Chinaflux第十五次通量观测理论与技术培训

Eddy Covariance Method: The Basics

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Aug 24, 2020

Outline

1. Eddy covariance theory – Basic micrometeorology theory
2. EC data processing principles; including de-spiking,

   coordinate rotation, density correction (WPL), etc

4. Spectra analysis
5. QA/QC
6. Examples of long-term flux measurements

Terminology and units

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

Mole Fraction: μmol CO_2 per mol total air, ppm, ppb
Dry Mole Fraction: μmol CO_2 per mol dry air, ppm, ppb
摩尔比

Terminology and units for CO_2 and CH_4 flux

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

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

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

Terminology and units for energy flux

Net radiation (R_{net}): (净辐射)	W m^{-2}
Sensible heat flux (H): (显热， 感热)	W m^{-2} (J m^{-2} s^{-1})
Latent heat flux (LE): (潜热)	$LE = \lambda E$ (W m^{-2})
Soil heat flux (G): (土壤热通量)	W m^{-2}

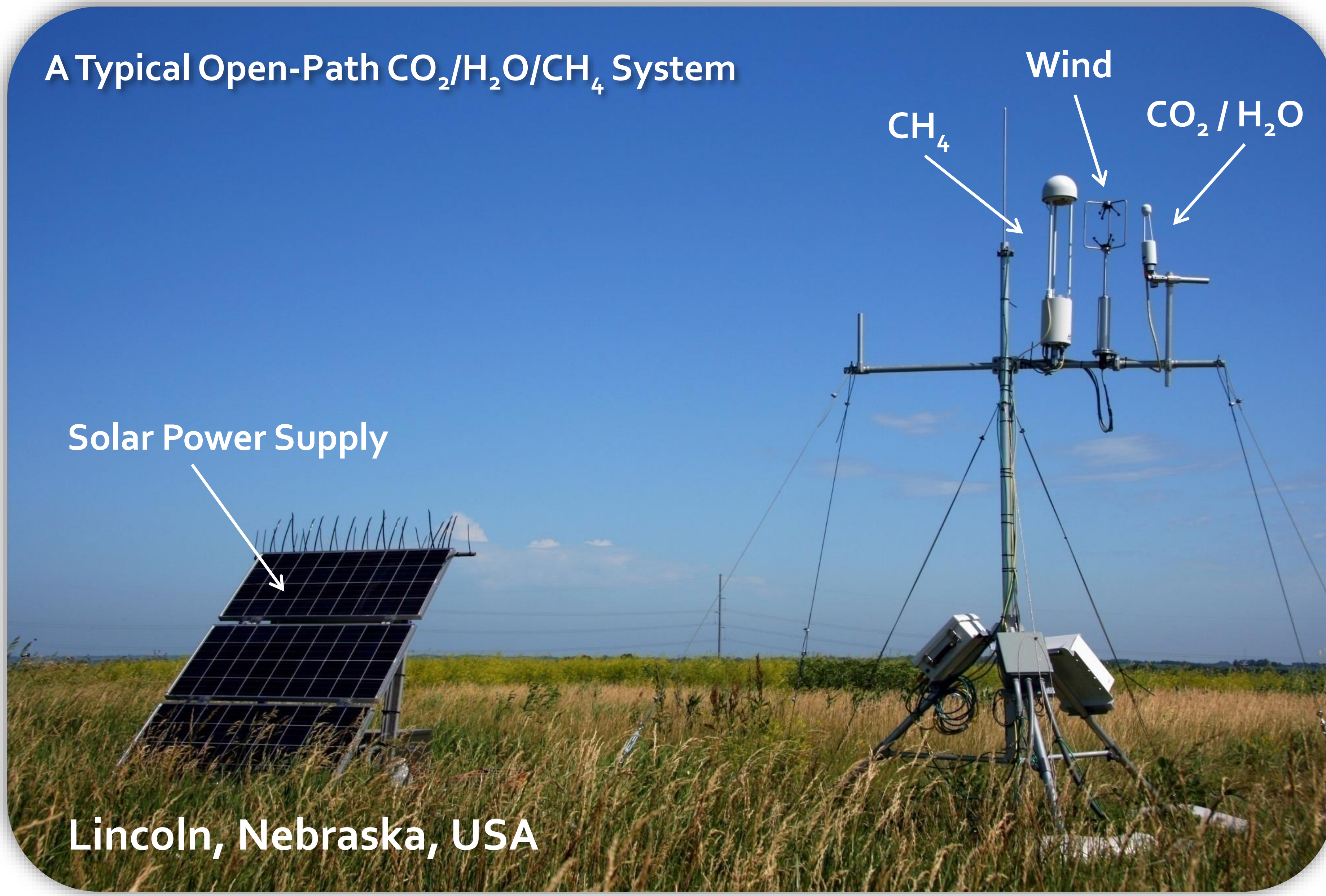
Definition of variance and covariance

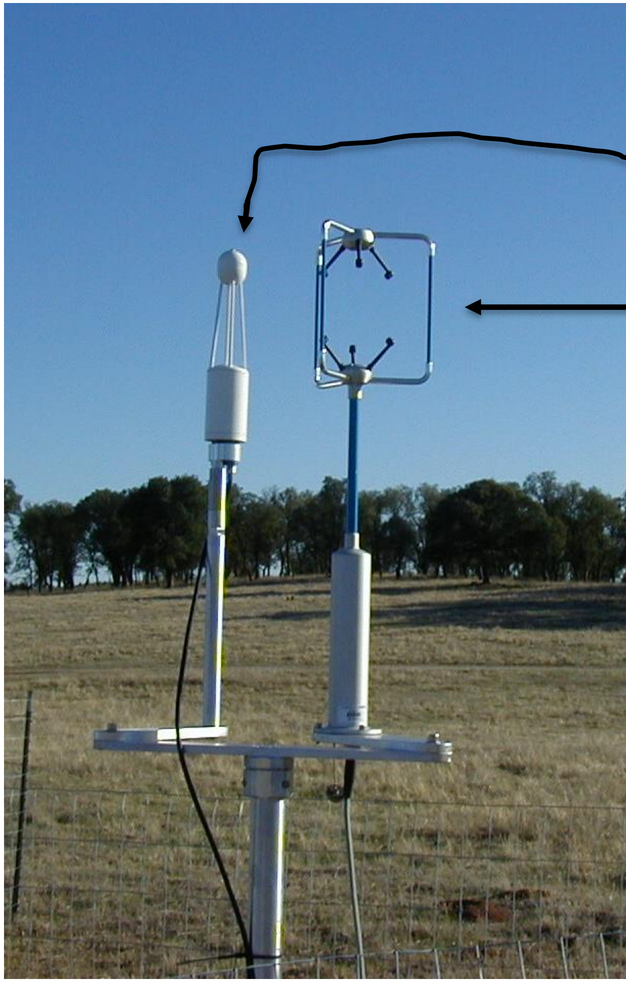
$x_1, x_2, x_3, x_4 \ldots\ldots\ldots\ldots x_n$

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

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

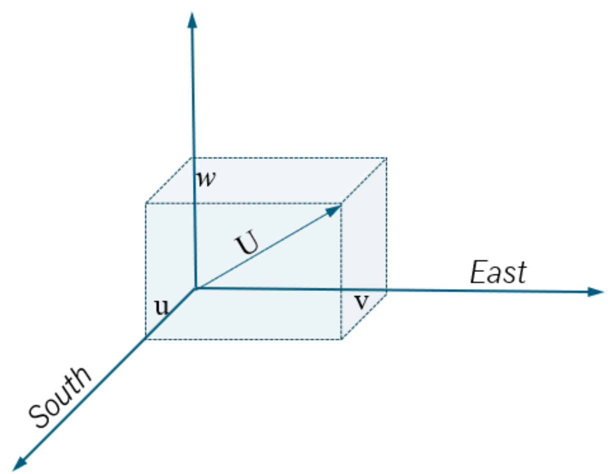

A Typical Open-Path CO_2/H_2O/CH_4 System
Wind
CH_4
CO_2 / H_2O
Solar Power Supply
Lincoln, Nebraska, USA



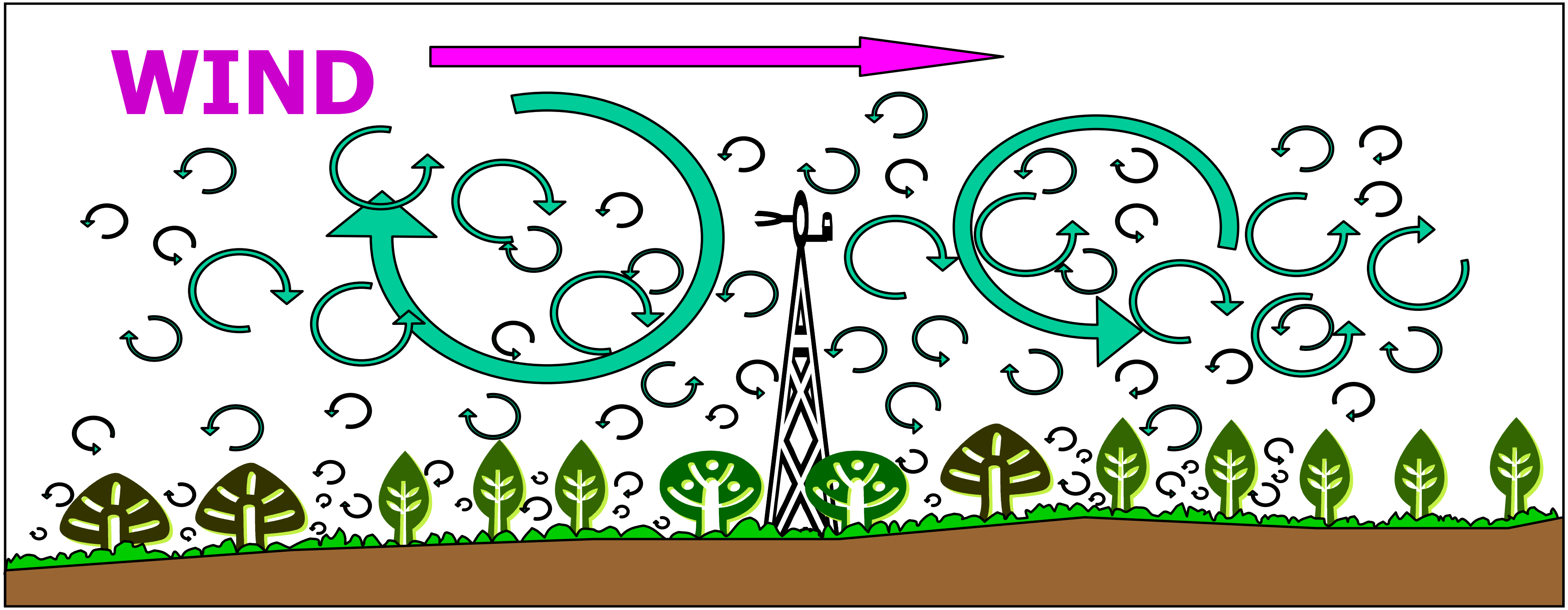
LI-7500: measures CO_2 and H_2O concentration

Sonic anemometer: u, v, w, sonic temperature

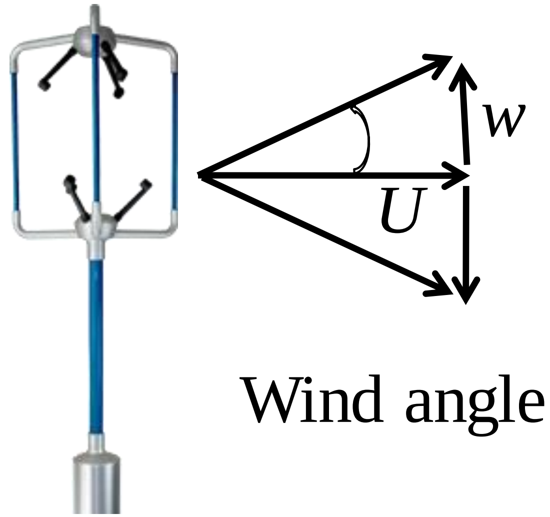
10 Hz data logging

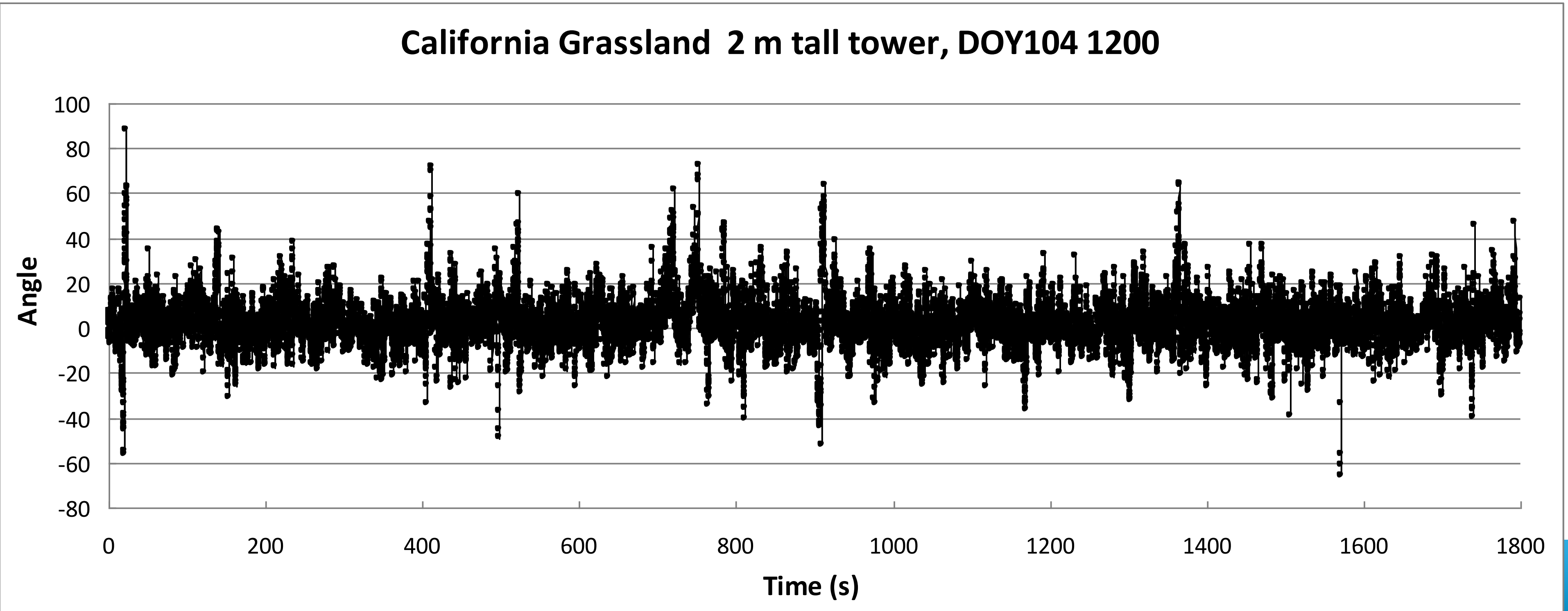


Eddy Covariance flux measurement

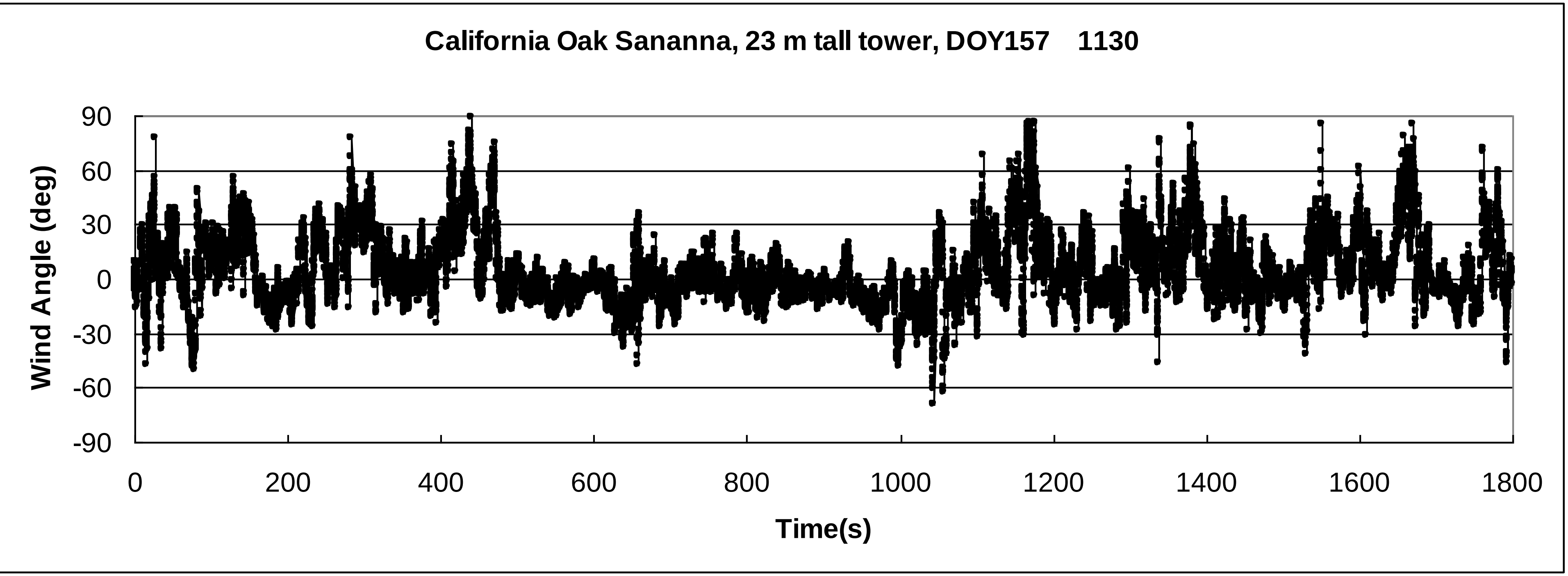


Here is more 10-Hz raw data…





More on wind angle…



Vertical profile for environmental variables

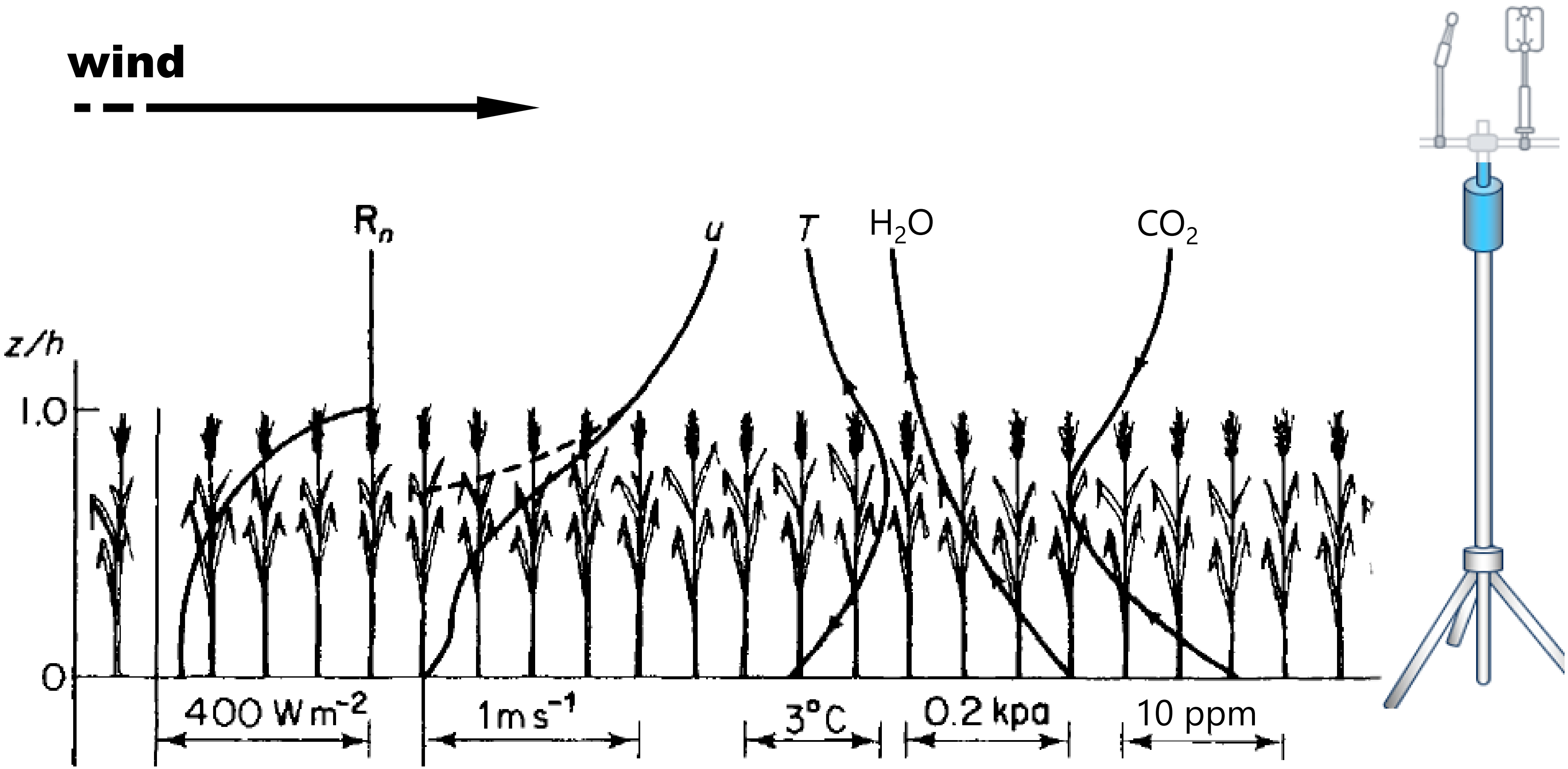
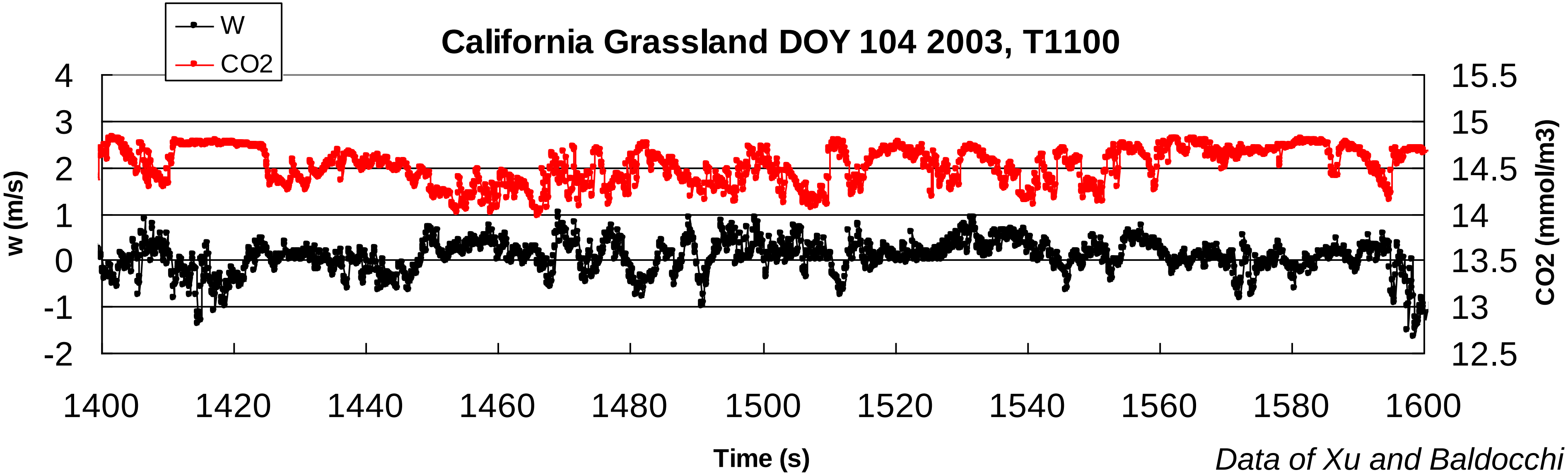


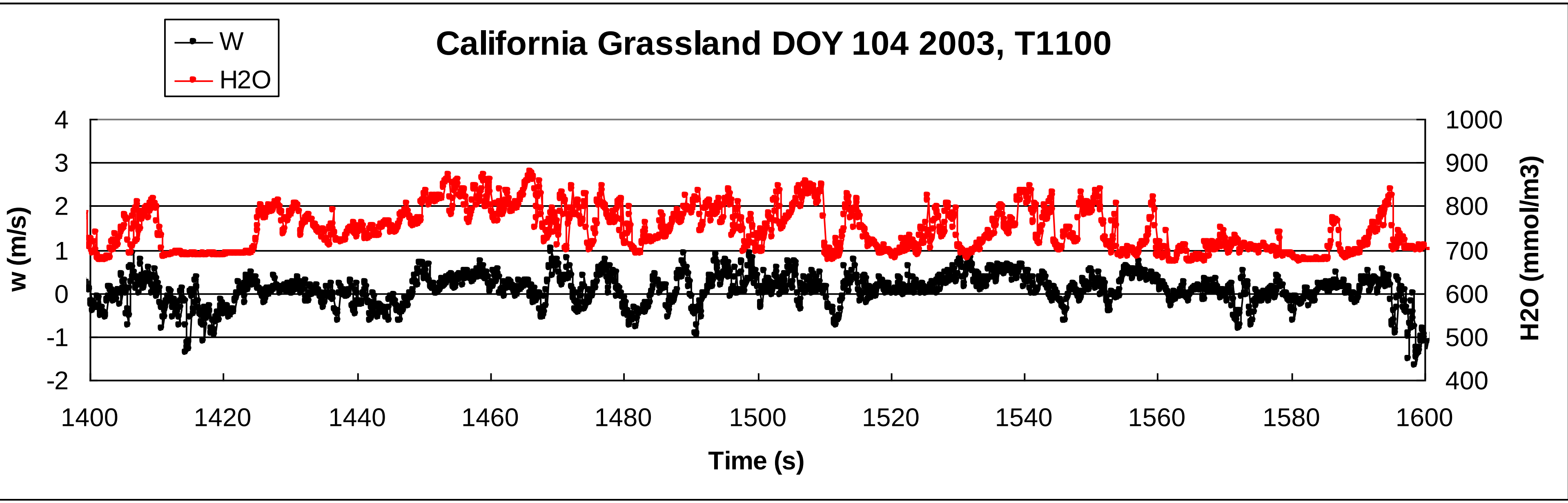
Fig. 16.5. Monteith and Unsworth , 2013. Environmental Physics.

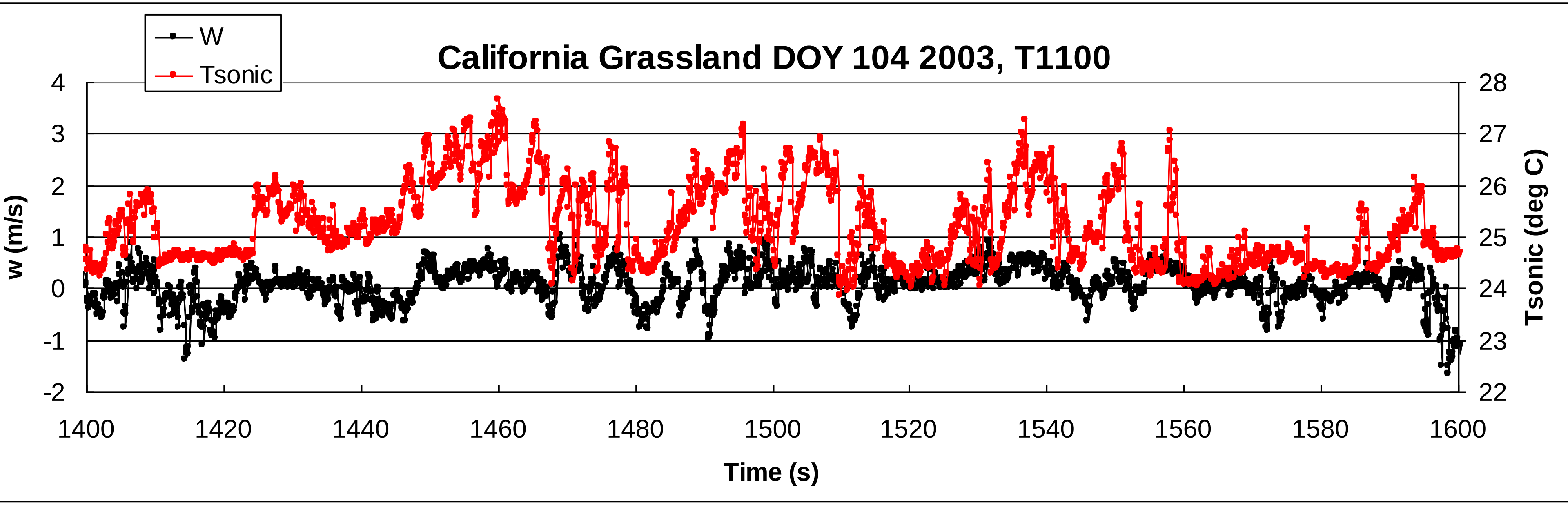
Let's see some 10-Hz real data!

courtesy of Dr. Youngryel Ryu

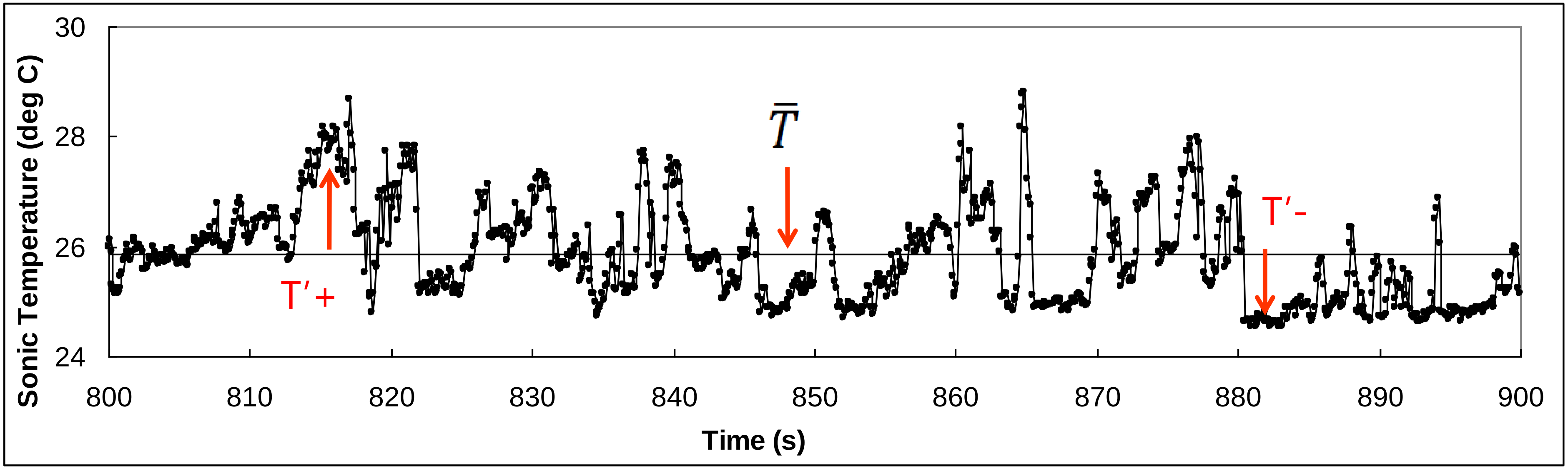


Data of Xu and Baldocchi


W
H2O
California Grassland DOY 104 2003, T1100
w (m/s)
H2O (mmol/m3)
Time (s)
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


W
Tsonic
California Grassland DOY 104 2003, T1100
w (m/s)
Tsonic (deg C)
Time (s)
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

Reynolds' Averaging Rules



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

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

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

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

Covariance; 协方差

EC theory: Complete equations

$$F = \overline{wc}$$

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

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

Mean of w is zero

The average of deviation from the mean is zero

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

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

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})**

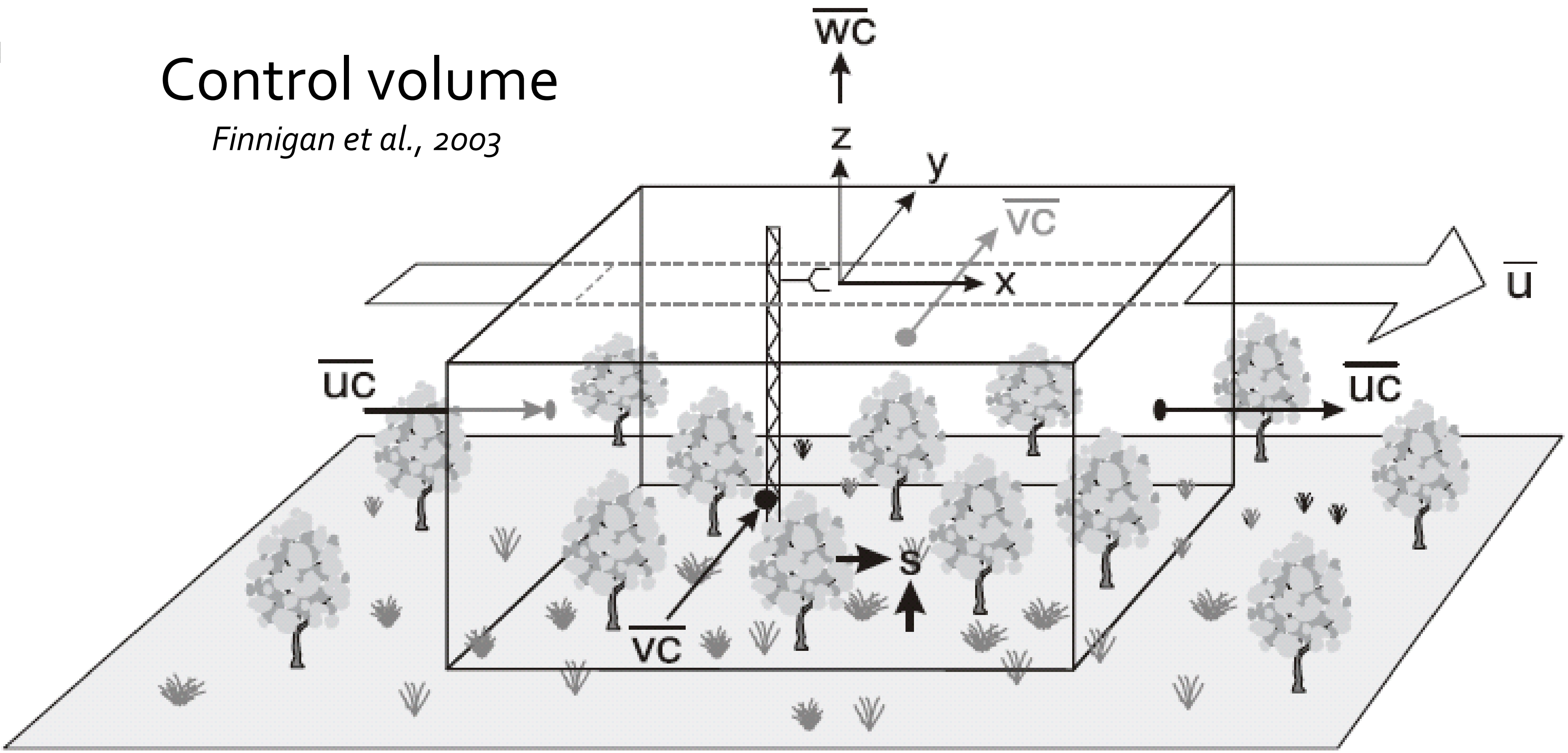
Basic assumptions:

1. no horizontal divergence or convergence,

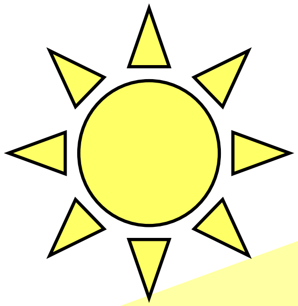
2. $\frac{d\bar{C}}{dt} = 0$ (Storage term = 0)

Control volume

Finnigan et al., 2003

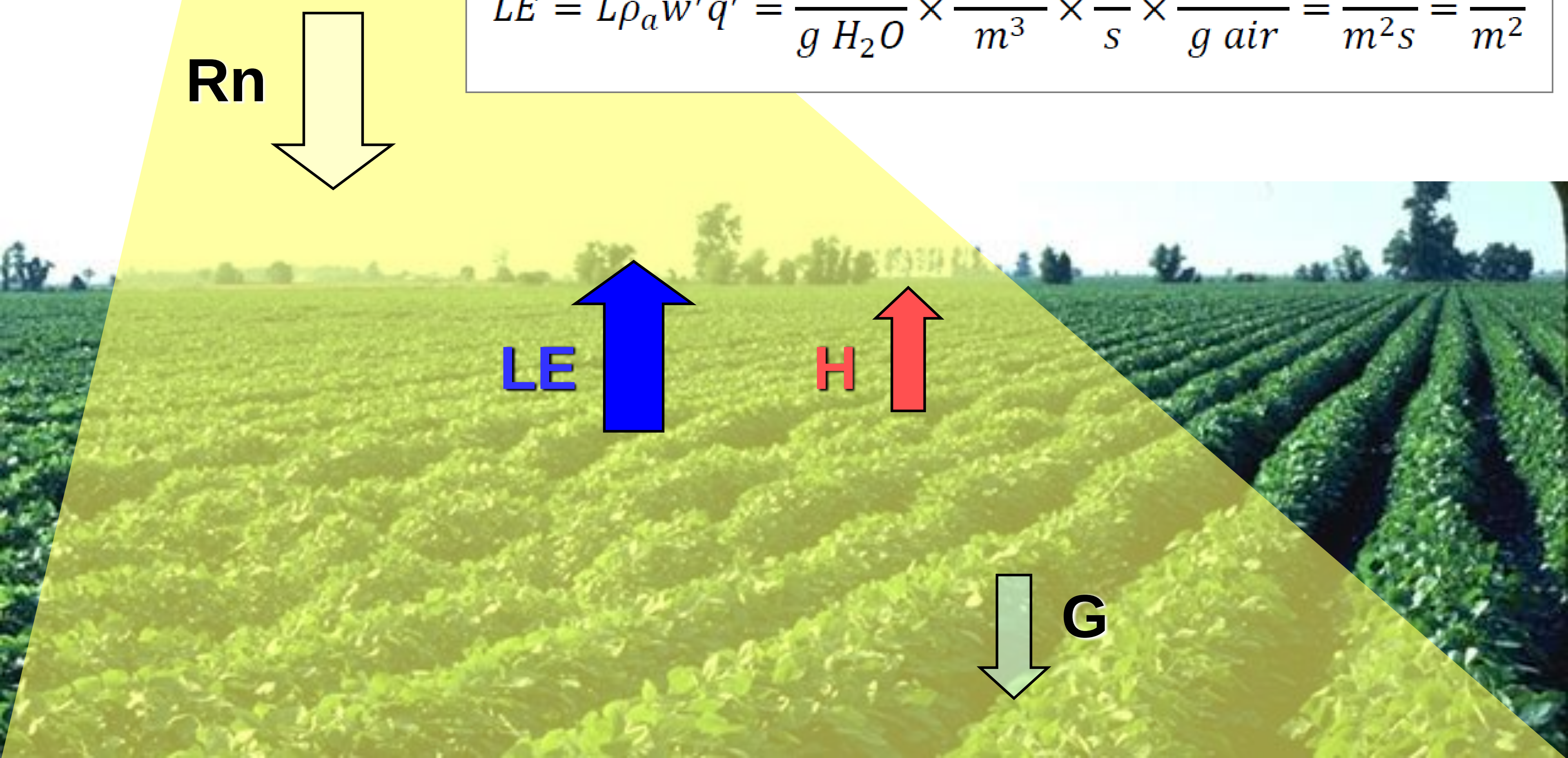


EC for energy flux measurement



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

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

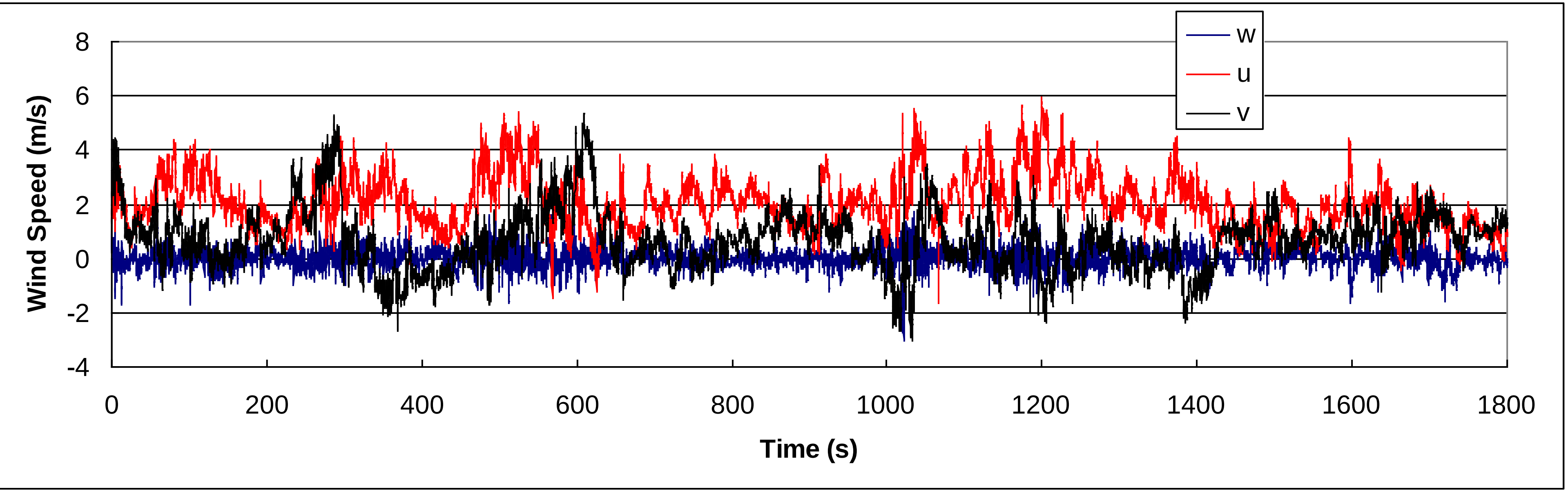


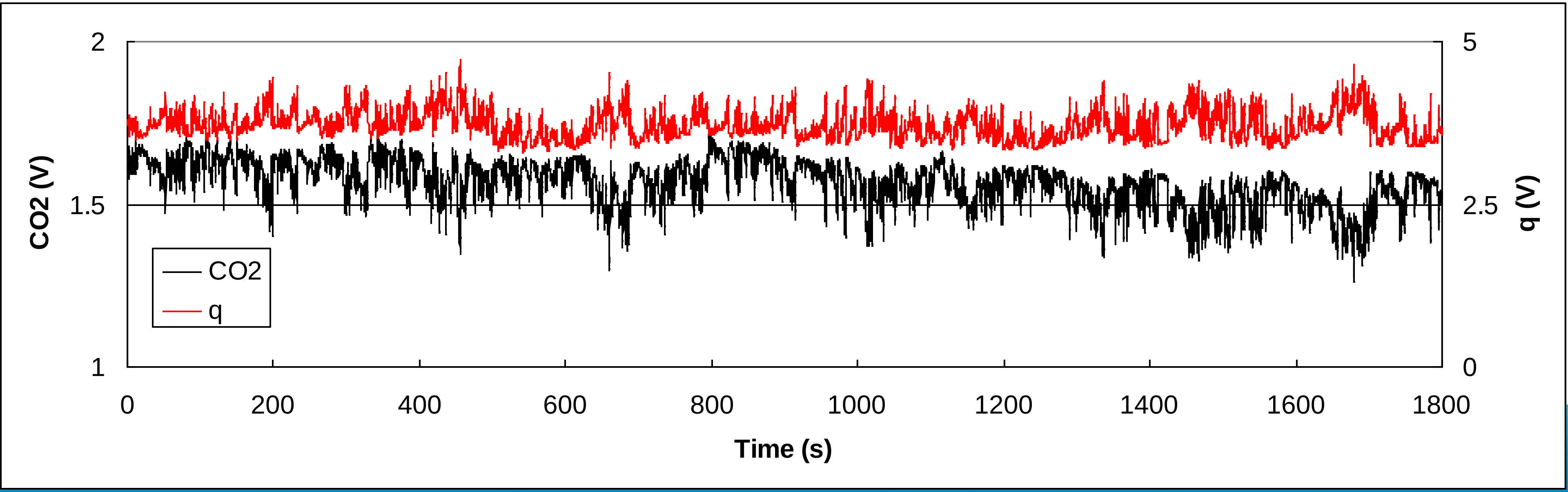
Fluxes from EC technique

- *Gas flux:* F_{CO2}, *ET*, F_{CH4},

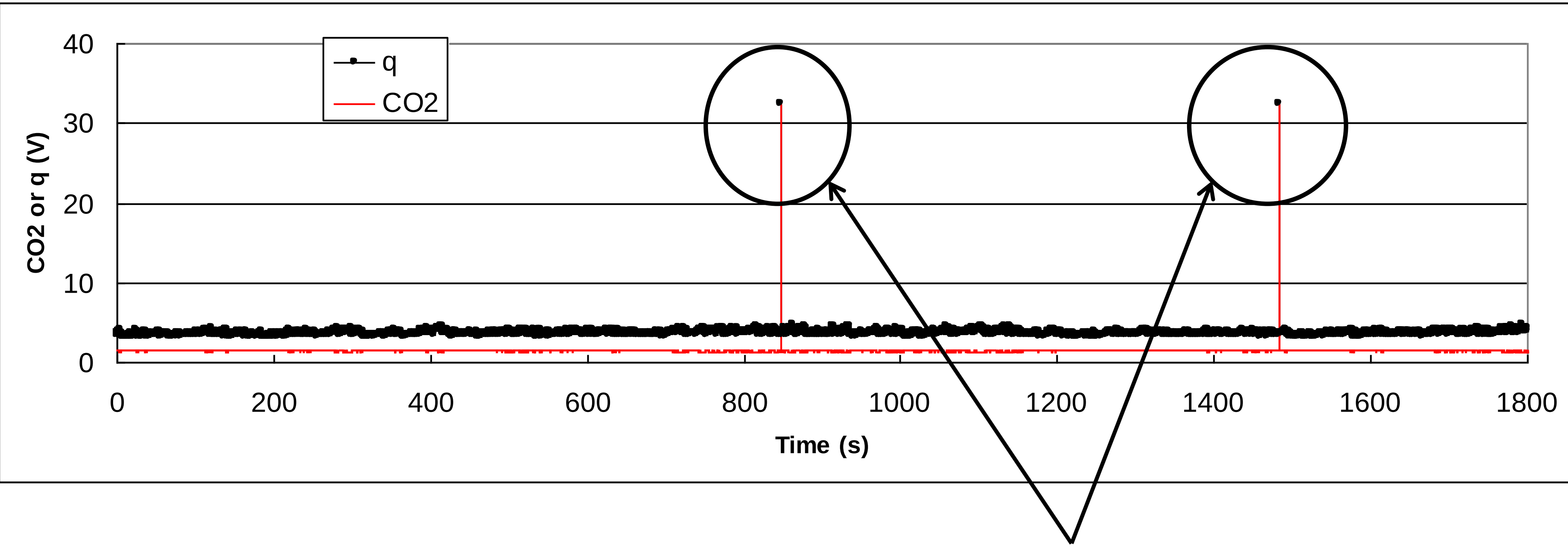
- *Energy flux: H, LE, G,* R_n

Data Processing: de-spiking





Data Processing: de-spiking …sometimes, you see this

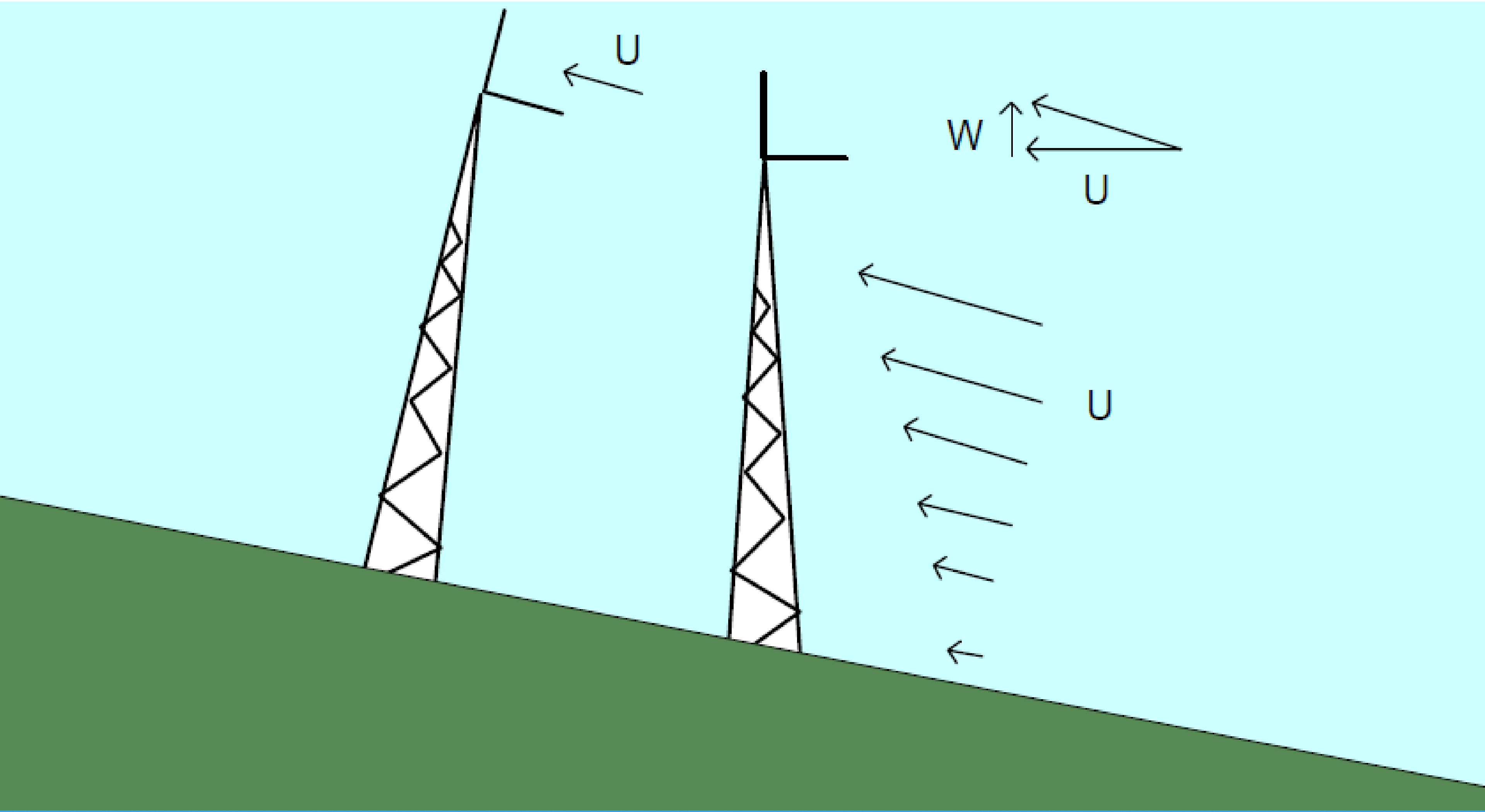


We need to get rid of spikes.

Data Processing: de-spiking

- unreasonable *u*, *v*, *w*
- abs(*u*′, *v*′, *w*′) > *n*x std; *n* = 4 - 6
- Abs (CO_2′, H_2O′)>nxstd; n = 4-6
- other criteria

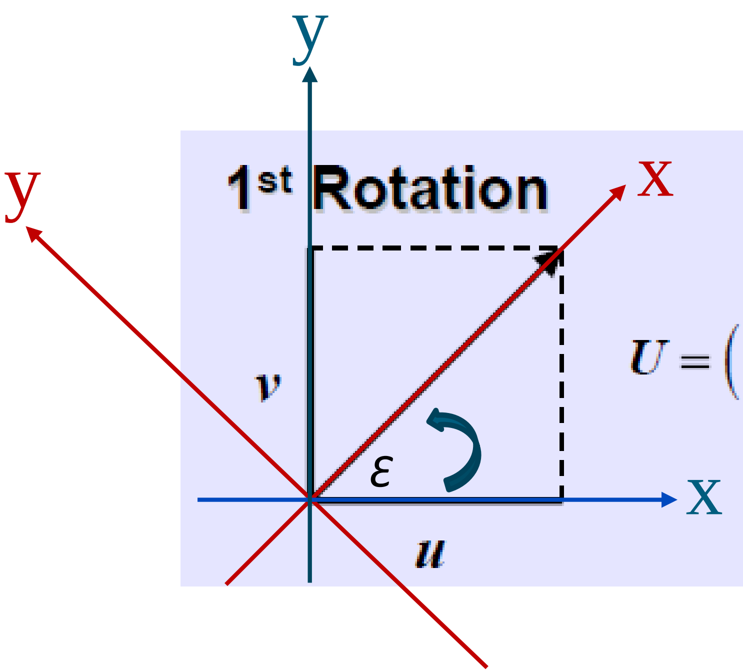
Data Processing: Coordinate rotation



Courtesy of Prof. Baldocchi

Data Processing: Coordinate rotation

1st Rotation



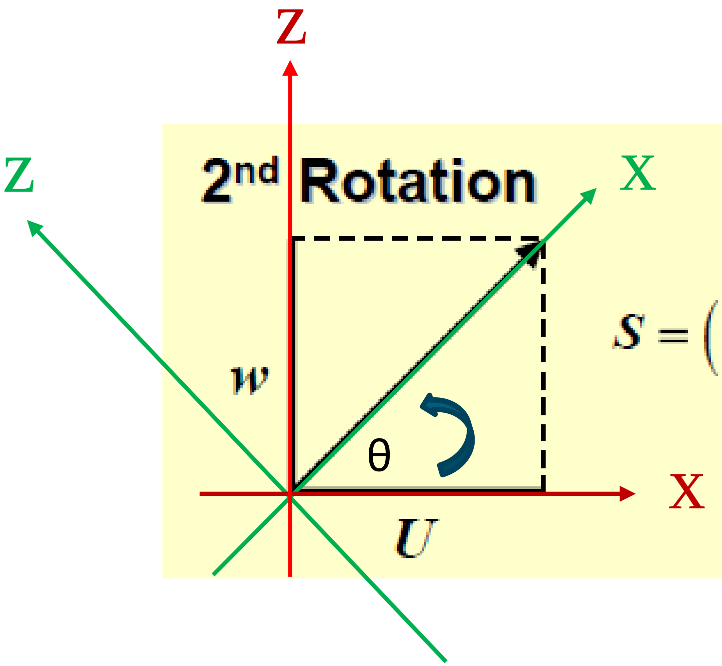
$$U = \left(u^2 + v^2\right)^{1/2}$$

$$\cos \varepsilon = \frac{u}{\left(u^2 + v^2\right)^{1/2}}$$

$$\sin \varepsilon = \frac{v}{\left(u^2 + v^2\right)^{1/2}}$$

Data Processing: Coordinate rotation

2nd Rotation



$$S = \left(u^2 + v^2 + w^2\right)^{\frac{1}{2}}$$

$$\cos\theta = \frac{U}{\left(u^2 + v^2 + w^2\right)^{\frac{1}{2}}}$$

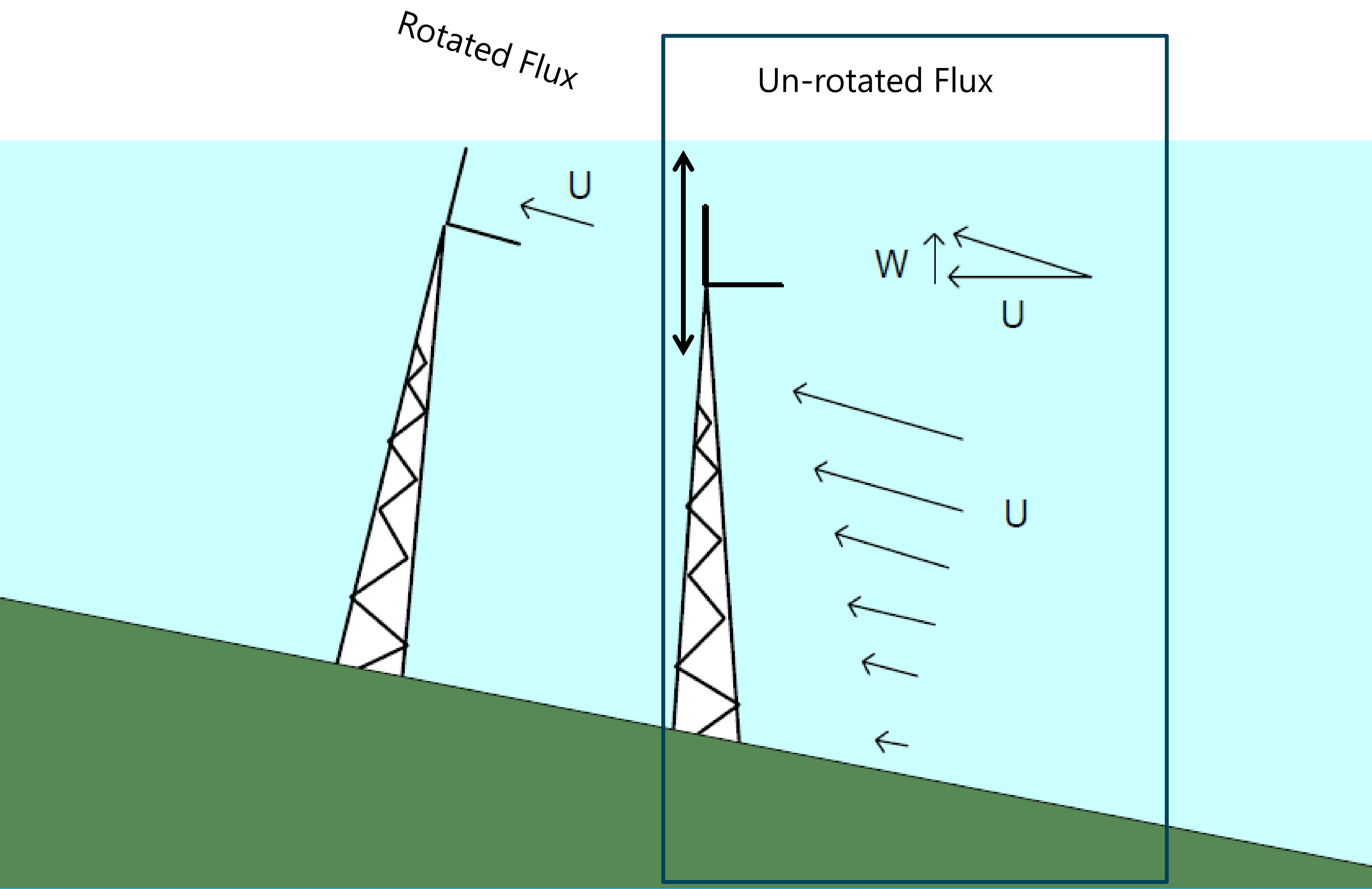
$$\sin\theta = \frac{w}{\left(u^2 + v^2 + w^2\right)^{\frac{1}{2}}}$$

Data Processing: Coordinate rotation

$$\overline{W'c'} = \overline{w'c'}cos\theta - \overline{u'c'}sin\theta cos\varepsilon - \overline{v'c'}sin\theta sin\varepsilon$$

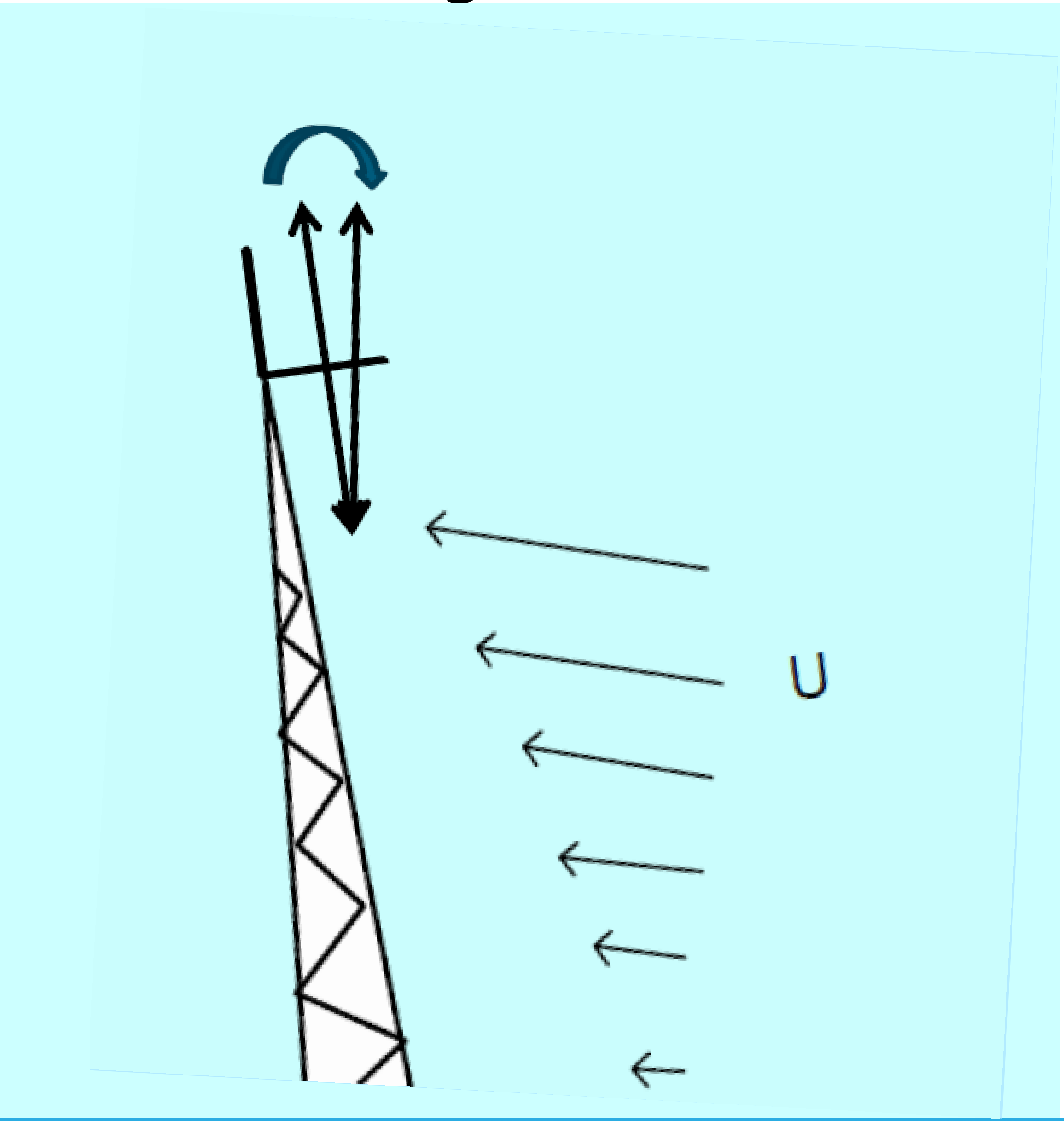
If the sonic is perfectly leveled along with the ground surface, then no coordinate rotation is needed!

However, this is very difficult to do, if not impossible. It is much easier to rotate the coordinates to force the mean of *w* to zero.



Courtesy of Prof. Baldocchi

Data Processing: Coordinate rotation

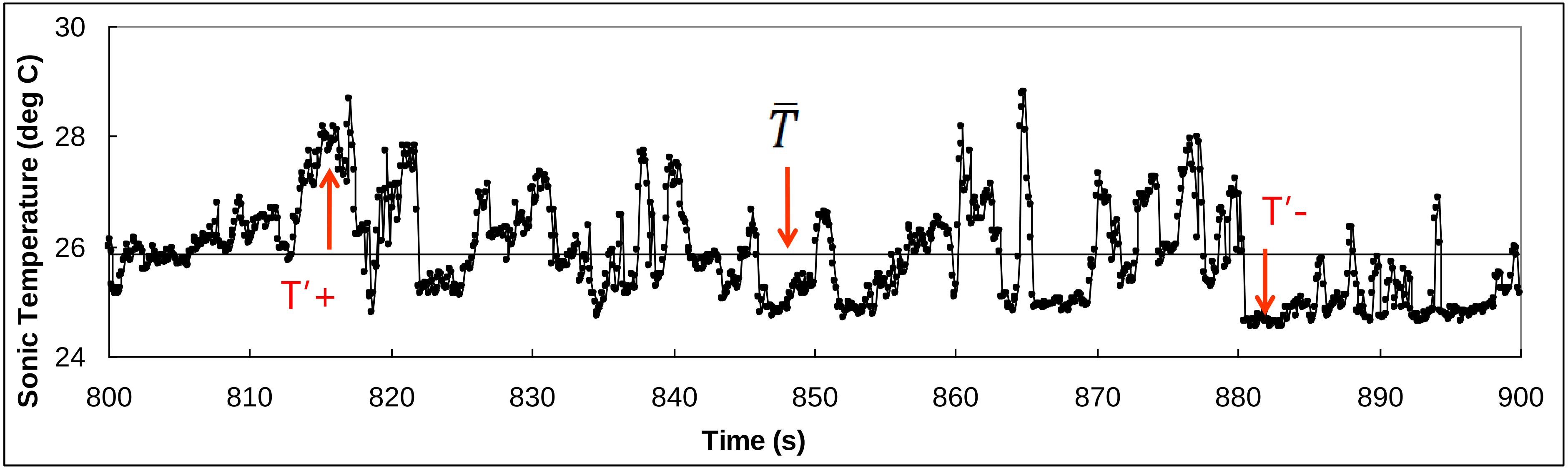


Data Processing: Coordinate rotation

To determine the flux normal to the underlying surface!

计算出垂直于下垫面的通量!

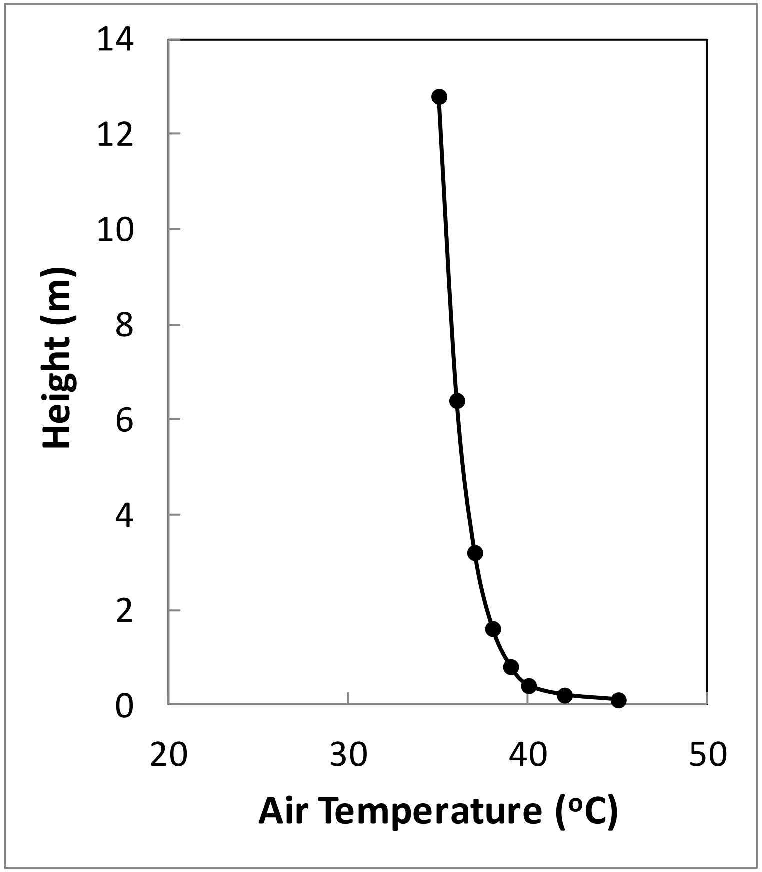
Reynolds' Averaging Rules



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

Covariance; 协方差

Density correction for open-path analyzer~ WPL



Imagine a situation: over a dry parking lot

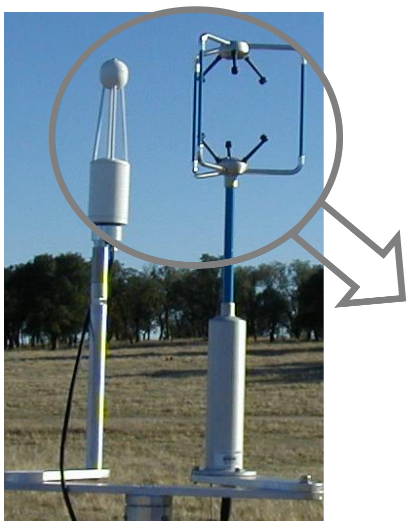
No CO_2 flux

Hot, dry summer afternoon

WPL due to sensible heat flux

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

LI-COR open-path analyzer measures density (mmol CO_2 m^{-3}). It changes with T, P.



W' –
T' –
$CO_2{}'$ +

W' +
T' +
$CO_2{}'$ –

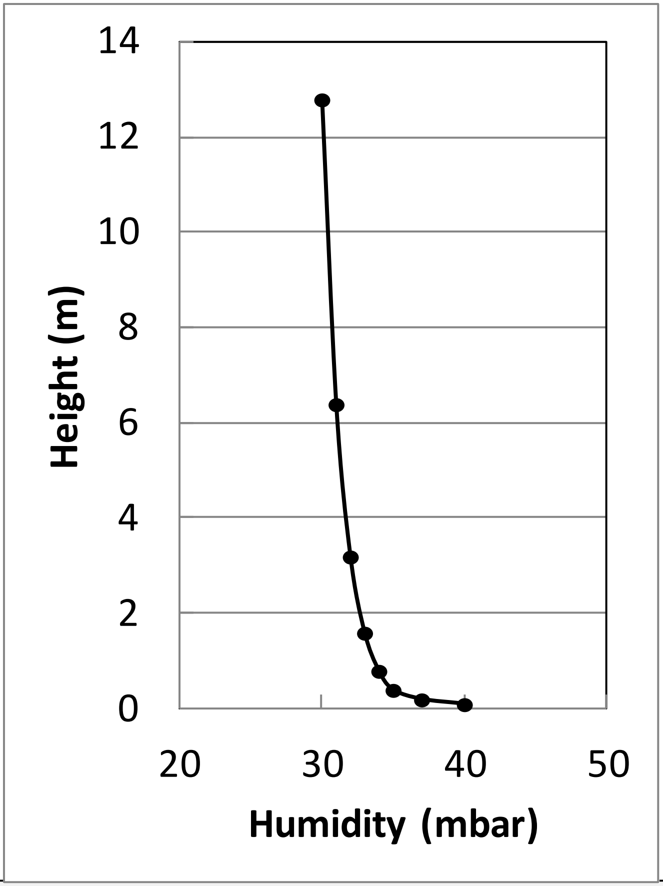
$\overline{w'CO_2{}'} < 0$, CO2 uptake?

Imagine a situation: over a dry parking lot

No CO_2 flux

Hot, dry summer afternoon

WPL due to latent heat flux

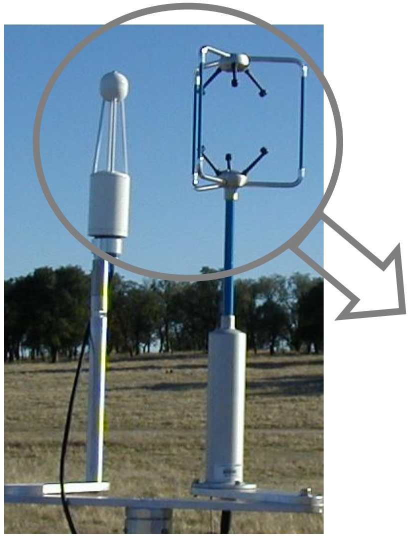


Imagine a situation: over a wet parking lot

No CO_2 flux

Hot summer afternoon

WPL due to latent heat flux



W' –
H_2O' –
CO_2' +

W' +
H_2O' +
CO_2' –

$\overline{w'CO_2'} < 0$, CO2 uptake?

Imagine a situation: over a <u>wet</u> parking lot

<u>No</u> CO_2 flux

Hot summer afternoon

Final density correction equation (WPL)

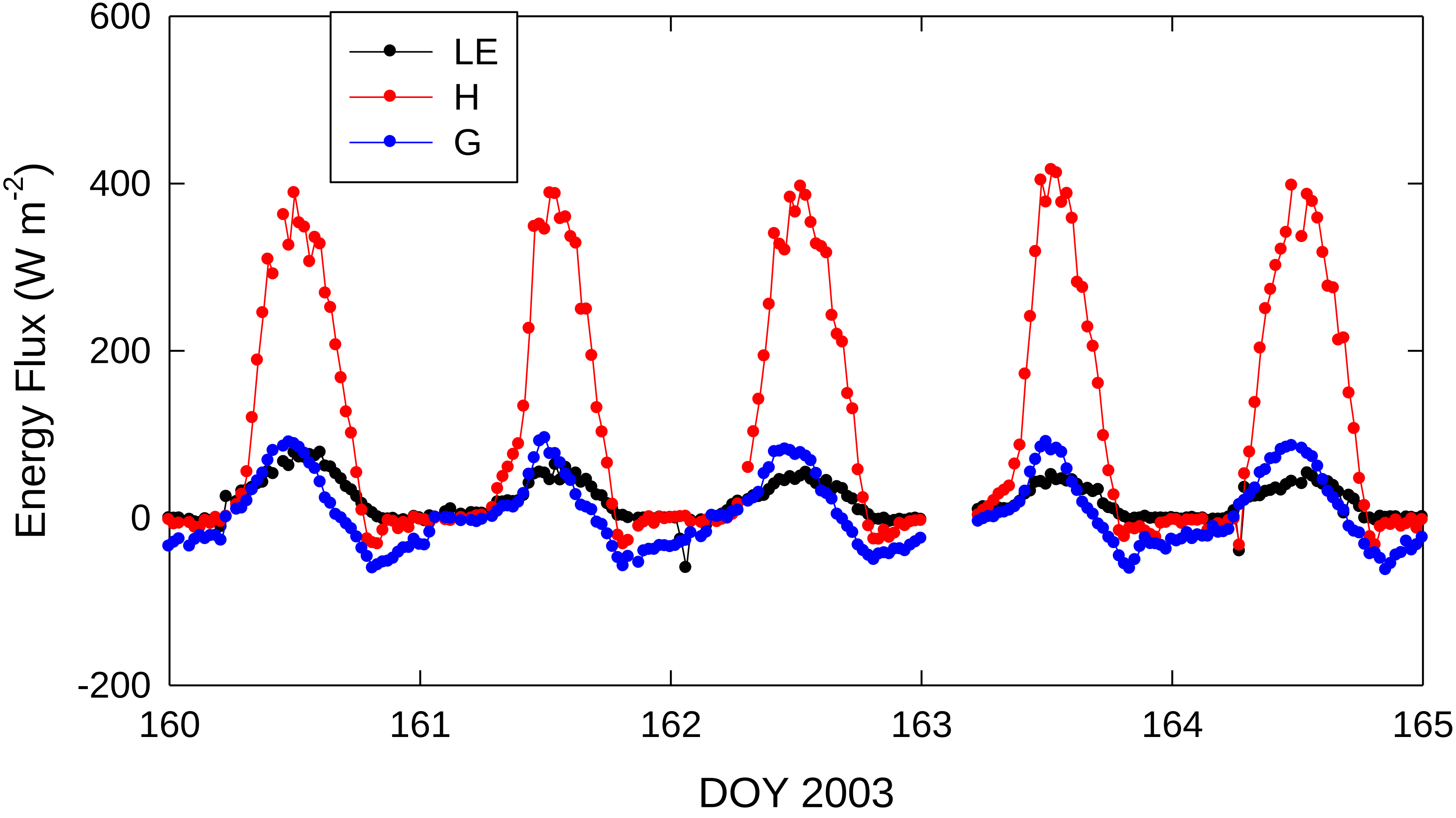
Webb, Pearman, Leuning Algorithm:
Correction for Density Fluctuations when using
OpenPath Sensors

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

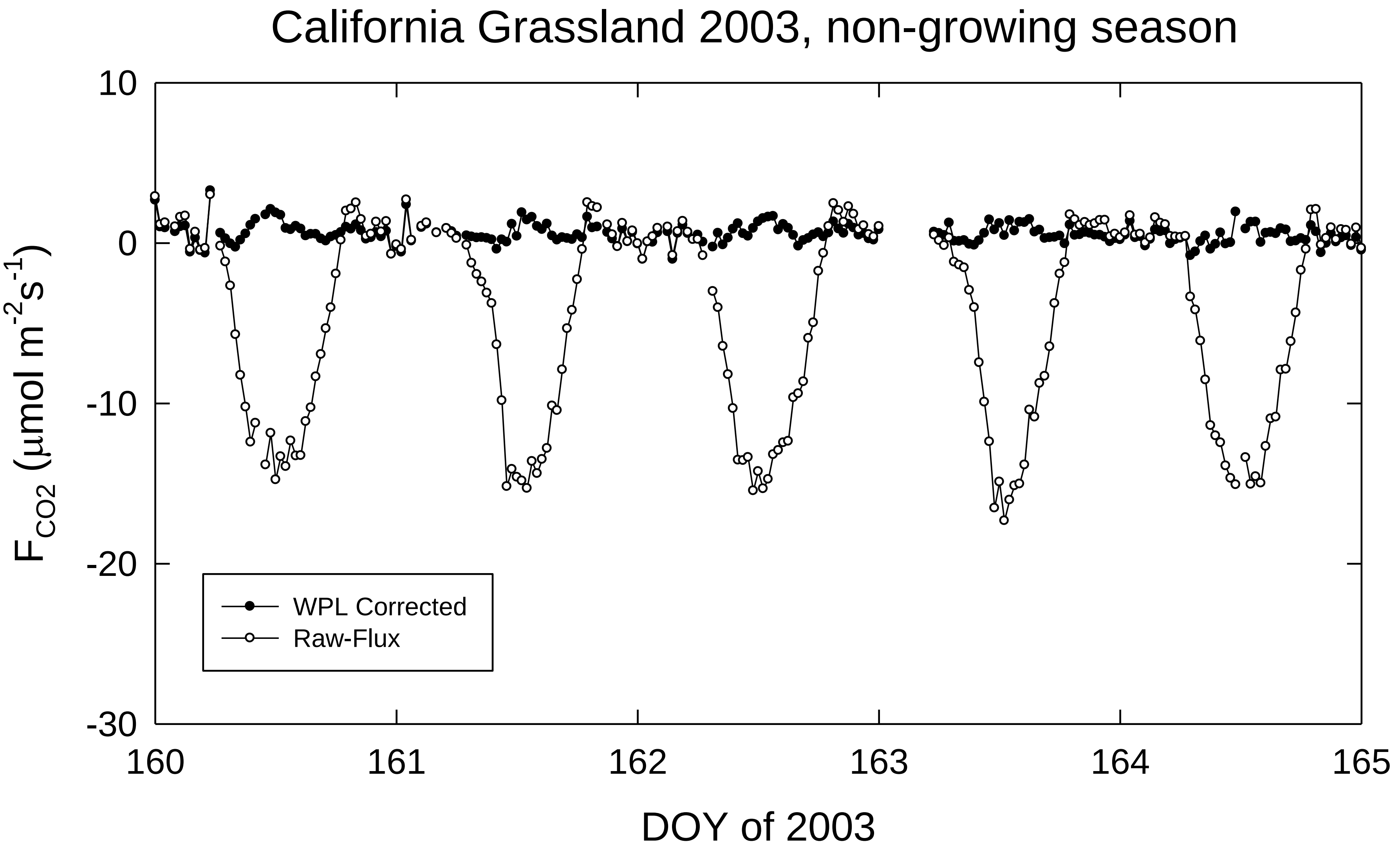
Webb et al., 1980

Magnitude of the density correction

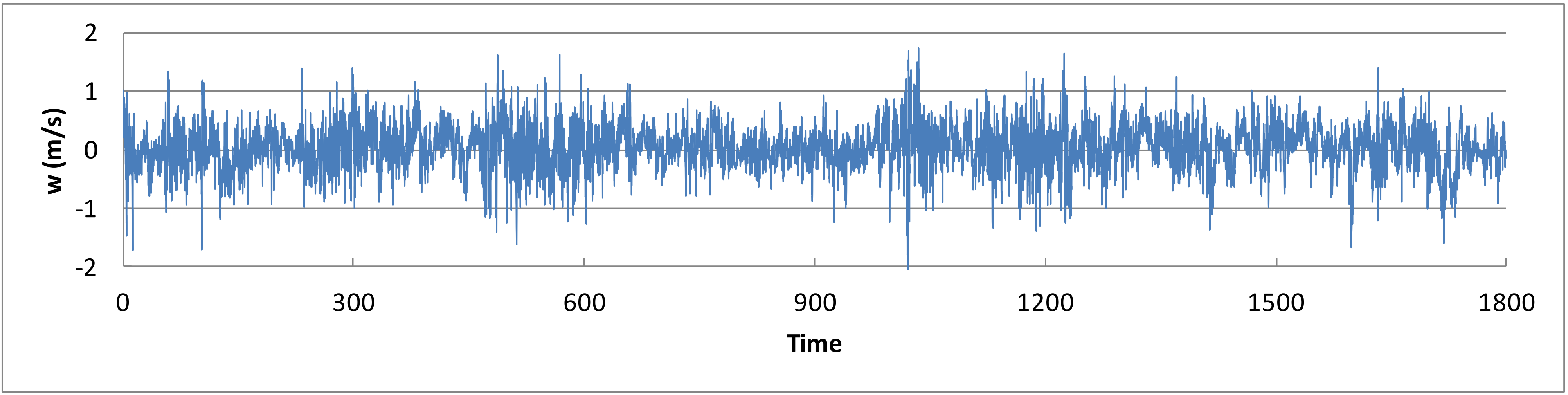
Magnitude of the density correction

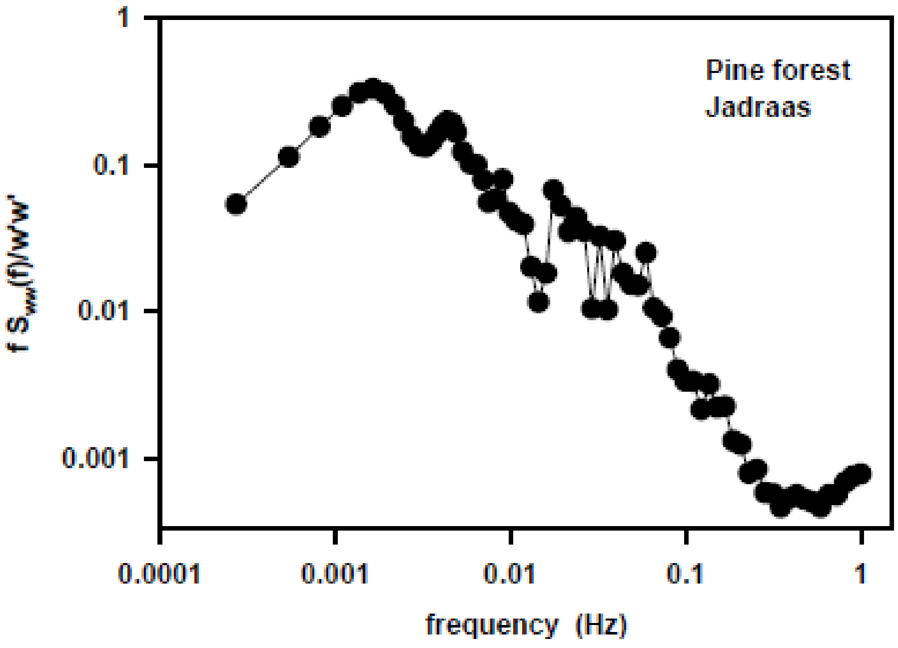


Magnitude of the density correction



Power Spectra Analysis





Kinetic Energy

Kinetic energy (KE), m is mass, U is mean wind speed

$$KE = 0.5\, mU^2$$

Mean Kinetic energy (MKE)

$$\frac{MKE}{m} = \frac{1}{2}(\bar{U}^2 + \bar{V}^2 + \bar{W}^2)$$

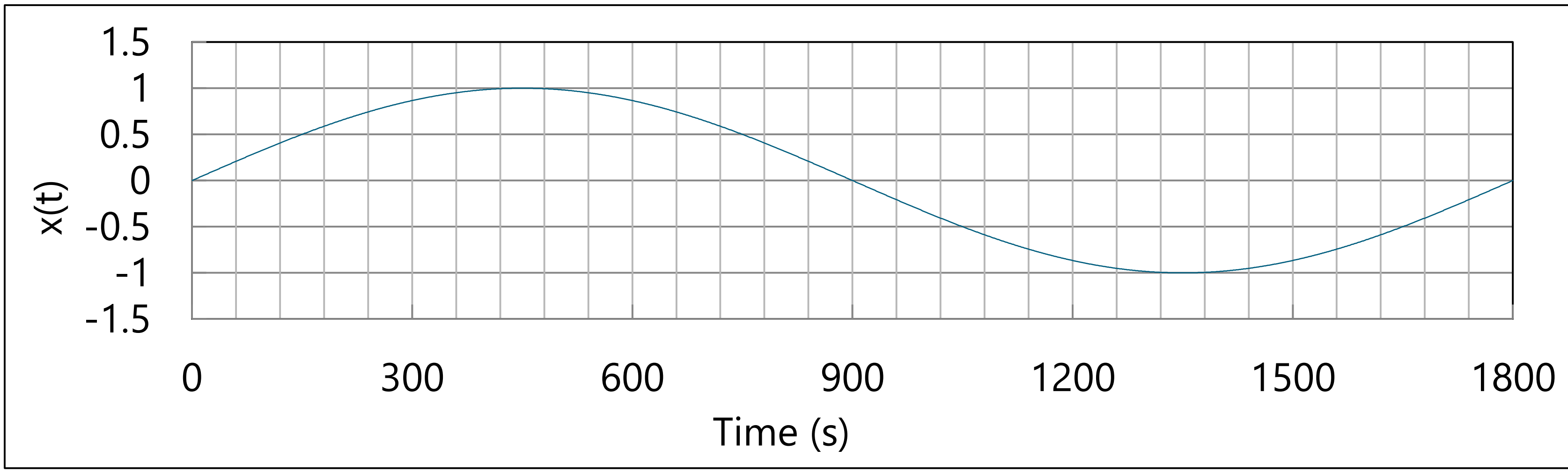
Turbulence Kinetic energy (TKE)

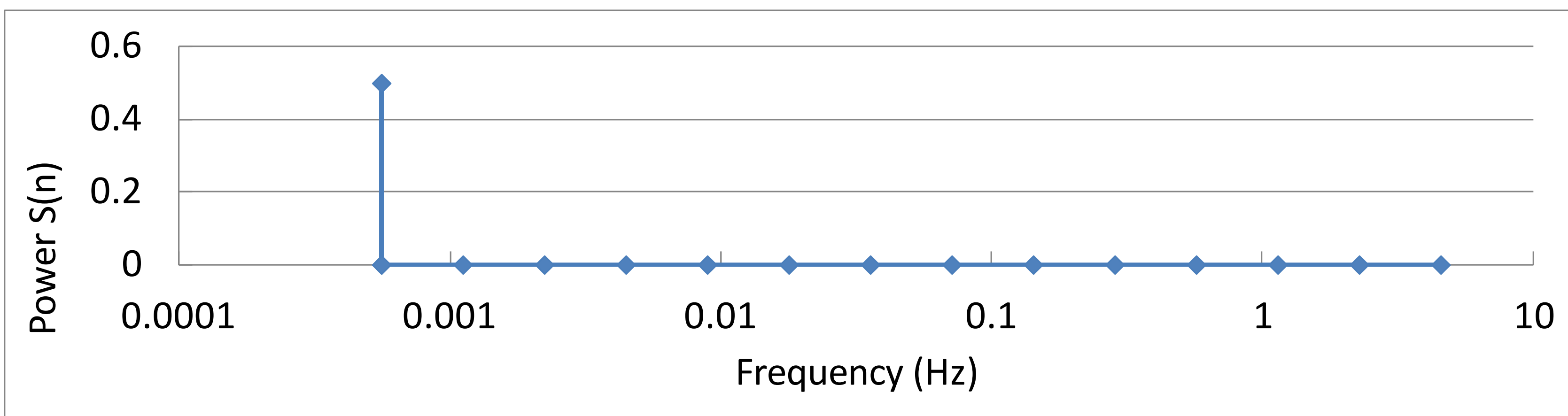
$$\frac{TKE}{m} = \frac{1}{2}(u'^2 + v'^2 + w'^2)$$

Period =30 min=1800 s
Frequency=1/1800=0.000556 Hz

$$x(k) = \sin\left(\frac{2\pi}{1800} k\Delta t\right)$$

k=0, 1,2,3, N-1





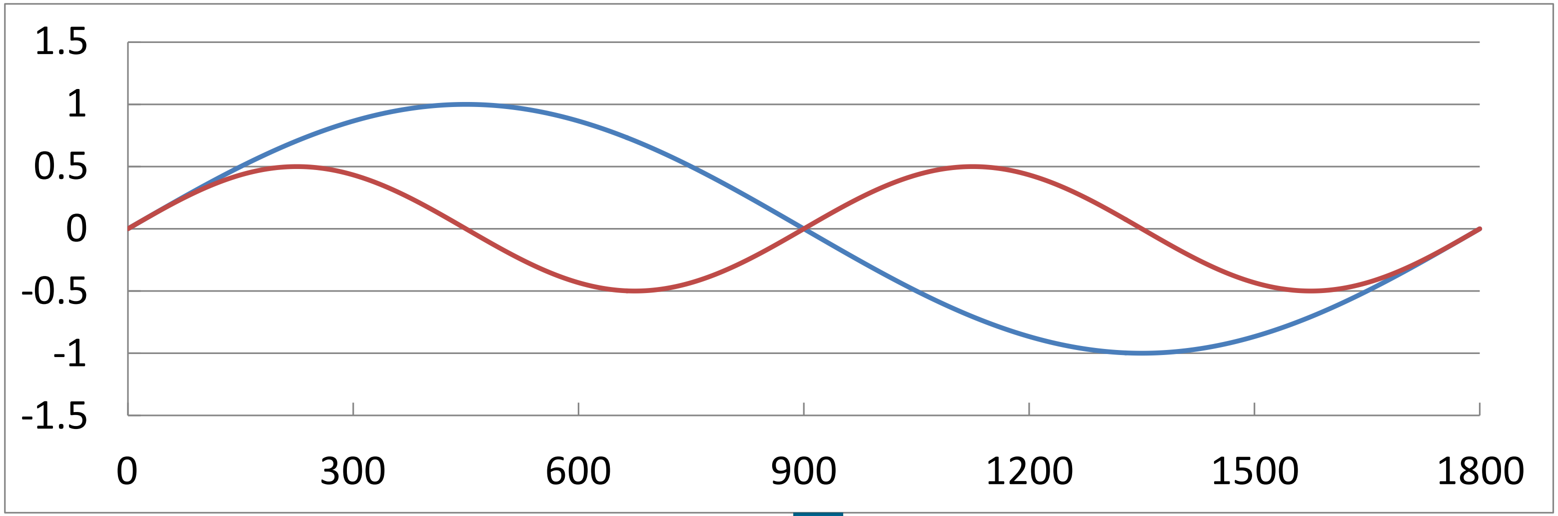
Period =30 min=1800 s
Frequency=1/1800=0.000556 Hz

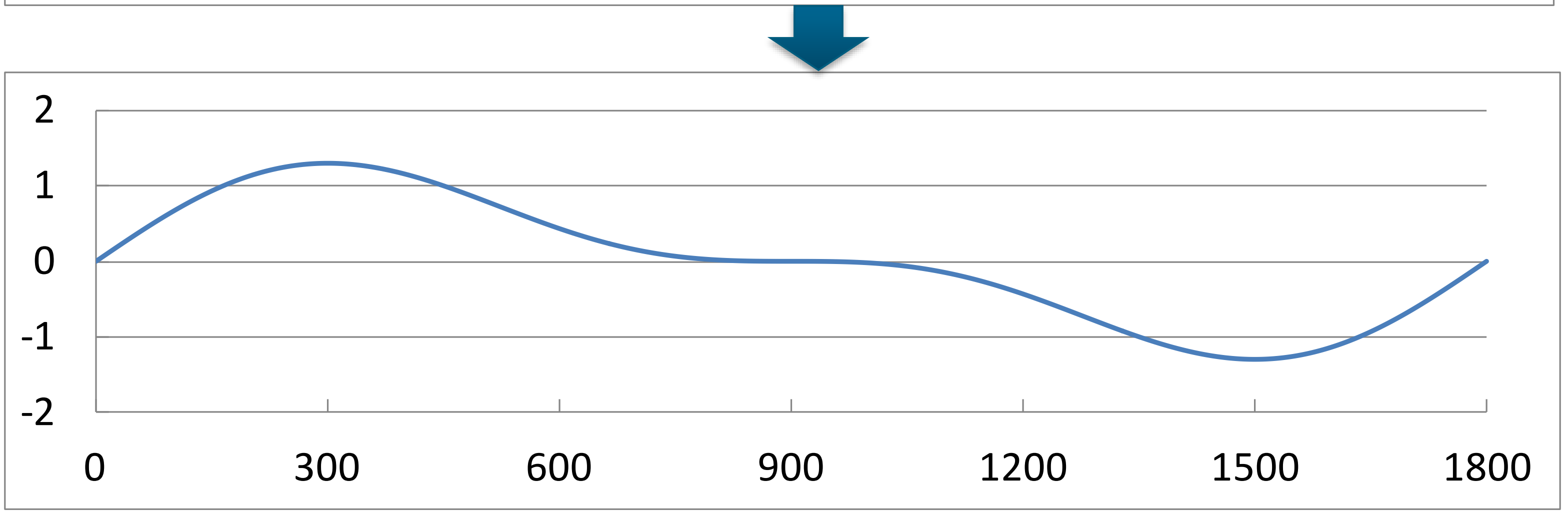
$$x(k) = \sin\left(\frac{2\pi}{1800} k\Delta t\right)$$

k=0, 1,2,3, N-1

Period =15 min=900 s
Frequency=1/900=0.001111 Hz

$$x(k) = \frac{1}{2}\sin\left(\frac{2\pi}{900} k\Delta t\right)$$





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Period =15 min=900 s

Frequency=1/900=0.001111 Hz

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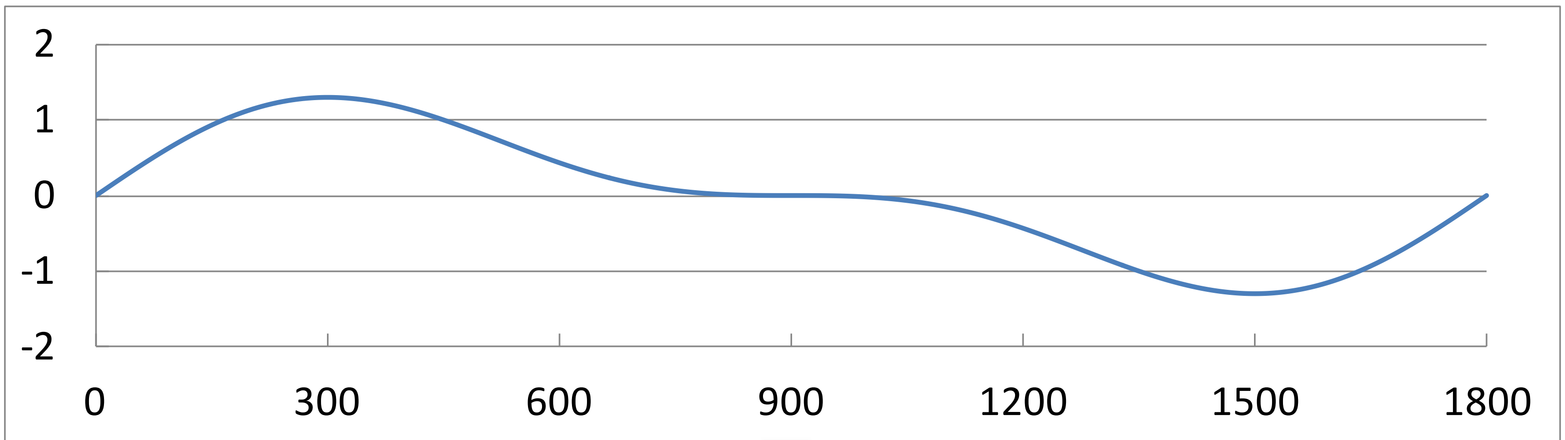
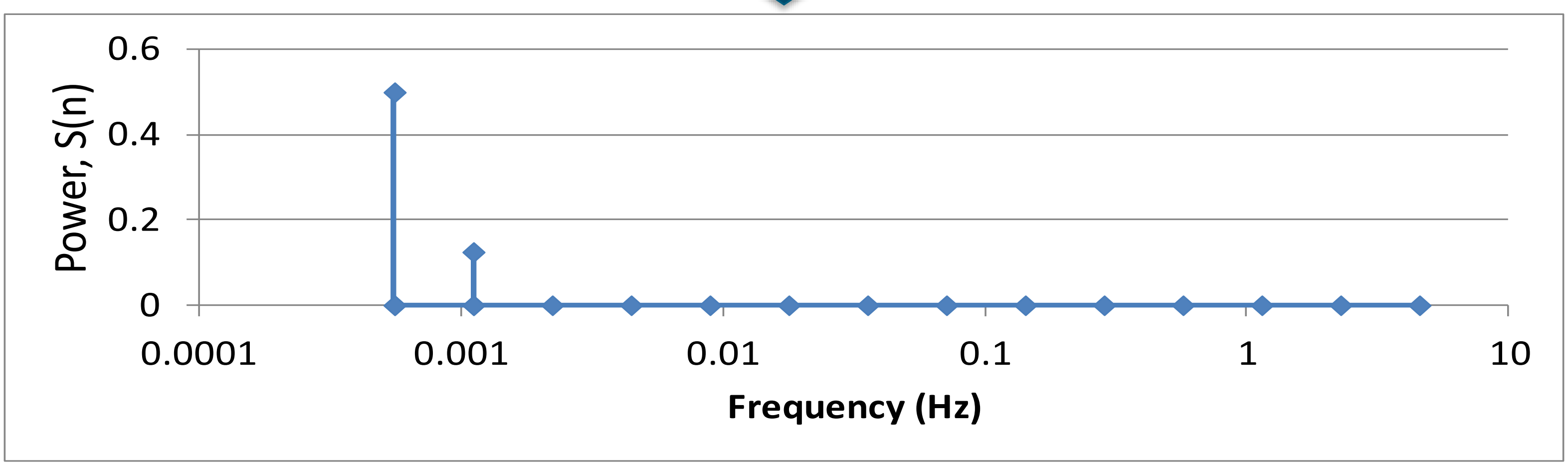
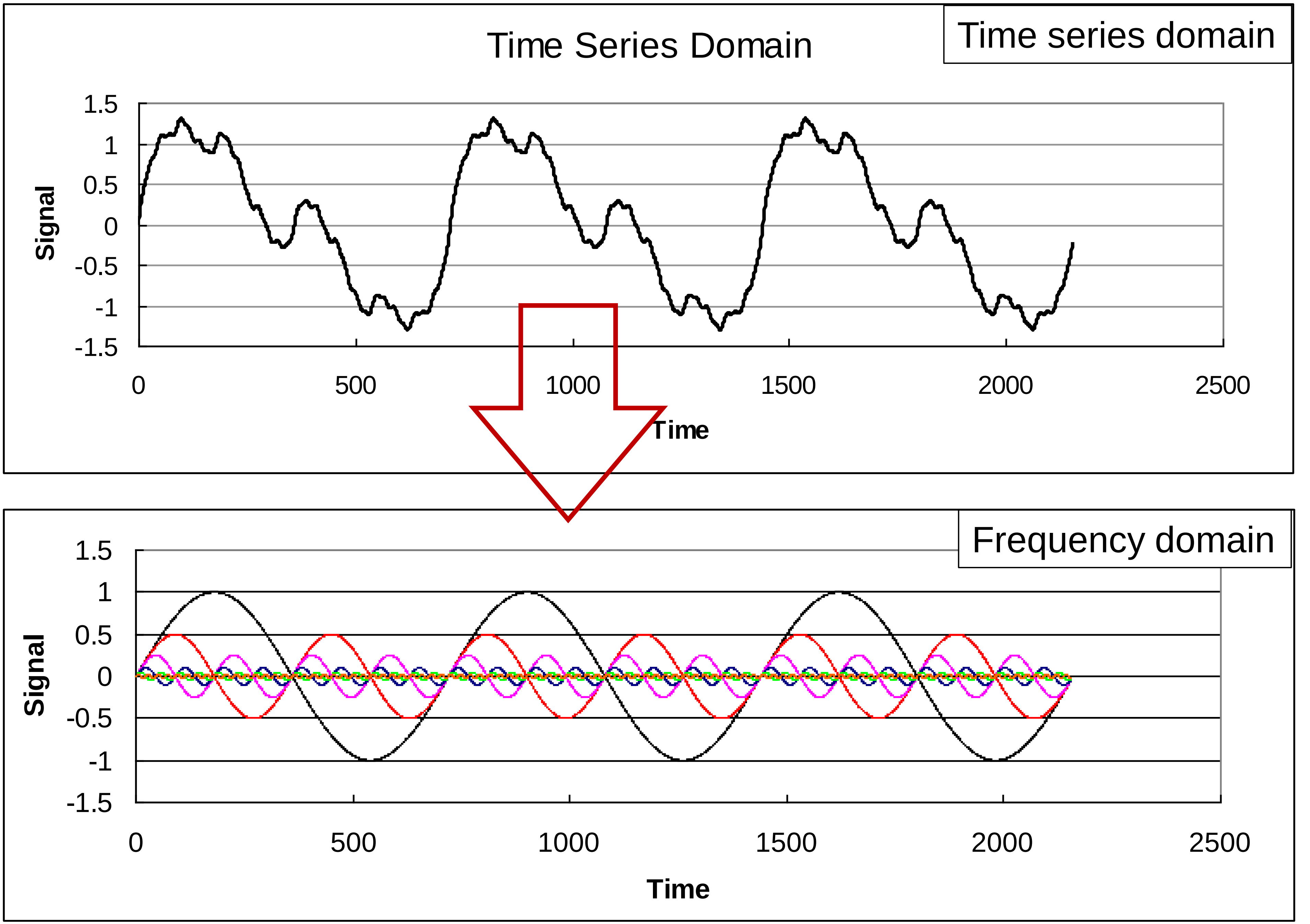





Time Series Domain
Time series domain
Signal
1.5
1
0.5
0
-0.5
-1
-1.5
0
500
1000
1500
2000
2500
Time
Frequency domain
Signal
1.5
1
0.5
0
-0.5
-1
-1.5
0
500
1000
1500
2000
2500
Time

Mathematically

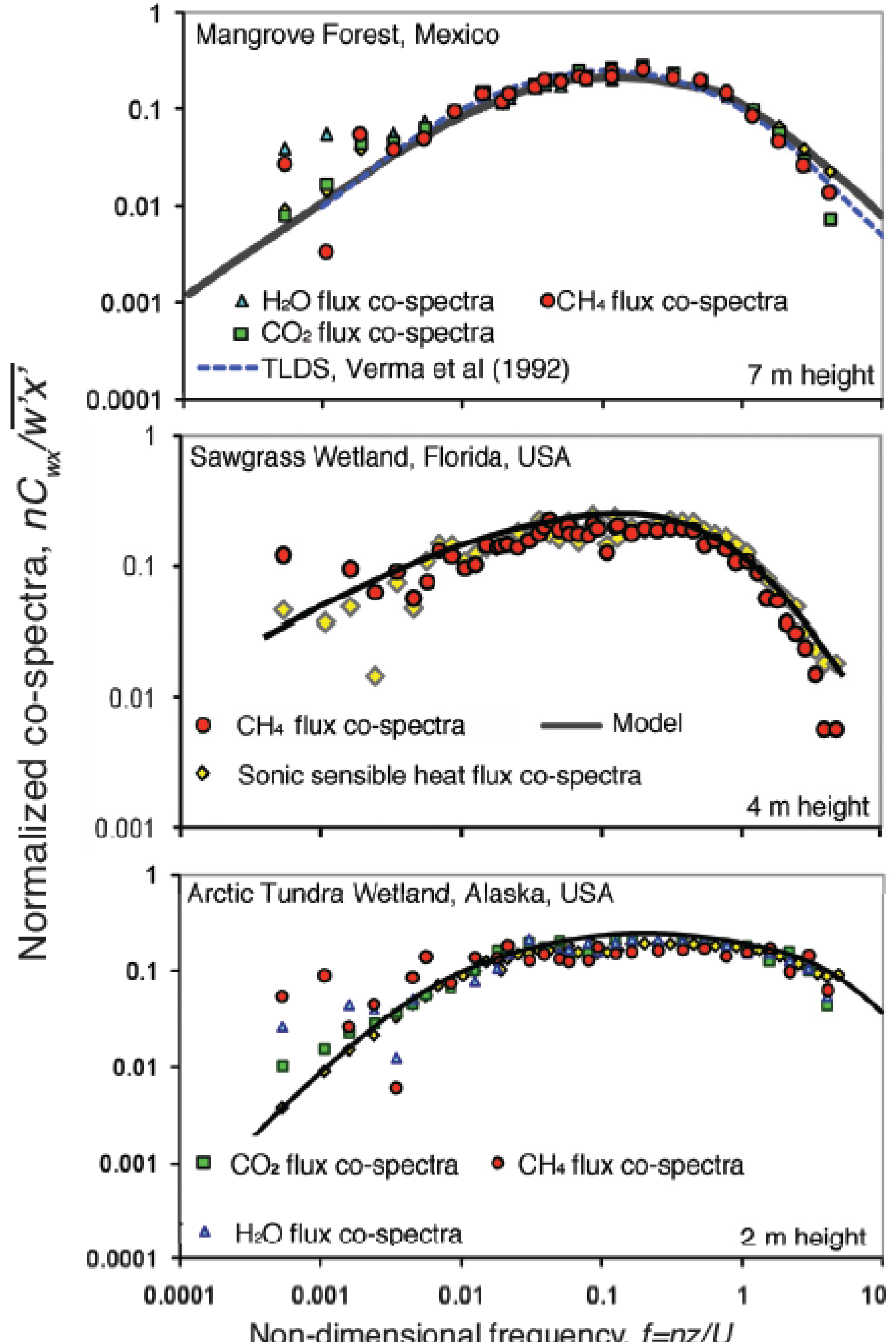
$$x(k) = \sum_{n=1}^{N-1} \mathrm{a}_n \sin\left(\frac{2\pi nk}{P}\Delta t\right) + \sum_{n=1}^{N-1} b_n \cos\left(\frac{2\pi nk}{P}\Delta t\right)$$

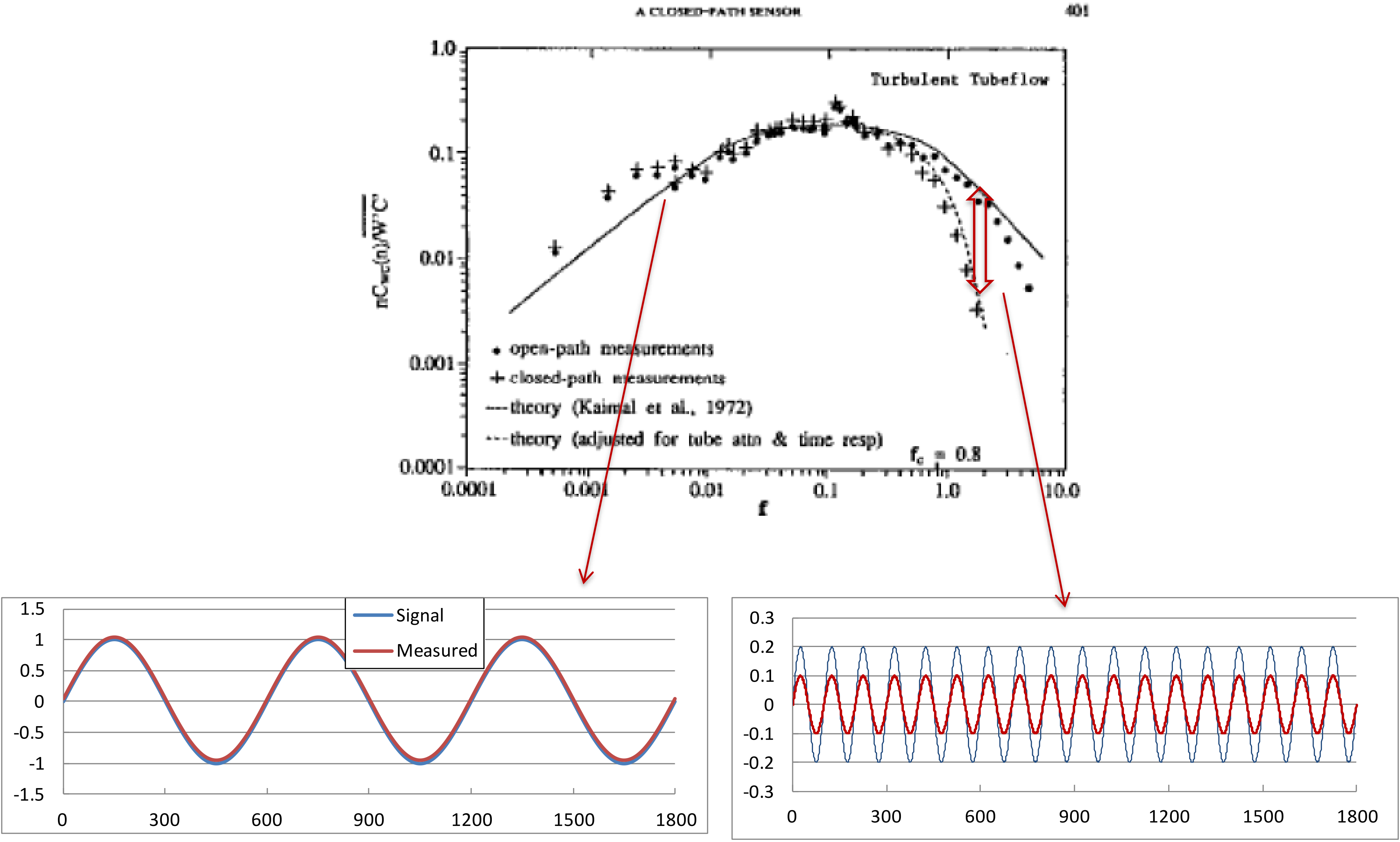
$$\sigma_x^2 = \int S_{(n)}\,dn = \frac{1}{n}\sum (x_{(k)} - \bar{x})^2$$

Variance, 方差

The Power spectral density is defined as such that its integral over all frequencies is equal to the total variance

Spectra Analysis



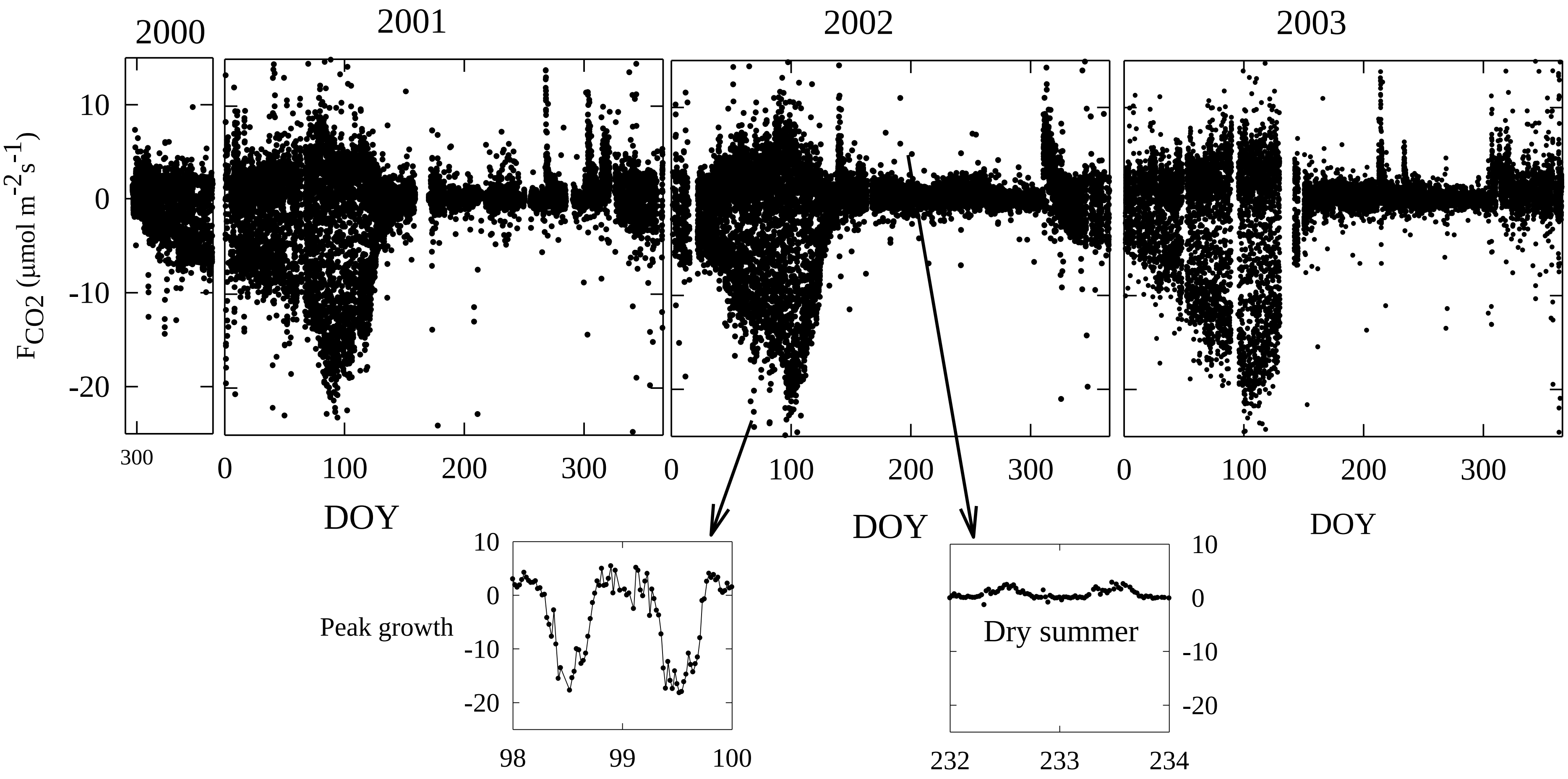


Suyker and Verma, 1993 BLM

EC Flux Data QA/QC

- *w, u, v* ~ off the scale
- T_s, *q*, CO_2 ~ off the scale
- If spikes > *n* (*n* ~ 10%)
- Reynolds stress (*u'w'*) too high
- Unreasonable skewness
- Unreasonable kurtosis
- Unreasonable flux
- other criteria

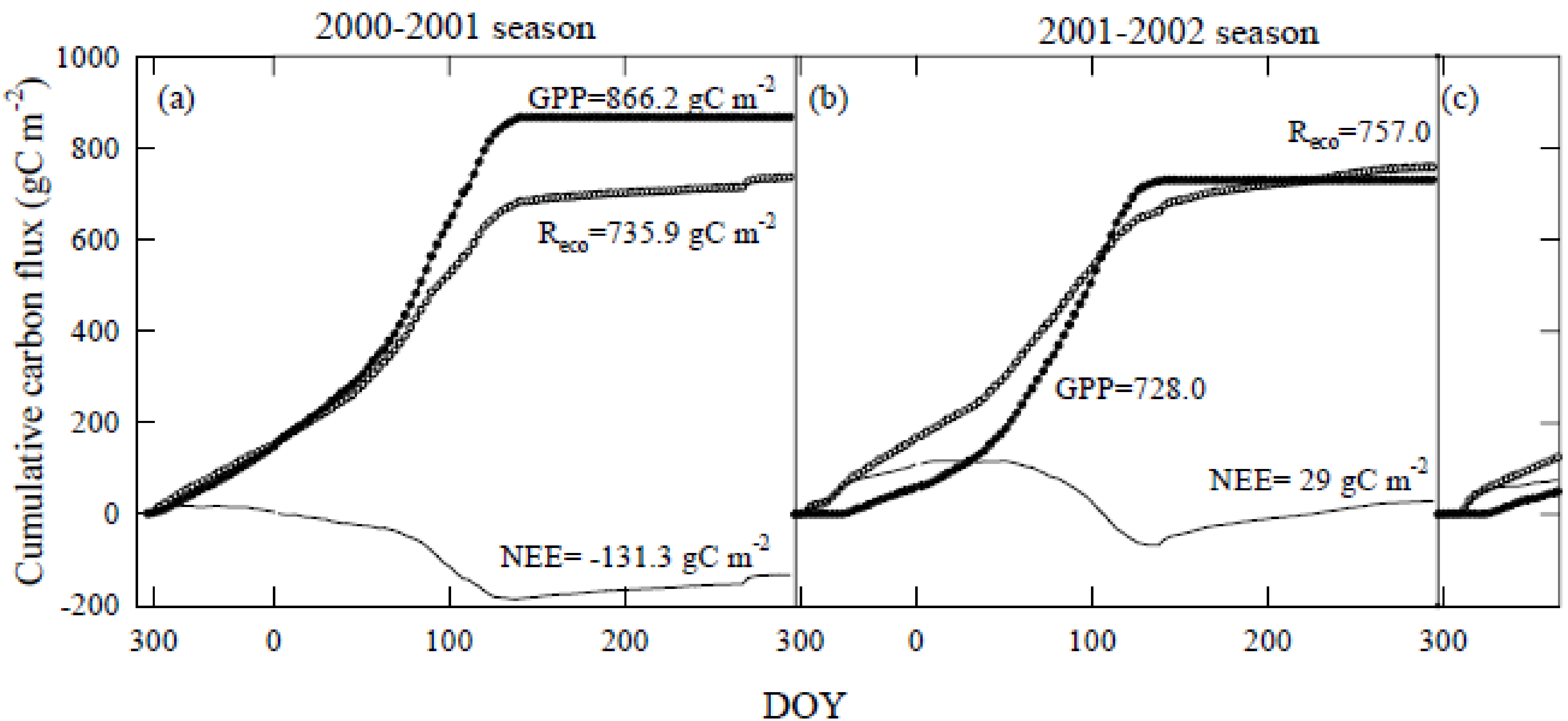
Example of long-term flux data (2000-2003)
California grassland



Xu and Baldocchi, 2004

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

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



Advantages of the EC Method over other methods

- direct measure of the flux density,
- *in situ*,
- No disturbance on the system,
- Quasi-continuous,
- Represents a large upwind area,
- Others.

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Summary

1. Eddy covariance theory – Basic micrometeorology theory
2. EC data processing principles; including de-spiking, coordinate rotation, density correction, etc
3. Spectra analysis
4. QA/QC
5. Examples of long-term flux measurements

Any questions ?