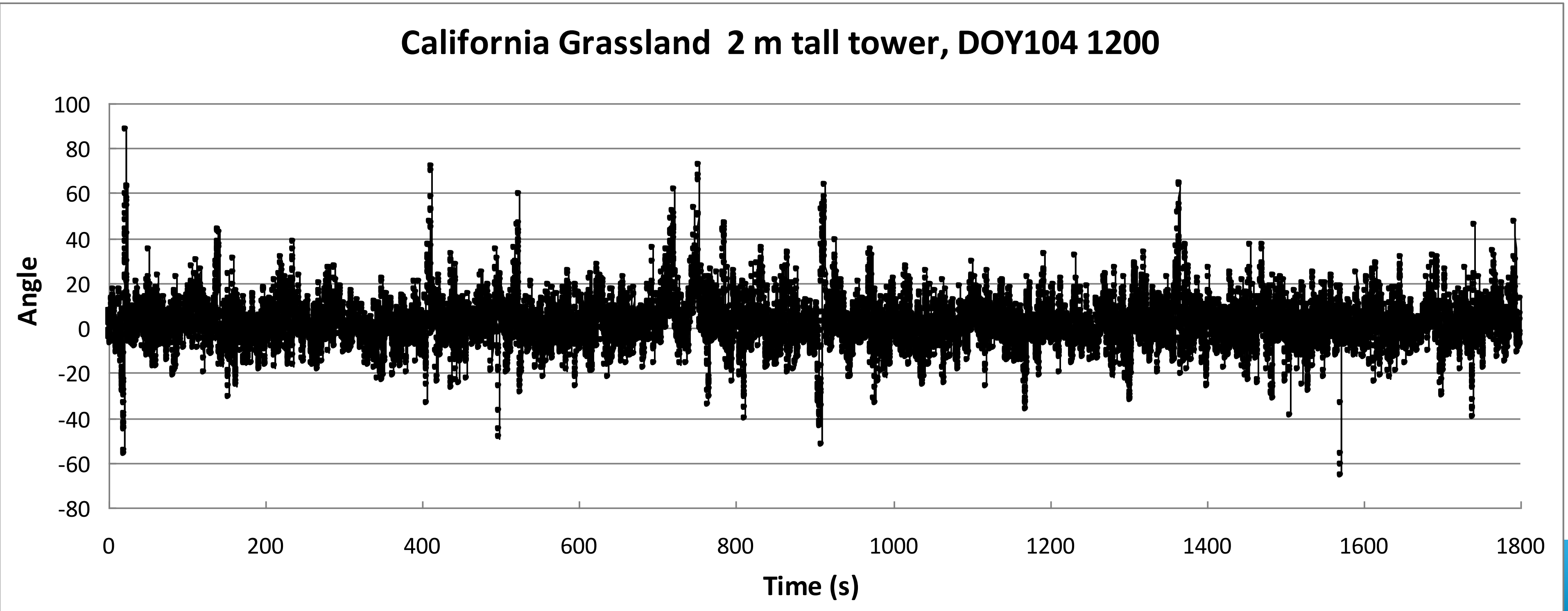
Fig. 16.5. Monteith and Unsworth , 2013. Environmental Physics.

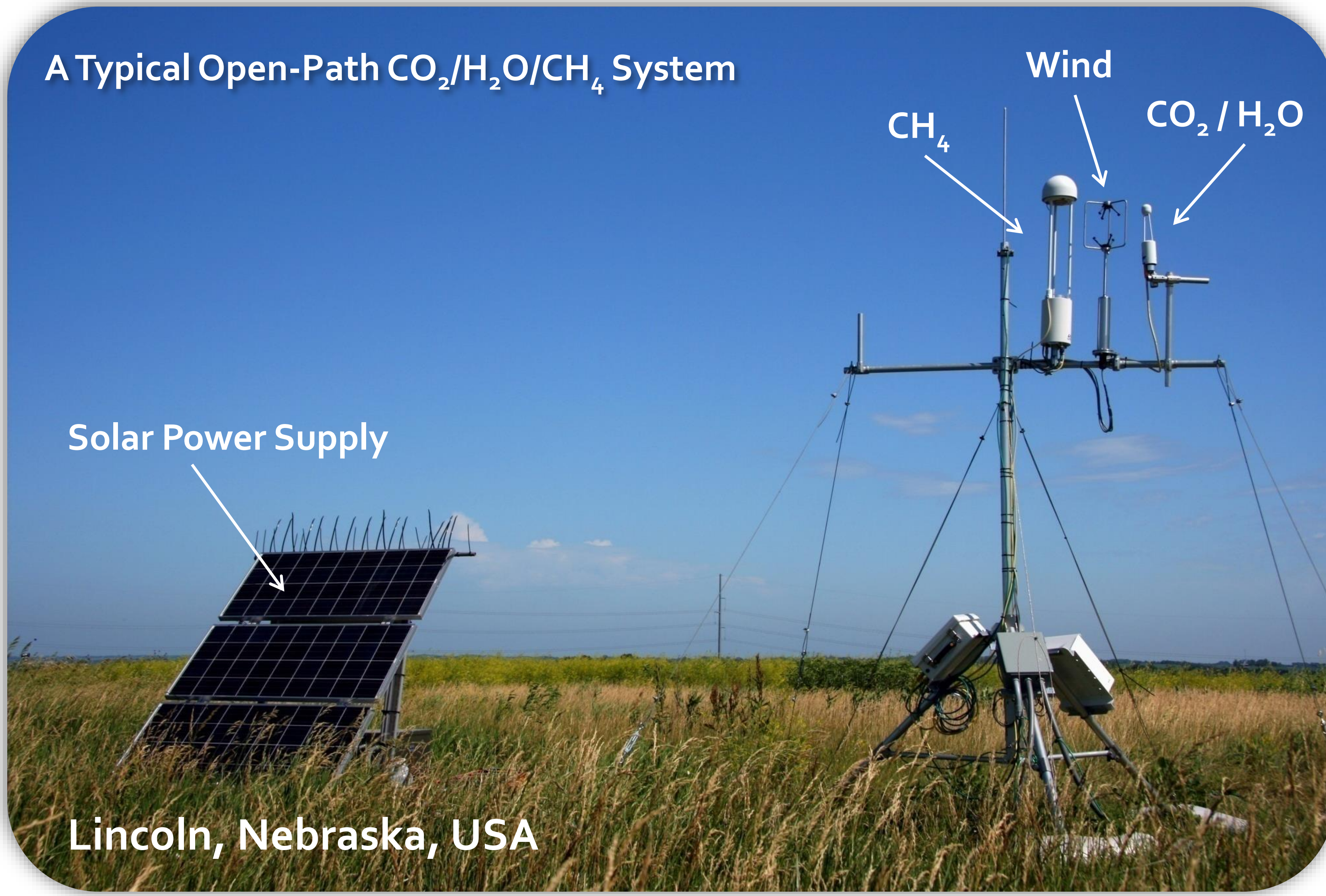
Eddy Covariance flux measurement



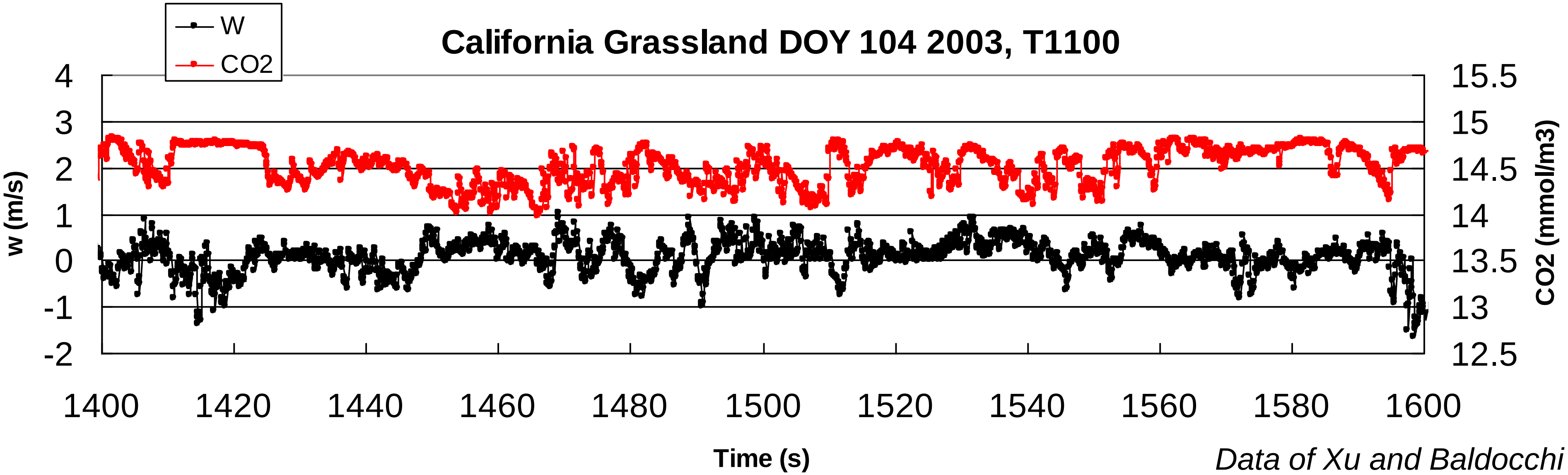
Here is more 10-Hz raw data…



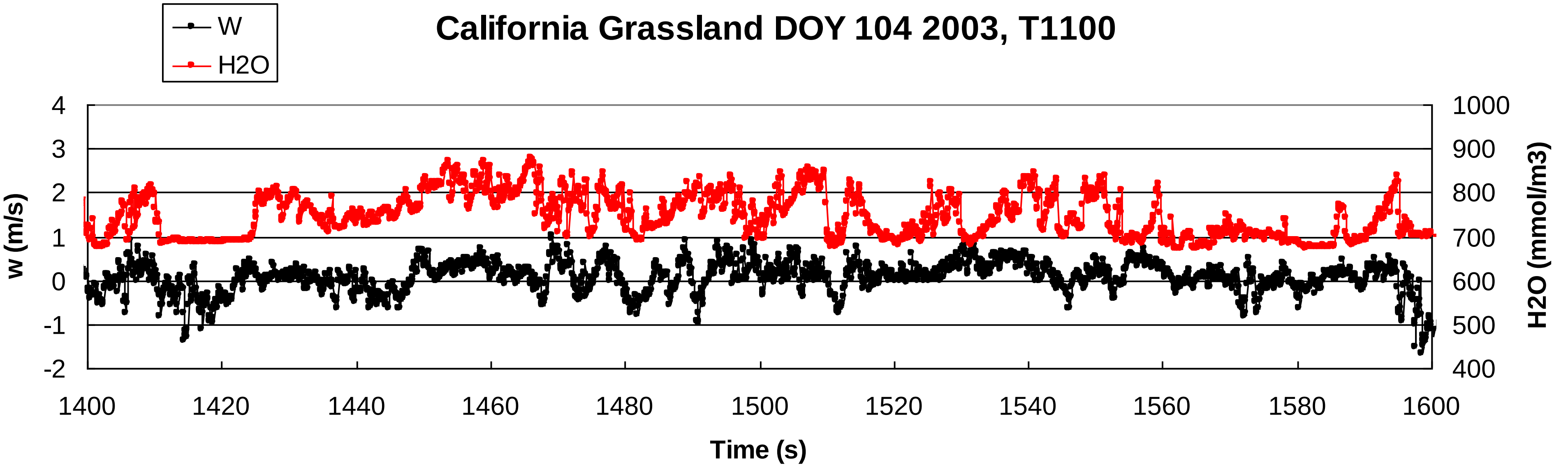


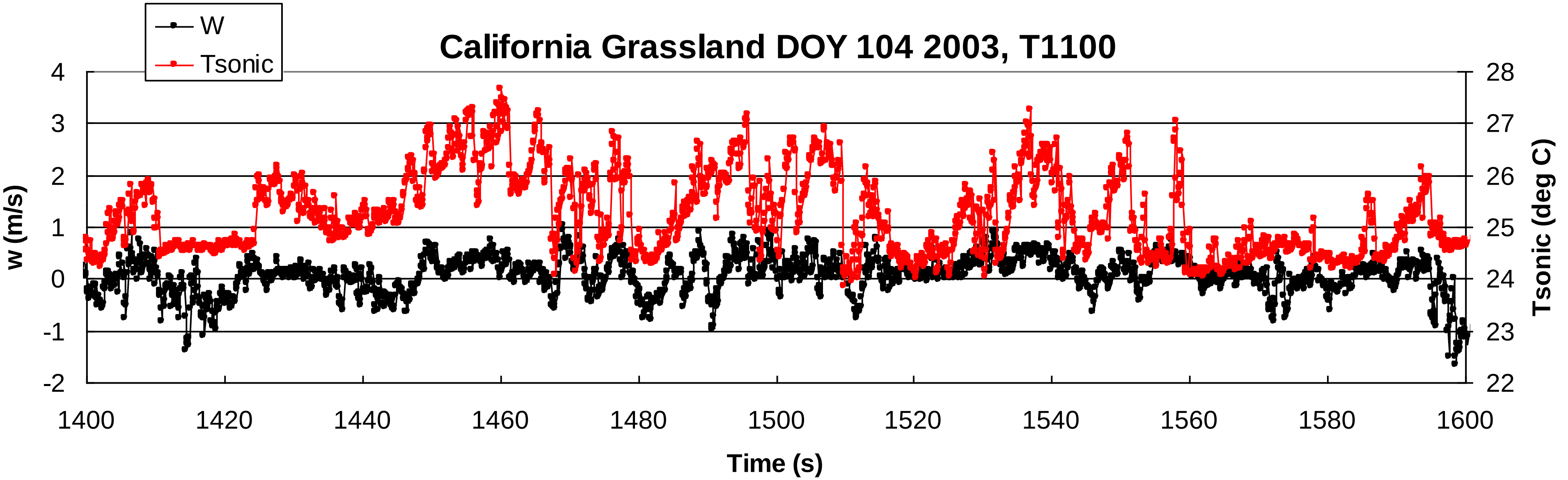

A Typical Open-Path $CO_2/H_2O/CH_4$ System
Wind
CH_4
CO_2 / H_2O
Solar Power Supply
Lincoln, Nebraska, USA

Let's see some 10-Hz real data!



Data of Xu and Baldocchi

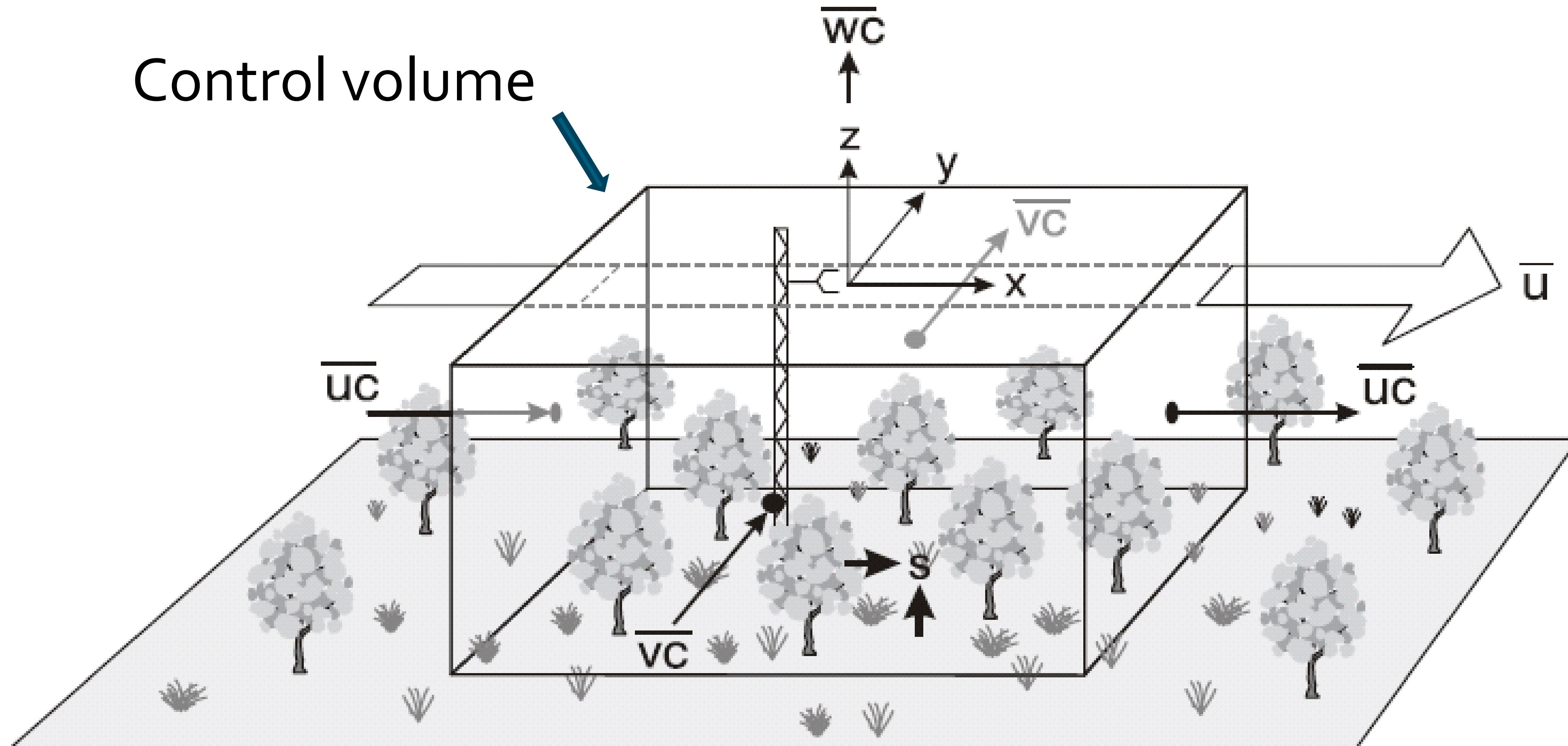

W
H2O
California Grassland DOY 104 2003, T1100
w (m/s)
H2O (mmol/m3)
4
3
2
1
0
-1
-2
1000
900
800
700
600
500
400
1400
1420
1440
1460
1480
1500
1520
1540
1560
1580
1600
Time (s)


W
Tsonic
California Grassland DOY 104 2003, T1100
w (m/s)
Tsonic (deg C)
4
3
2
1
0
-1
-2
28
27
26
25
24
23
22
1400
1420
1440
1460
1480
1500
1520
1540
1560
1580
1600
Time (s)

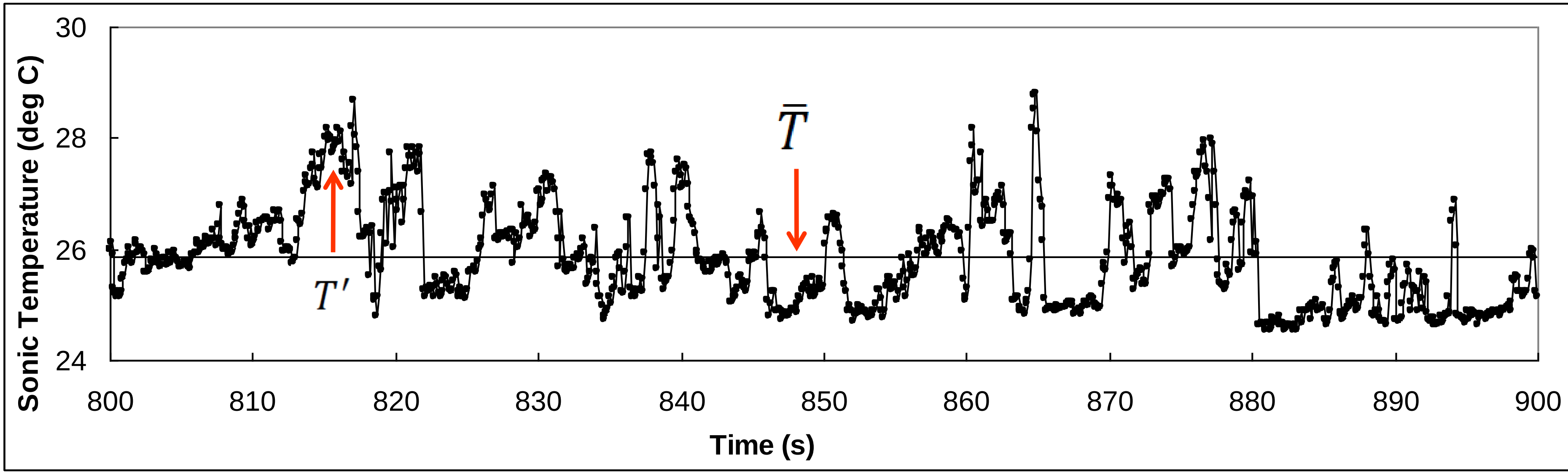
Basic assumptions:

1. no horizontal divergence or convergence,

2. $\frac{d\bar{C}}{dt} = 0$



Reynolds' Averaging Rules



$$x = \bar{x} + x' \qquad \overline{x'} = 0$$

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

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

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

EC theory: Complete equations

$$F = \overline{wc} \qquad F = \overline{(\bar{w} + w')(\bar{c} + c')}$$

$$F = \overline{\bar{w}\bar{c} + \bar{w}c' + w'\bar{c} + w'c'}$$

$$\bar{w} = 0 \qquad \overline{w'} = 0$$

$$F = \overline{w'c'} = \frac{1}{18000}\sum_{i=1}^{18000}(w - \bar{w})(c - \bar{c})$$

$$\frac{m}{s} \times \frac{\mu mol\ CO_2}{m^3} = \frac{\mu mol}{m^2 s}$$

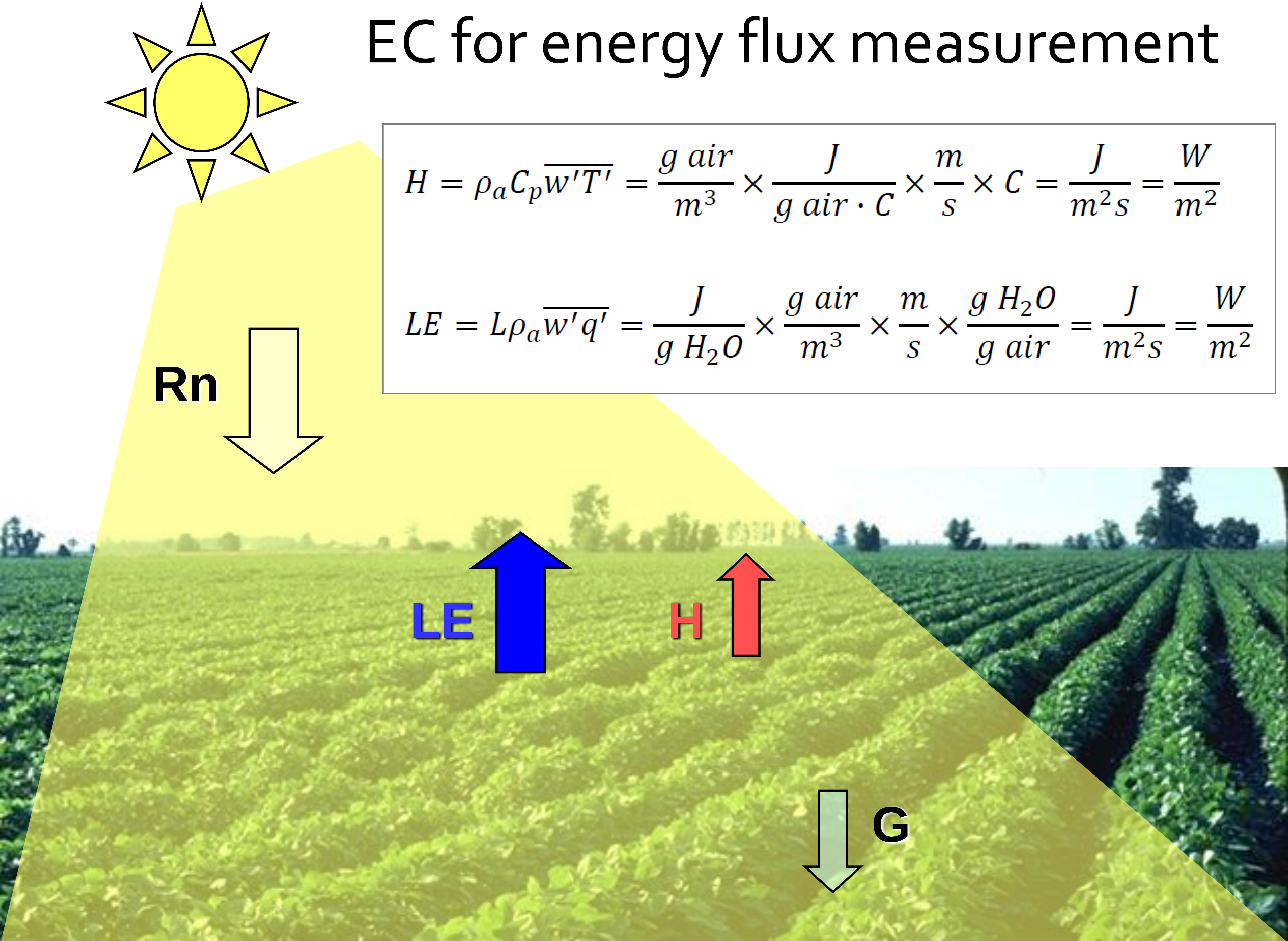
Density unit!

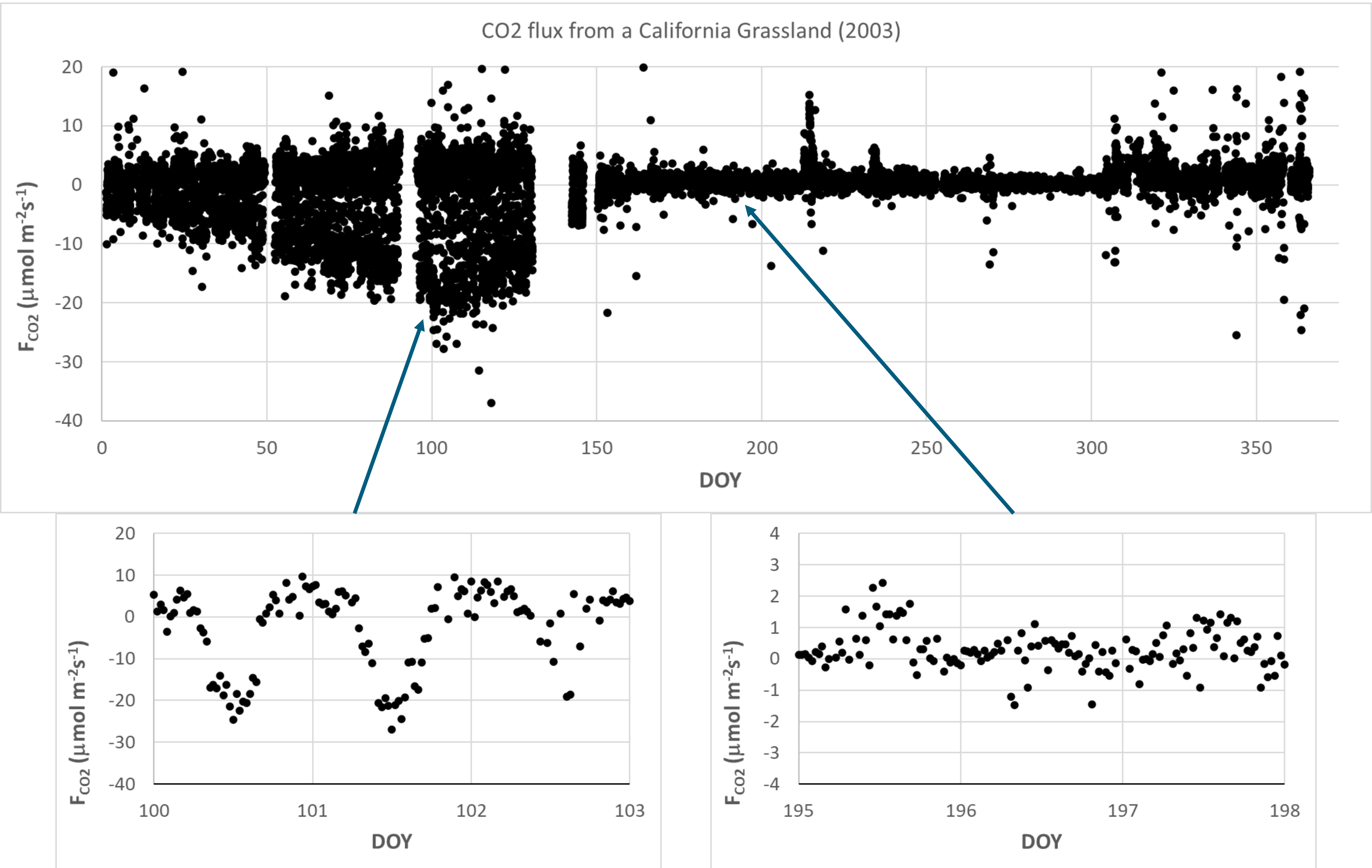
Time	CO_2 (mmol m^{-3})	W (m s^{-1})	CO_2'	W'	$W'CO_2'$	
0	15.511	-0.253	0.108	-0.253	-0.027	
0.1	15.483	-0.348	0.080	-0.348	-0.028	
0.2	15.442	-0.290	0.039	-0.290	-0.011	
0.3	15.420	-0.052	0.017	-0.052	-0.001	
0.4	15.414	0.091	0.012	0.091	0.001	
0.5	15.409	0.159	0.006	0.159	0.001	
0.6	15.401	0.276	-0.002	0.276	-0.001	
0.7	15.407	0.401	0.004	0.401	0.002	
0.8	15.403	0.496	0.001	0.496	0.000	
.	.	.	.	.	.	
.	.	.	.	.	.	
1800	15.369	0.212	-0.034	0.212	-0.007	
mean	**15.403**	**0.000**		$\overline{w'CO_2'} =$	**-0.014**	**(mmol $m^{-2}s^{-1}$)**

EC for energy flux measurement

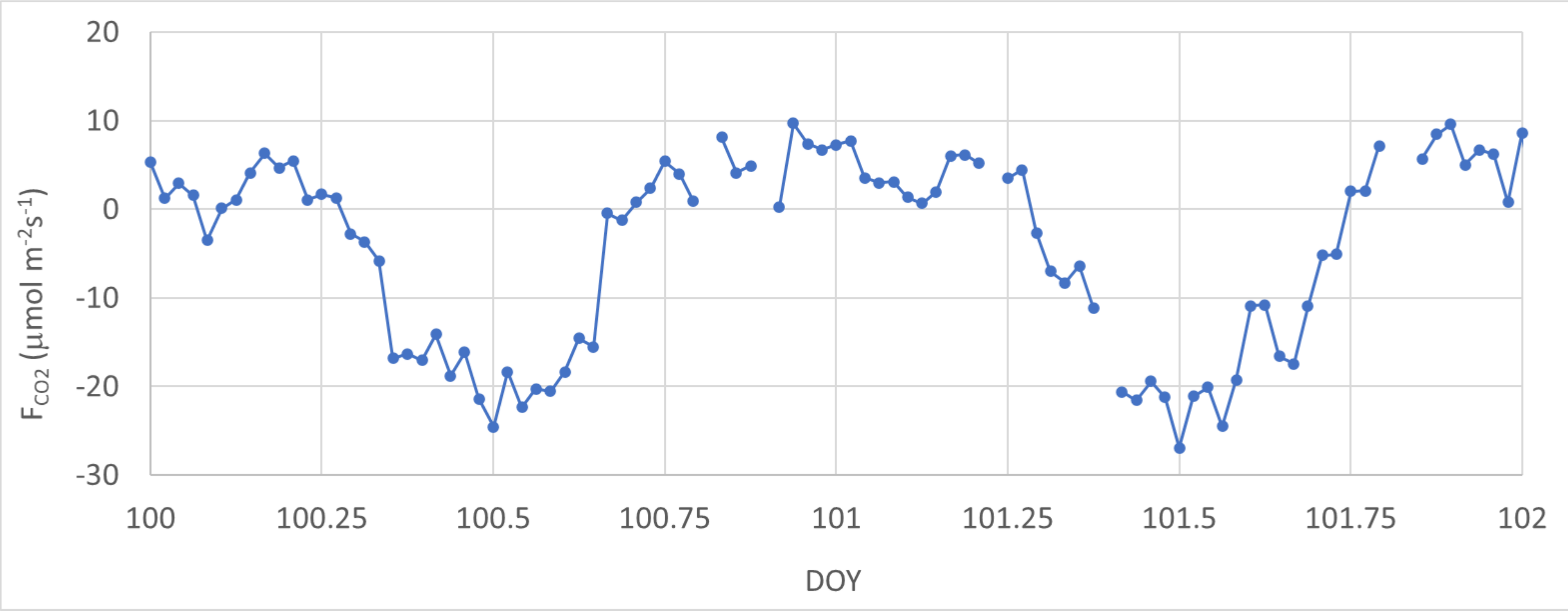
$$H = \rho_a C_p \overline{w'T'} = \frac{g\ air}{m^3} \times \frac{J}{g\ air \cdot C} \times \frac{m}{s} \times C = \frac{J}{m^2 s} = \frac{W}{m^2}$$

$$LE = L\rho_a \overline{w'q'} = \frac{J}{g\ H_2O} \times \frac{g\ air}{m^3} \times \frac{m}{s} \times \frac{g\ H_2O}{g\ air} = \frac{J}{m^2 s} = \frac{W}{m^2}$$

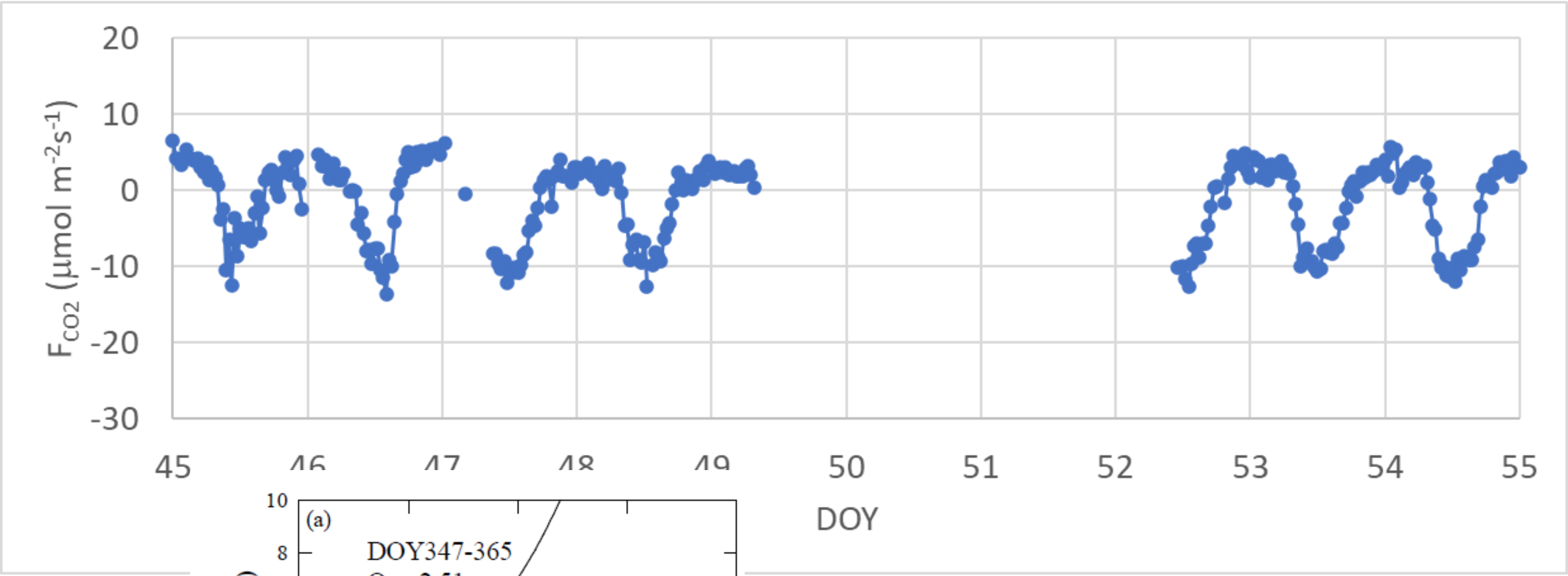


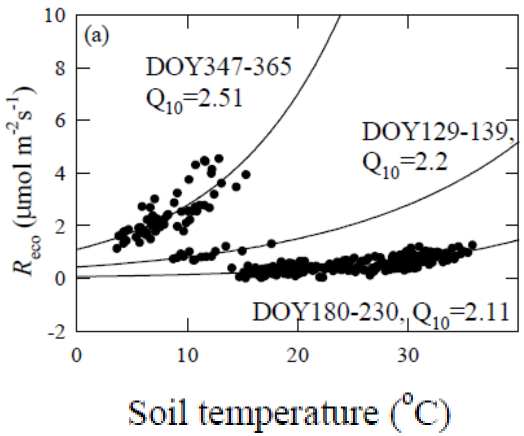

CO2 flux from a California Grassland (2003)
F_{CO2} (µmol m^{-2}s^{-1})
DOY
20
10
0
-10
-20
-30
-40
0
50
100
150
200
250
300
350
100
101
102
103
195
196
197
198
4
3
2
1
-1
-2
-3
-4
LI-COR

Gap filling for short time

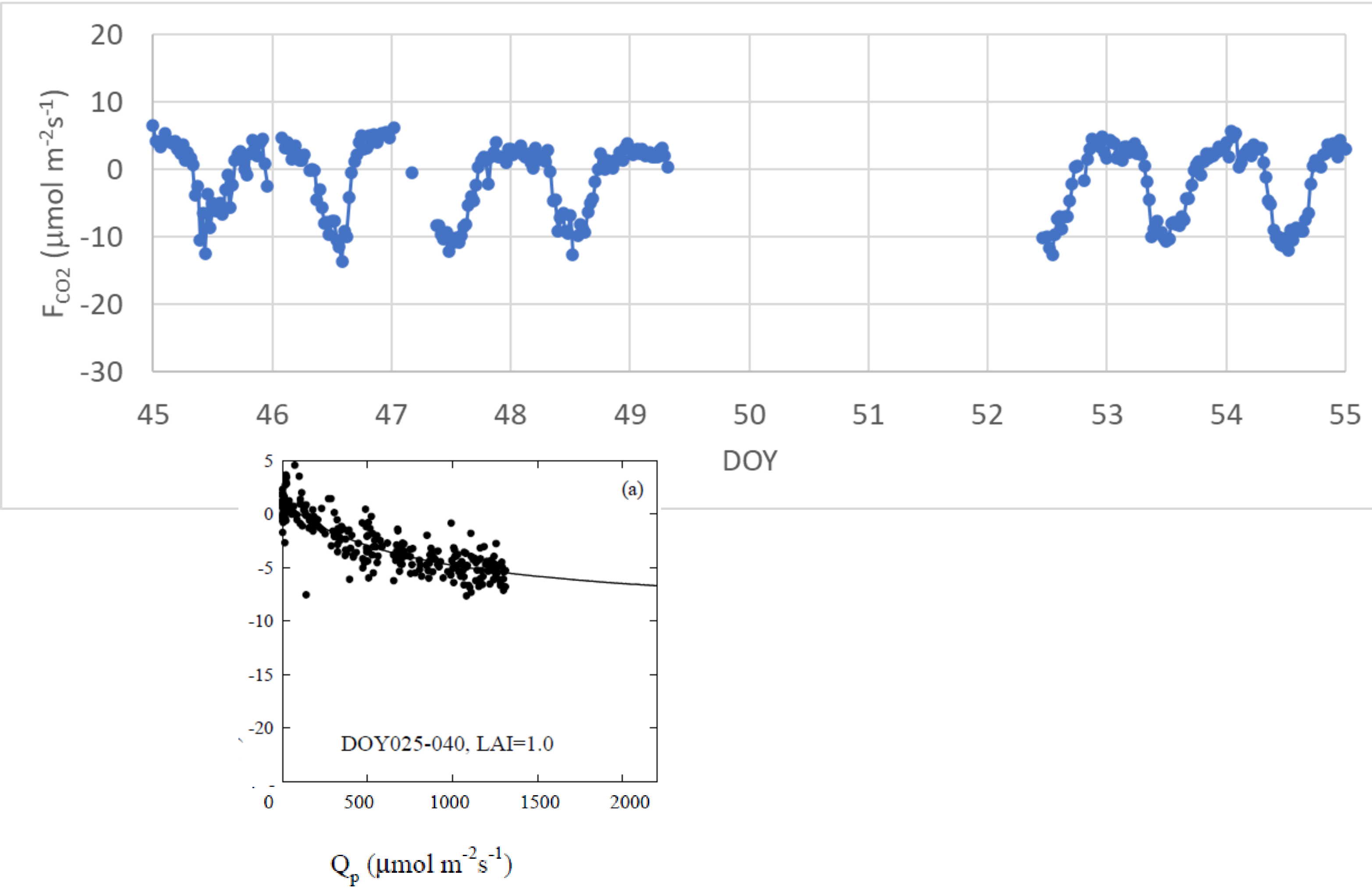


Gap filling nighttime flux data



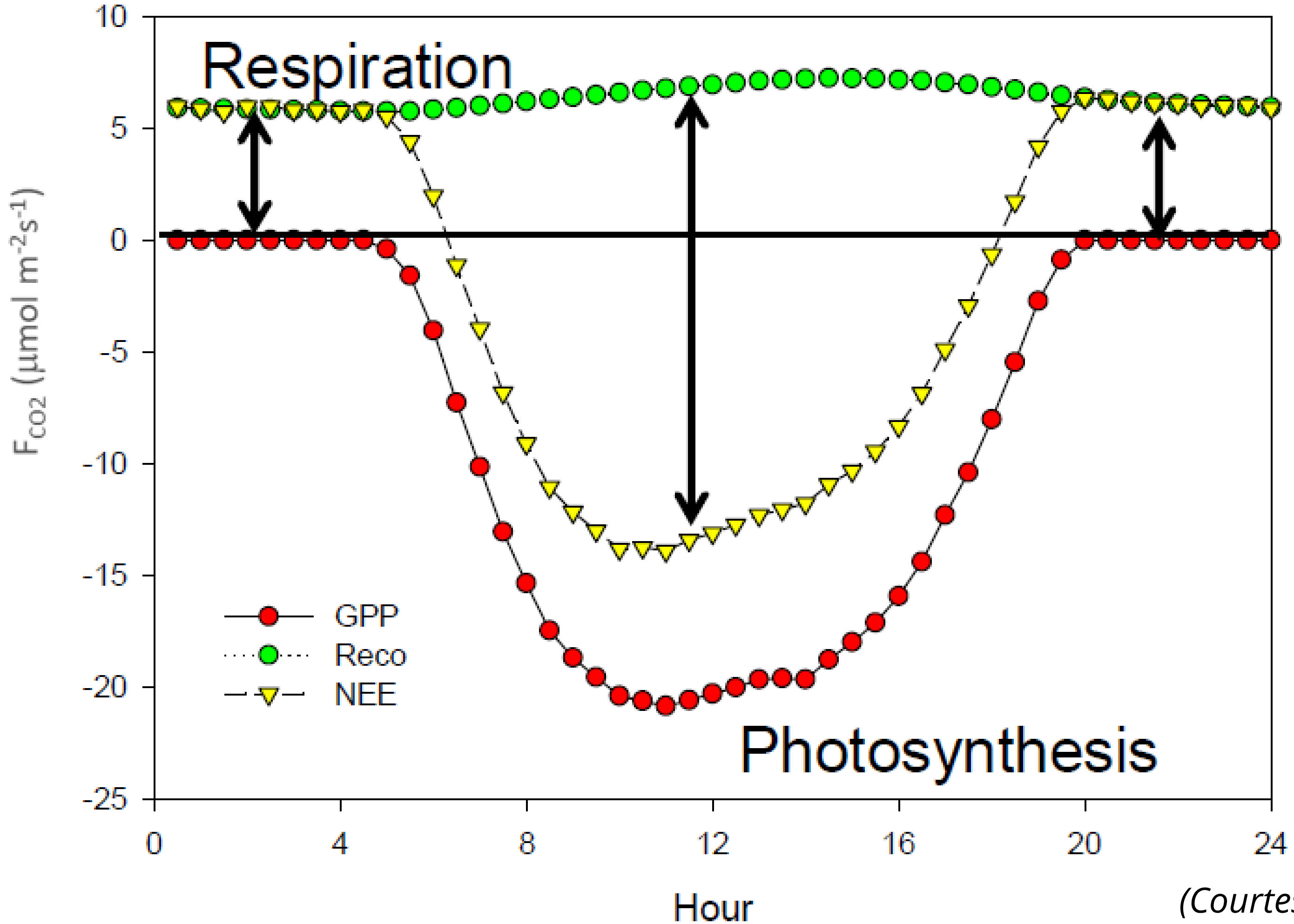


Gap filling daytime flux data



GPP estimation

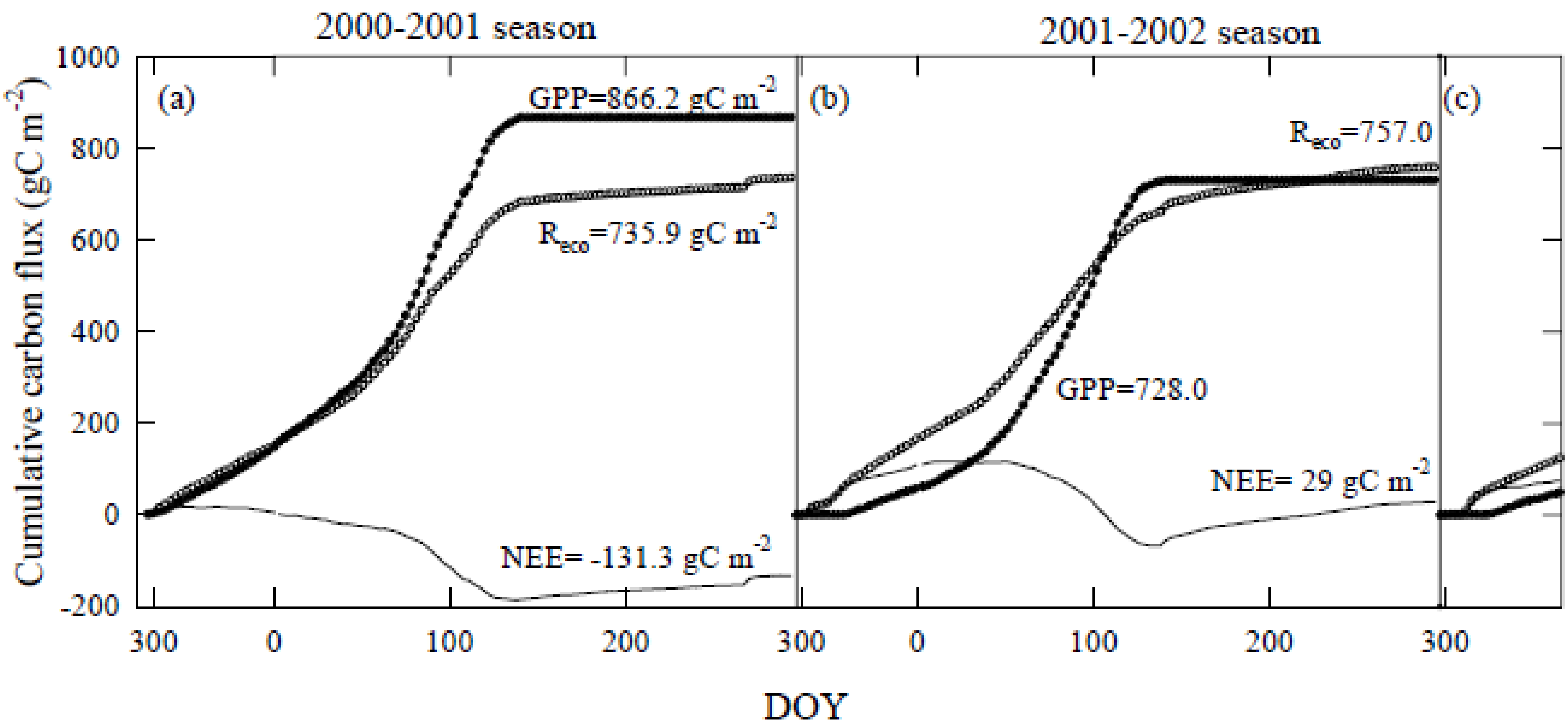
$$GPP = R_{eco} - NEE$$



(Courtesy of Dr. Baldocchi)

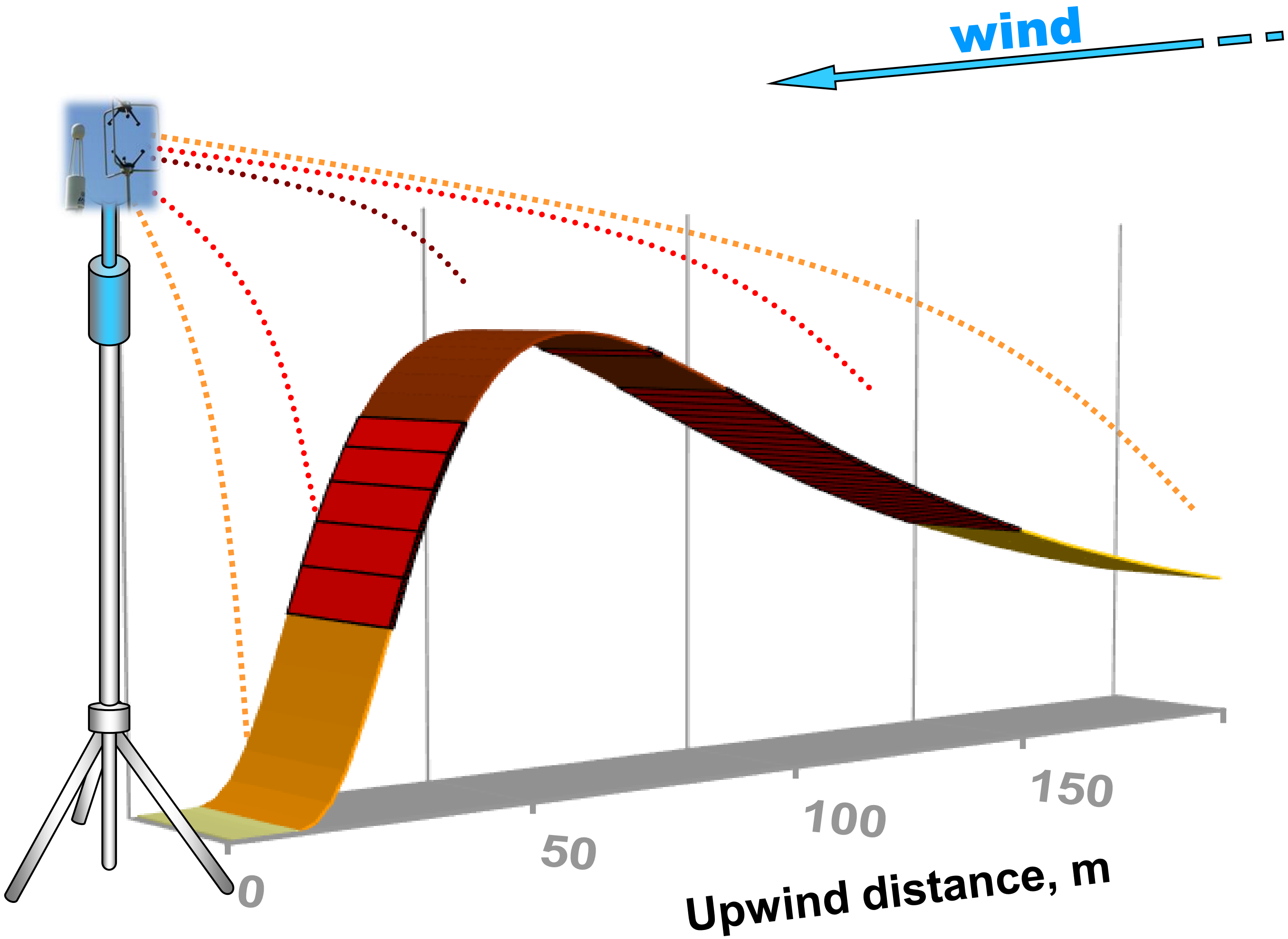
Example of long-term flux data (2000-2003)
California grassland

L. Xu, D.D. Baldocchi / Agricultural and Forest Meteorology 1232 (2004) 79–96

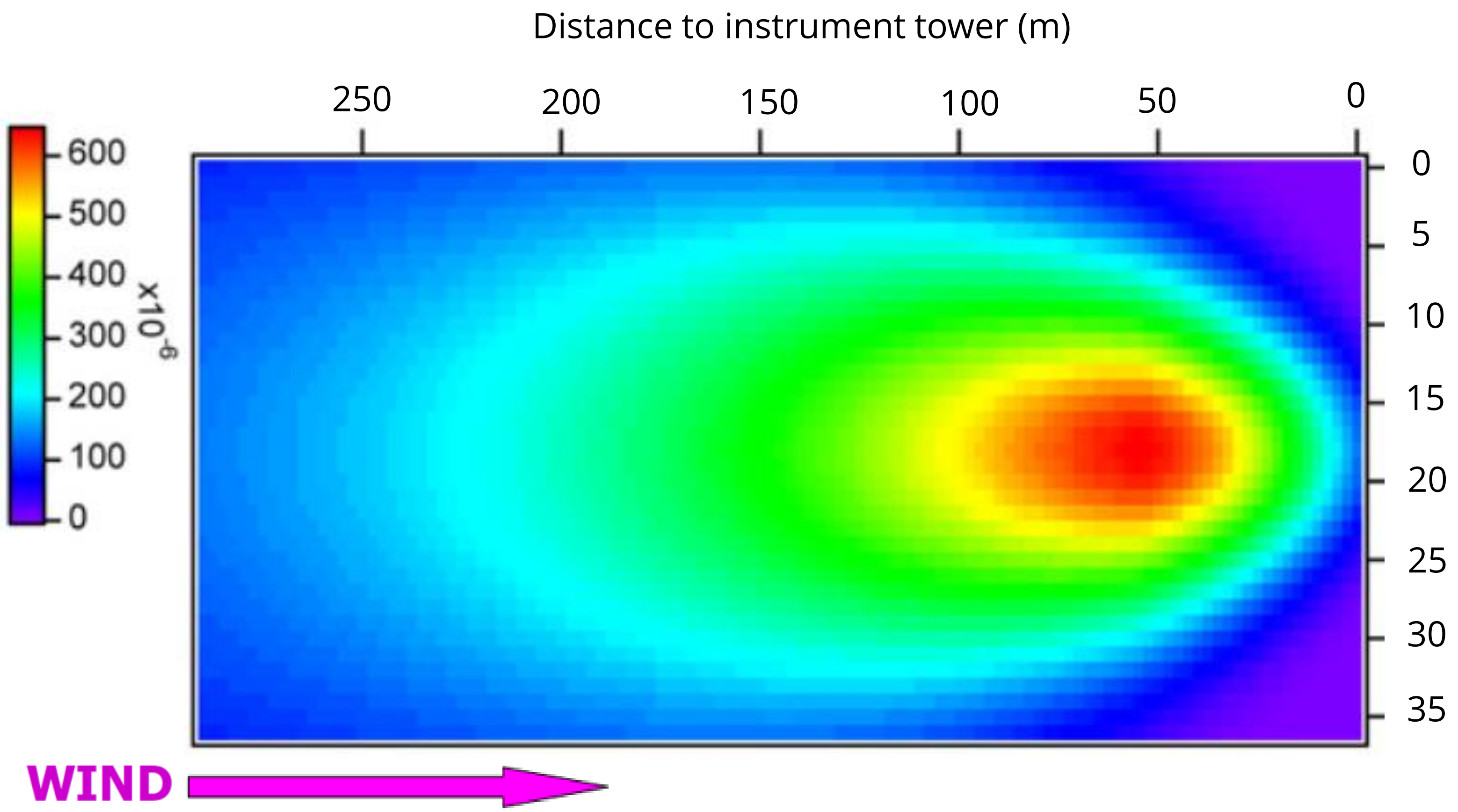


No disturbance to your ecosystem: > 10,000 m^2

The footprint is defined as the relative contribution at different location (in the upwind direction) to the measured vertical flux



Footprint of EC measurement-2D



LI-COR®

Advantages of the EC Method

1. Direct measure of the flux density
2. *in situ*
3. No disturbance to your ecosystem
4. Continuous
5. Represents a large upwind area

Disadvantages of the EC Method

1. Nighttime low turbulent conditions
2. Complex terrain affects your measurement
3. Cannot be used over a small area

Summary

1. Eddy covariance theory – Basic micrometeorology theory
2. Examples of long-term flux measurements
3. Gap filling
4. $GPP=R_{eco}-NEE$
5. Advantages of EC method

Q & A