Eddy Covariance Method: The Basics

Liukang Xu

Outline

1. Eddy covariance theory – 涡度协方差的基本理论
2. EC data processing; including de-spiking （去除异常值）, coordinate rotation （坐标旋转), density correction (WPL， 密度订正), etc
4. Spectra analysis 波谱分析
5. QA/QC 质量控制
6. Examples of long-term flux measurements 例子

任何时间，任何问题都可以问!

基本术语和单位 （Terminology and units ）

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

Mixing Ratio: g CO_2 per g dry air
g H_2O per g dry air

Specific Humidity: g H_2O per g moist air

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

CO_2 CH_4 通量和单位

CO_2 flux: μmol 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}
g CO_2 m^{-2} yr^{-1} (normally don't use this)

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}

能量通量和单位

Net radiation (R_{net}， 净辐射)： $W\ m^{-2}$ ($J\ m^{-2}\ s^{-1}$)

Sensible heat flux (H，显热，感热) : $W\ m^{-2}$

Latent heat flux (LE， 潜热): ($W\ m^{-2}$)

$LE = \lambda E$

Soil heat flux (G， 土壤热通量): $W\ m^{-2}$

主要环境参数的垂直廓线

白天

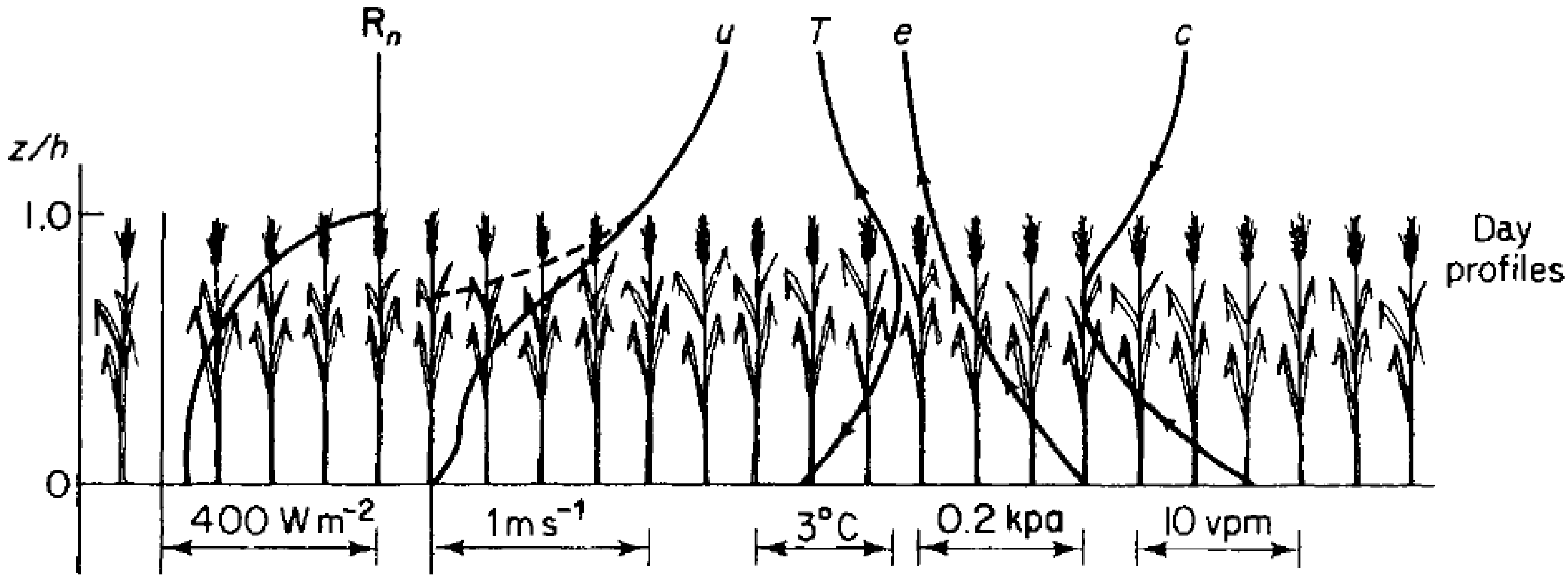


Fig. 16.5. Monteith and Unsworth , 2013. Environmental Physics.

晚上

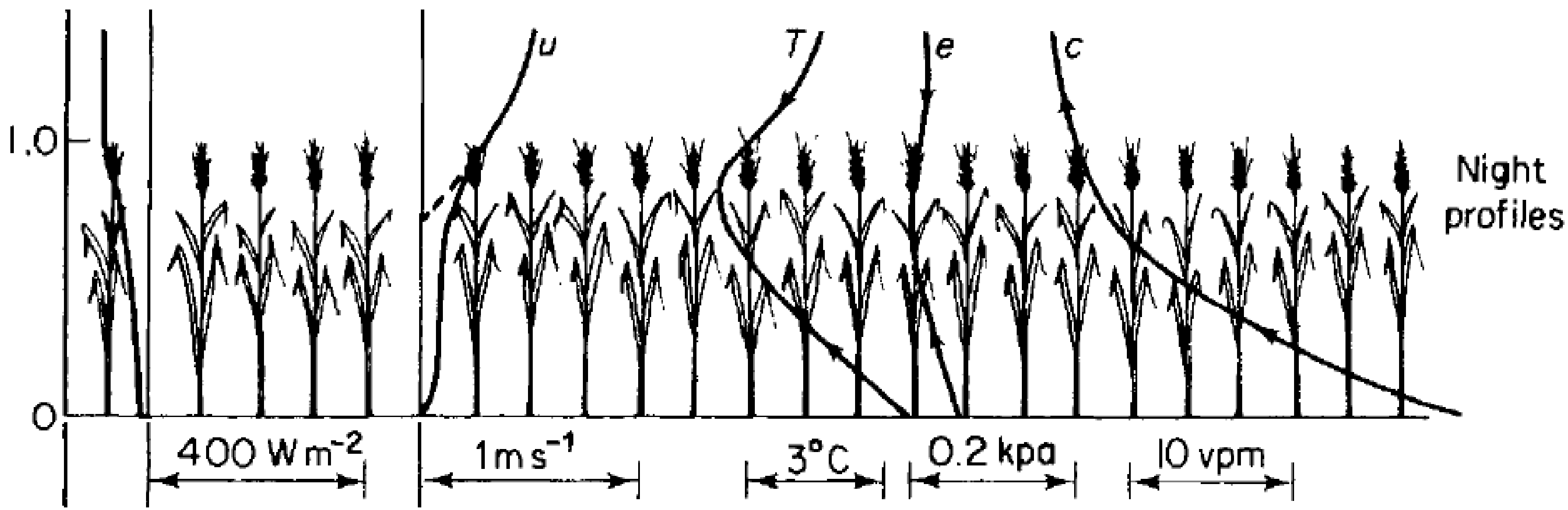
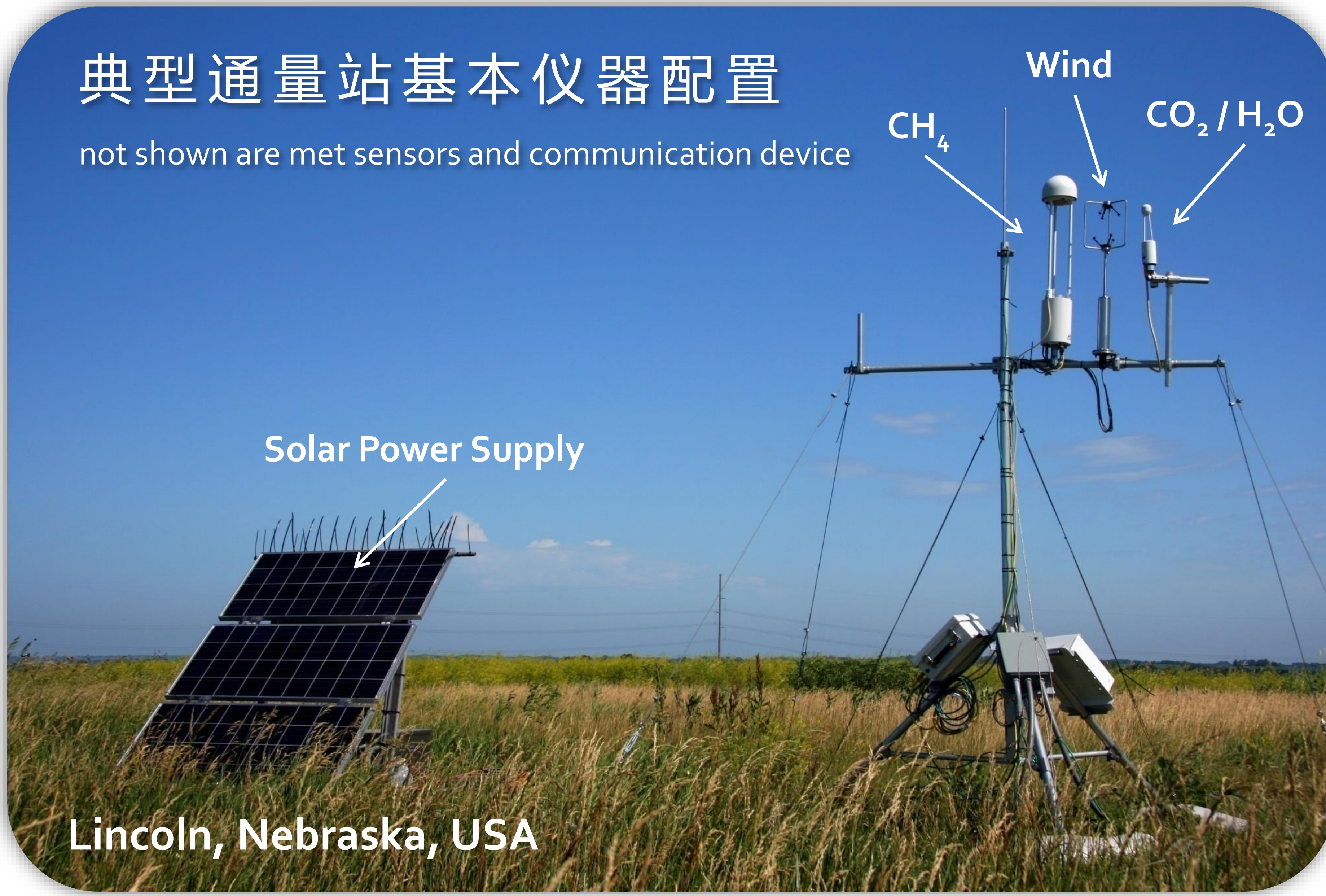


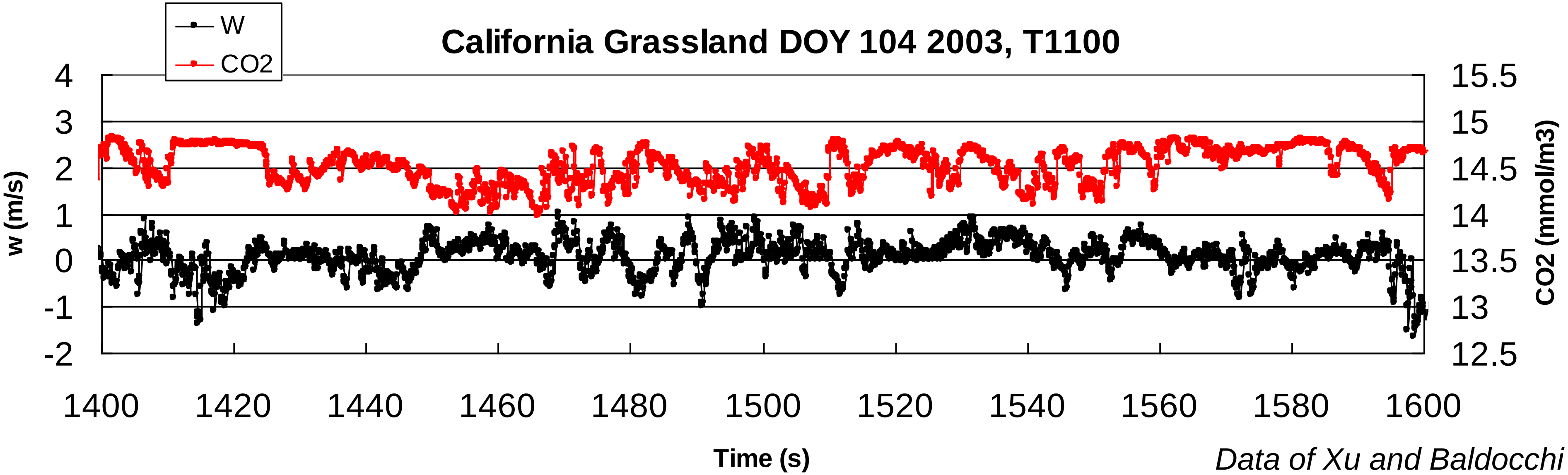
Fig. 16.5. Monteith and Unsworth , 2013. Environmental Physics.

典型通量站基本仪器配置

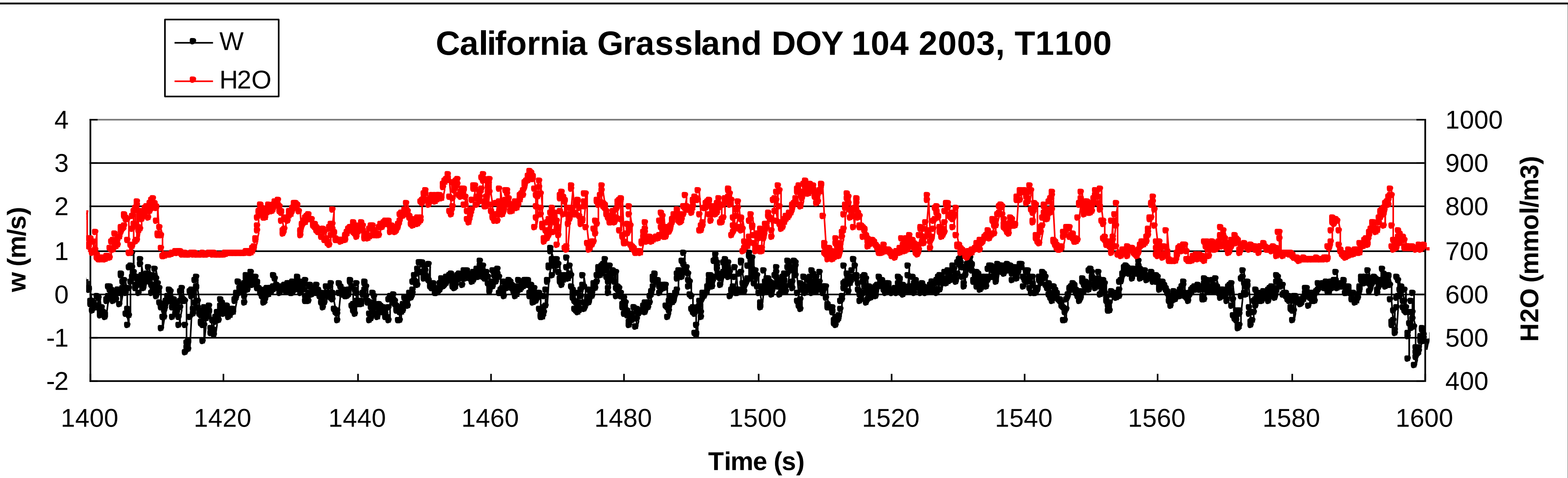
not shown are met sensors and communication device



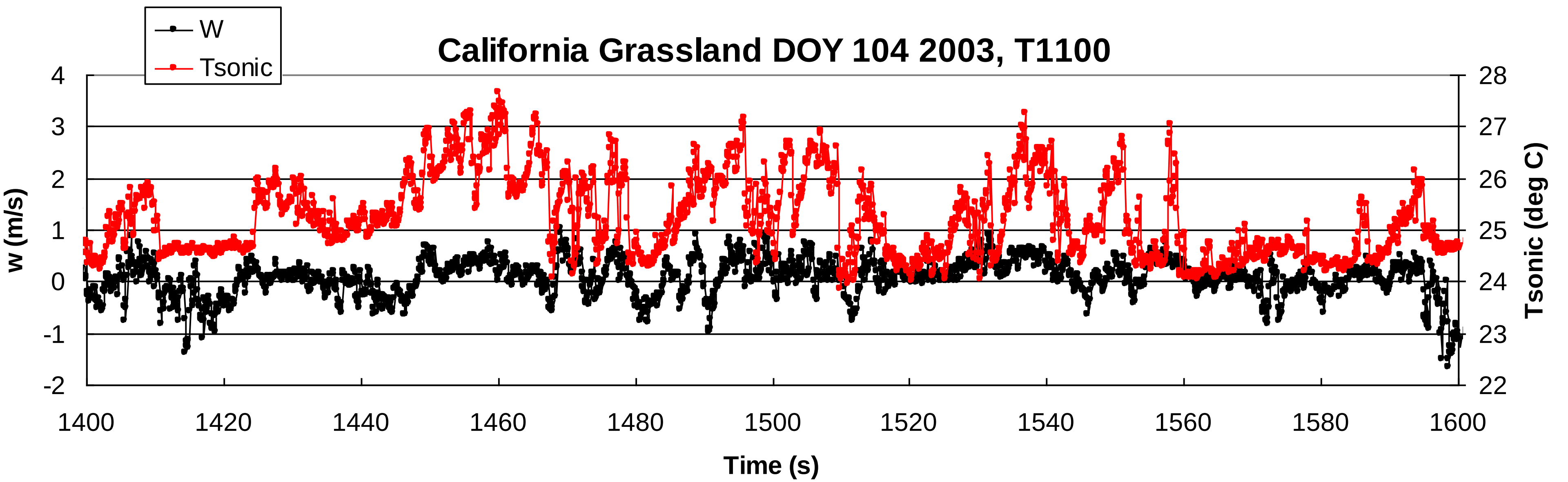
10-Hz 原始数据



Data of Xu and Baldocchi

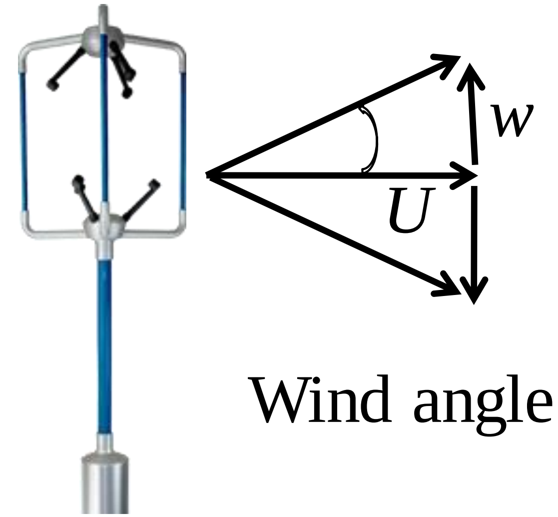


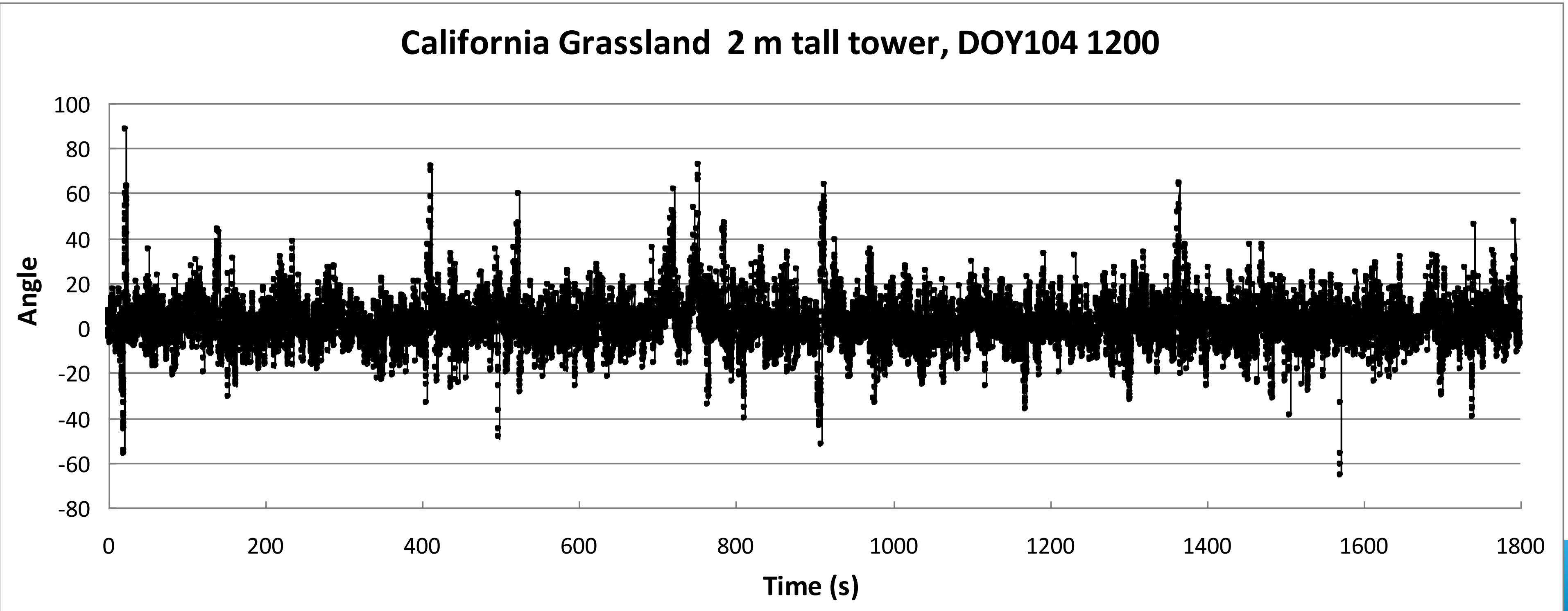
W
H2O
California Grassland DOY 104 2003, T1100
w (m/s)
H2O (mmol/m3)
4
3
2
1
0
-1
-2
1000
900
800
700
600
500
400
1400
1420
1440
1460
1480
1500
1520
1540
1560
1580
1600
Time (s)



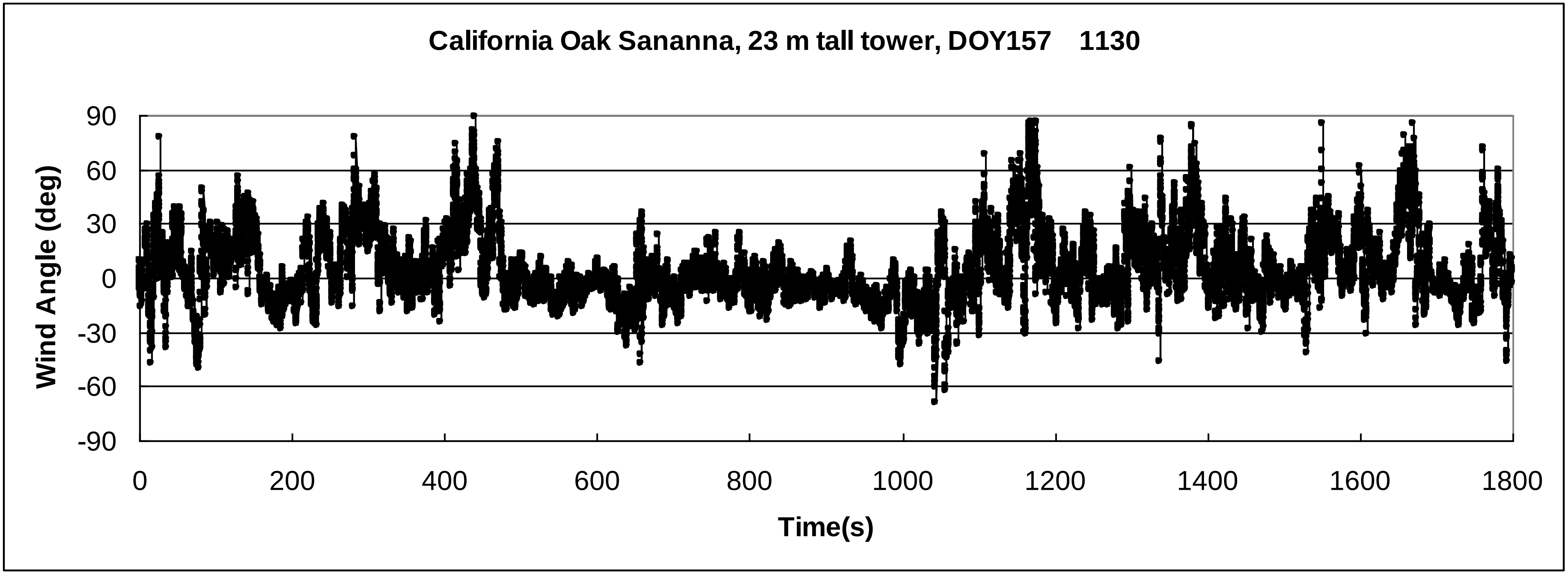
W
Tsonic
California Grassland DOY 104 2003, T1100
w (m/s)
Tsonic (deg C)
4
3
2
1
0
-1
-2
28
27
26
25
24
23
22
1400
1420
1440
1460
1480
1500
1520
1540
1560
1580
1600
Time (s)

Here is more 10-Hz raw data… 气团运动的角度

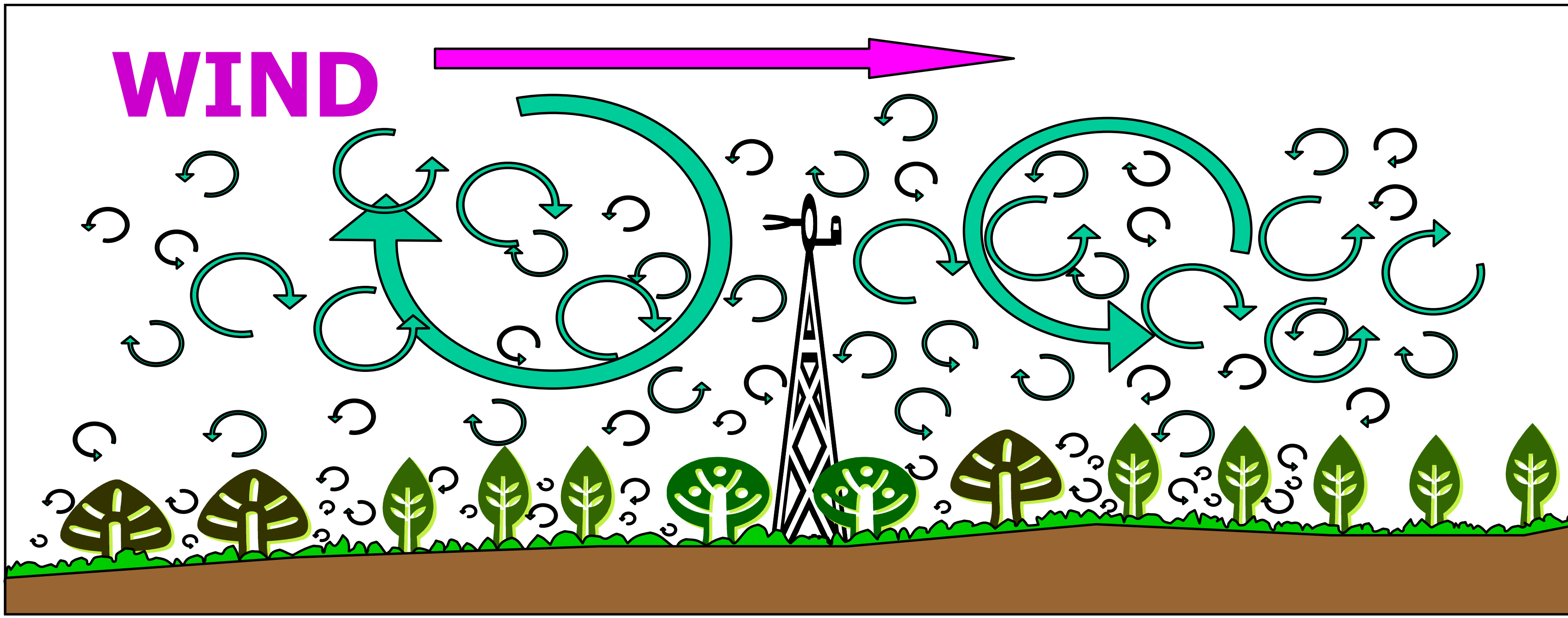




气团运动角度


California Oak Sananna, 23 m tall tower, DOY157 1130
Wind Angle (deg)
90
60
30
0
-30
-60
-90
0
200
400
600
800
1000
1200
1400
1600
1800
Time(s)

涡度协方差基本原理



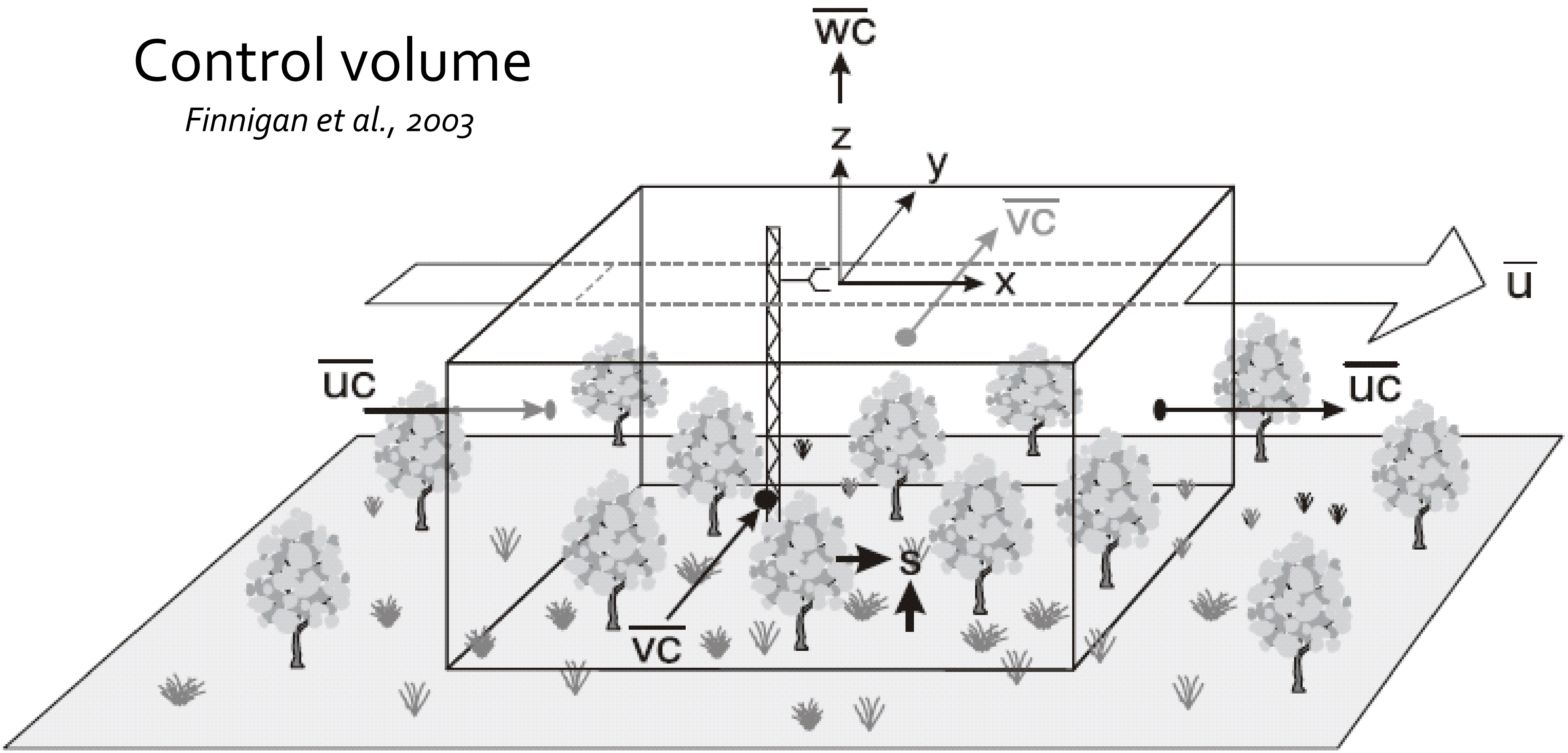
Basic assumptions: 基本假设条件

1. no horizontal divergence or convergence，无辐散和辐合

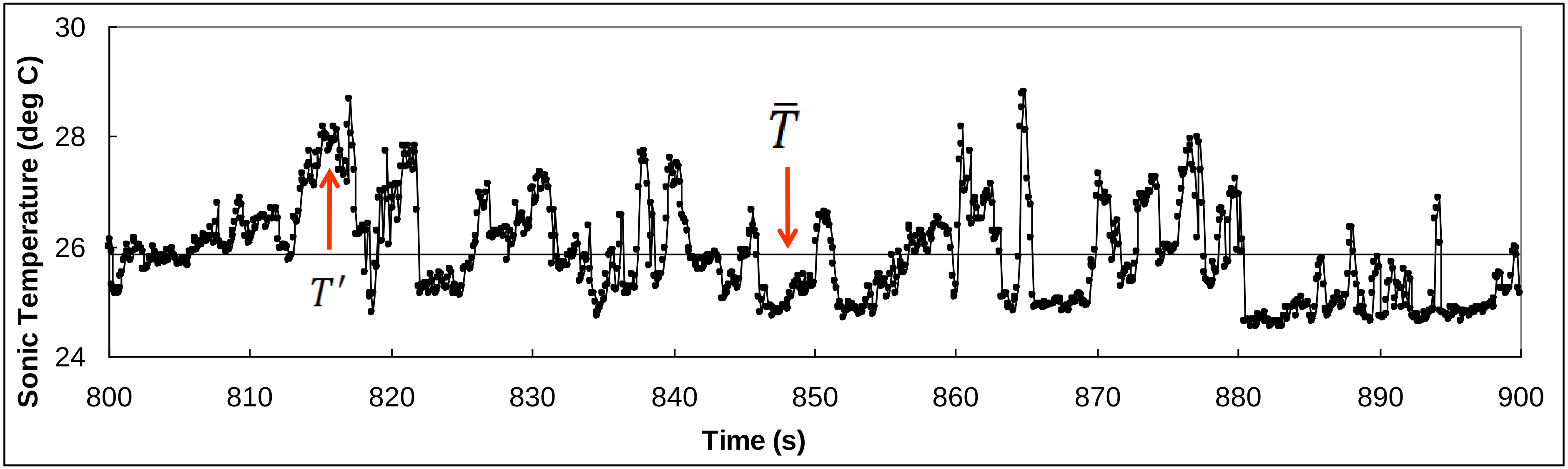
2. $\frac{d\bar{C}}{dt} = 0$ 储存项为零

Control volume

Finnigan et al., 2003



Reynolds' Averaging Rules，雷诺平均法则



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

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

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

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

Covariance, 协方差

涡度协方差的基本公式

$$F = \overline{\rho_a w s} \qquad \frac{g\ dry\ air}{m^3} \times \frac{m}{s} \times \frac{g\ CO_2}{g\ dry\ air} = \frac{g\ CO_2}{m^2 s}$$

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

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

Averaged deviation from the mean is zero

Dry air flux is zero

~0

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

s is mixing ratio with the unit of $g\ CO_2\ g^{-1}$ dry air

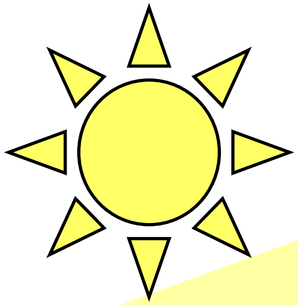
Density unit!

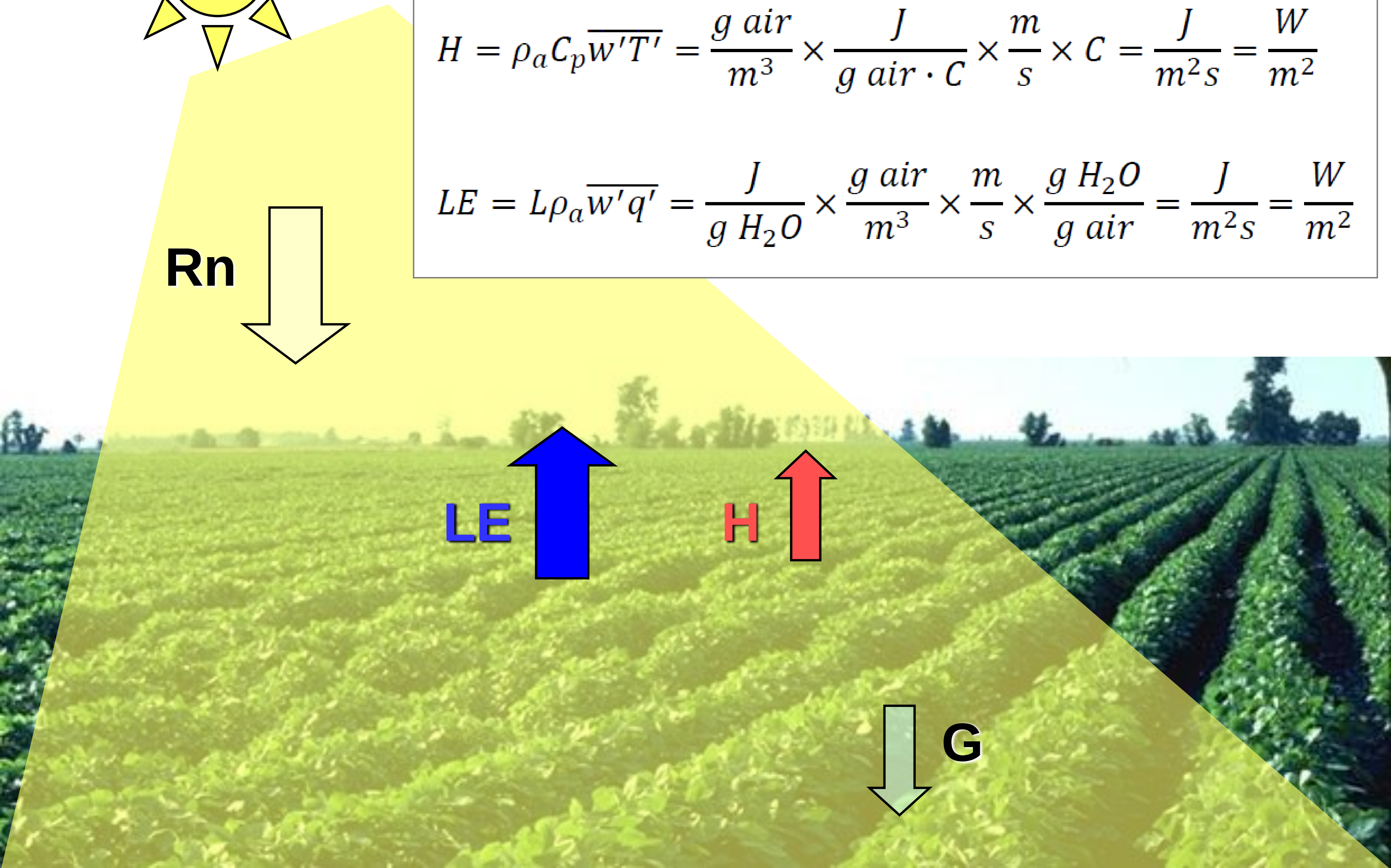
Time	CO_2 (mmol m^{-3})	W (m s^{-1})	CO_2'	W'	$W'CO_2'$	
0	15.511	-0.253	0.108	-0.253	-0.027	
0.1	15.483	-0.348	0.080	-0.348	-0.028	
0.2	15.442	-0.290	0.039	-0.290	-0.011	
0.3	15.420	-0.052	0.017	-0.052	-0.001	
0.4	15.414	0.091	0.012	0.091	0.001	
0.5	15.409	0.159	0.006	0.159	0.001	
0.6	15.401	0.276	-0.002	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 $m^{-2}s^{-1}$)**

用涡度测能量通量

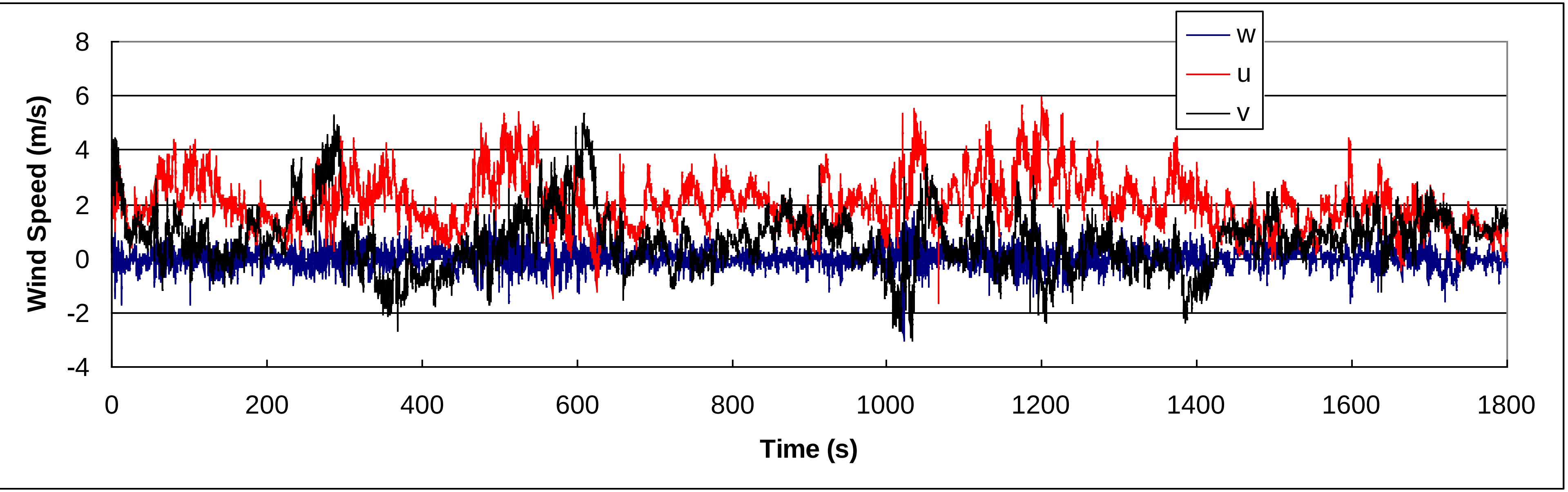
$$H = \rho_a C_p \overline{w'T'} = \frac{g\ air}{m^3} \times \frac{J}{g\ air \cdot C} \times \frac{m}{s} \times C = \frac{J}{m^2 s} = \frac{W}{m^2}$$

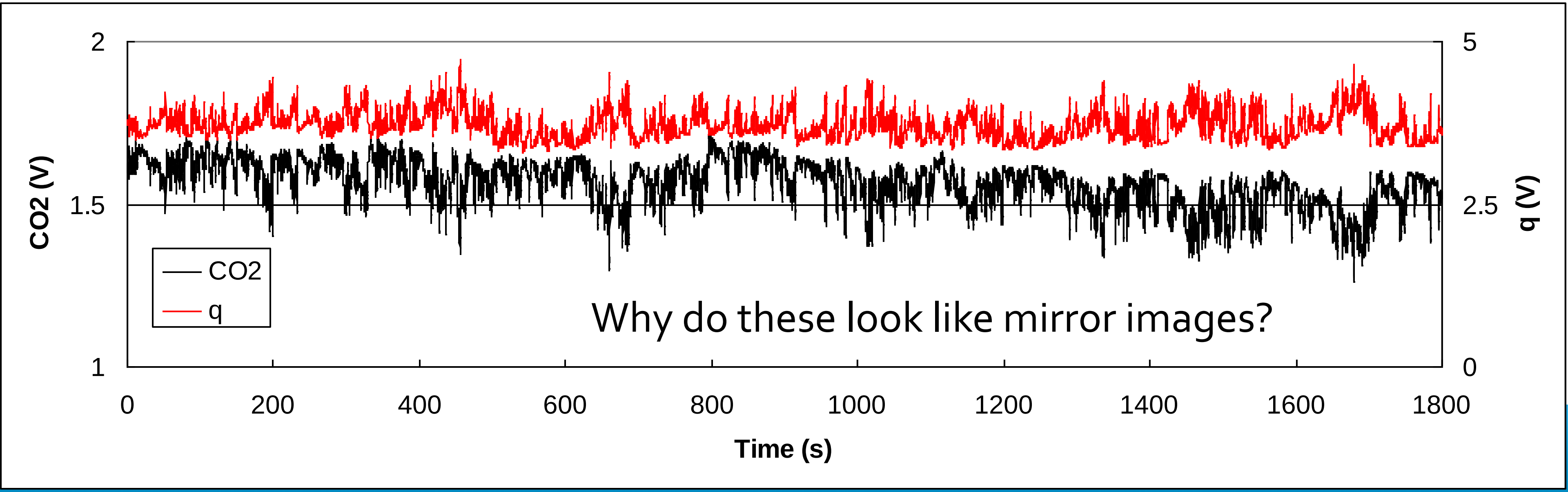
$$LE = L\rho_a \overline{w'q'} = \frac{J}{g\ H_2O} \times \frac{g\ air}{m^3} \times \frac{m}{s} \times \frac{g\ H_2O}{g\ air} = \frac{J}{m^2 s} = \frac{W}{m^2}$$





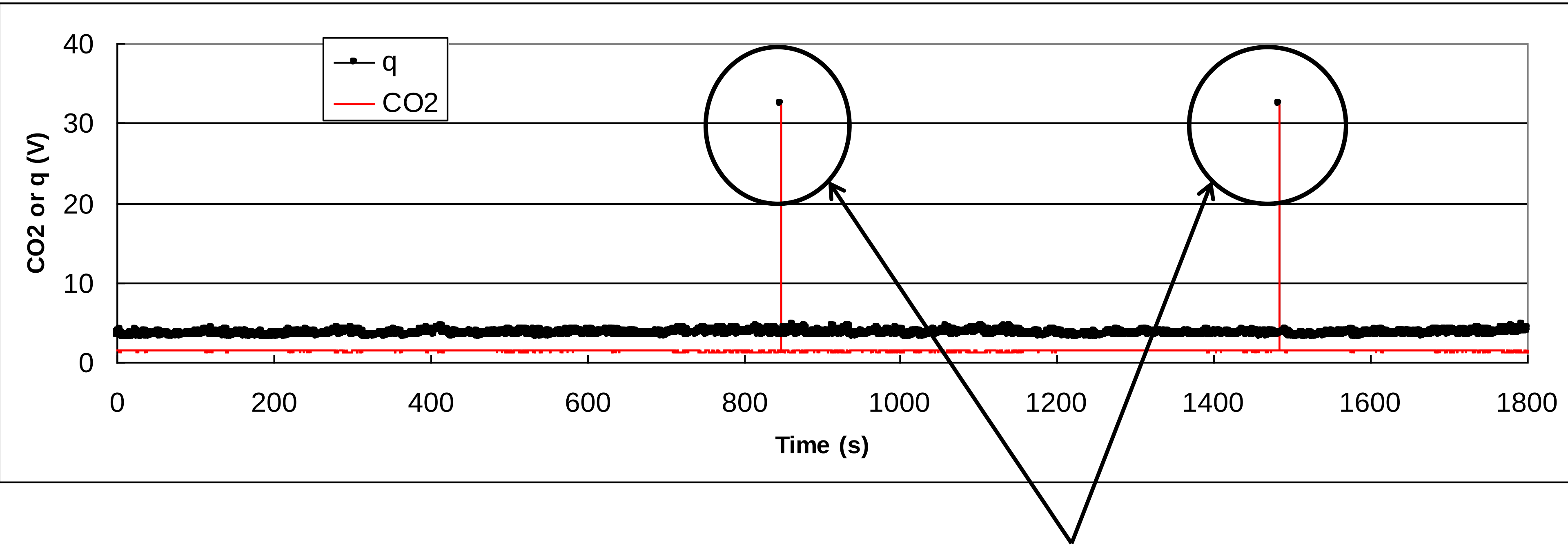
Data Processing: de-spiking， 剔除异常值





Why do these look like mirror images?

Data Processing: de-spiking，剔除异常值

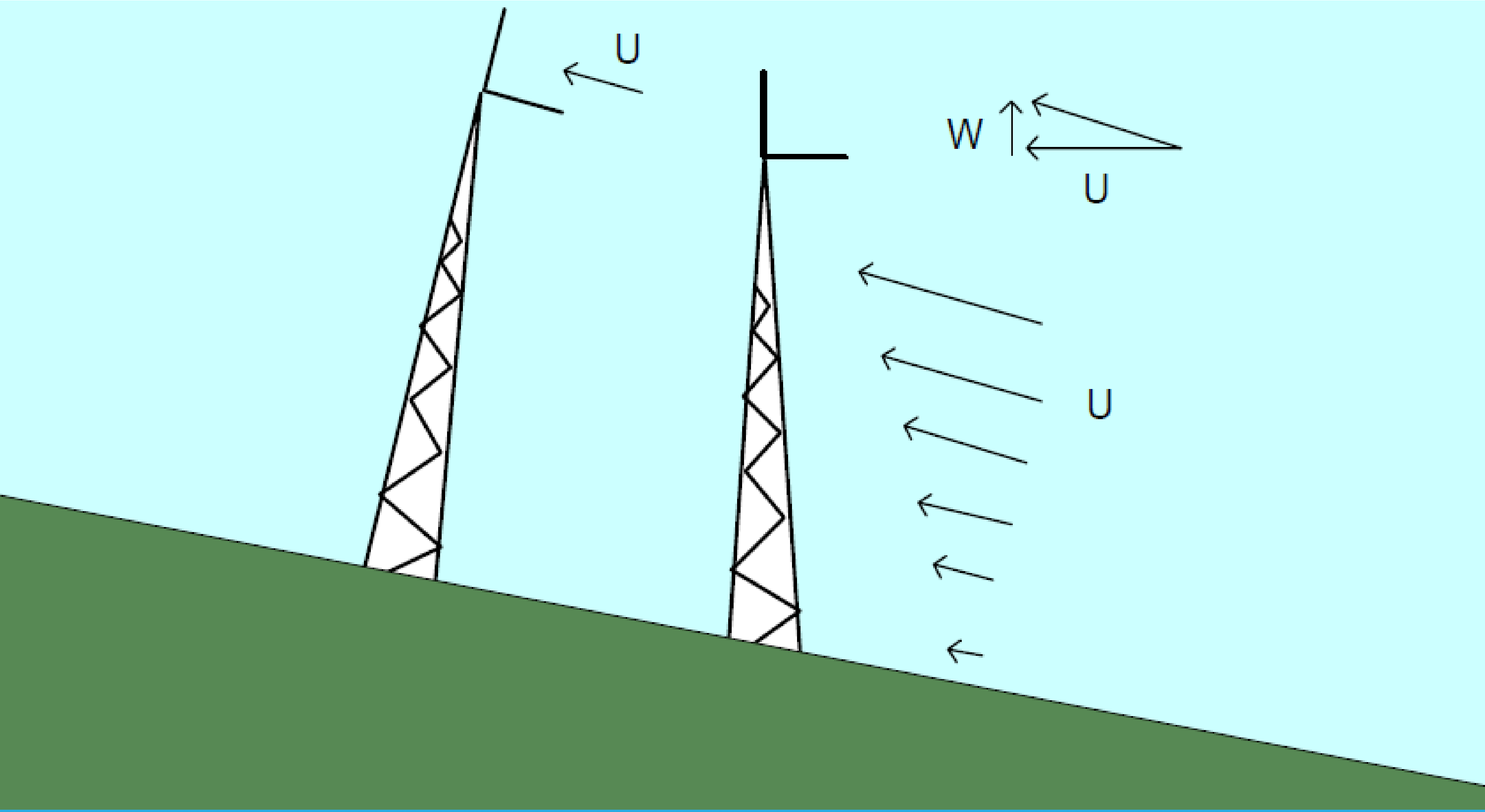


We need get rid of spikes.

Data Processing: de-spiking，剔除异常值

- unreasonable u, v, w
- abs(u', v', w') > x×std; x = 4 - 6
- other criteria

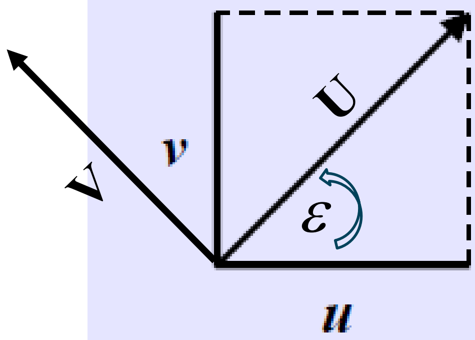
Coordinate rotation； 坐标旋转



Courtesy of Prof. Baldocchi

Coordinate rotation； 坐标旋转

1st Rotation

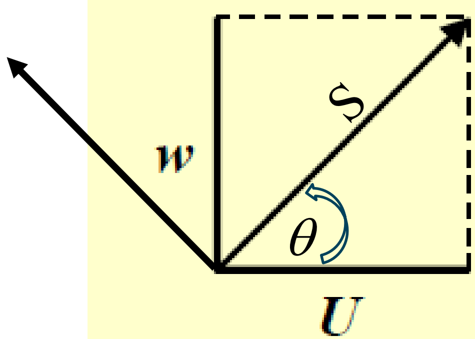


$$U = \left(u^2 + v^2\right)^{1/2}$$

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

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

2nd Rotation



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

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

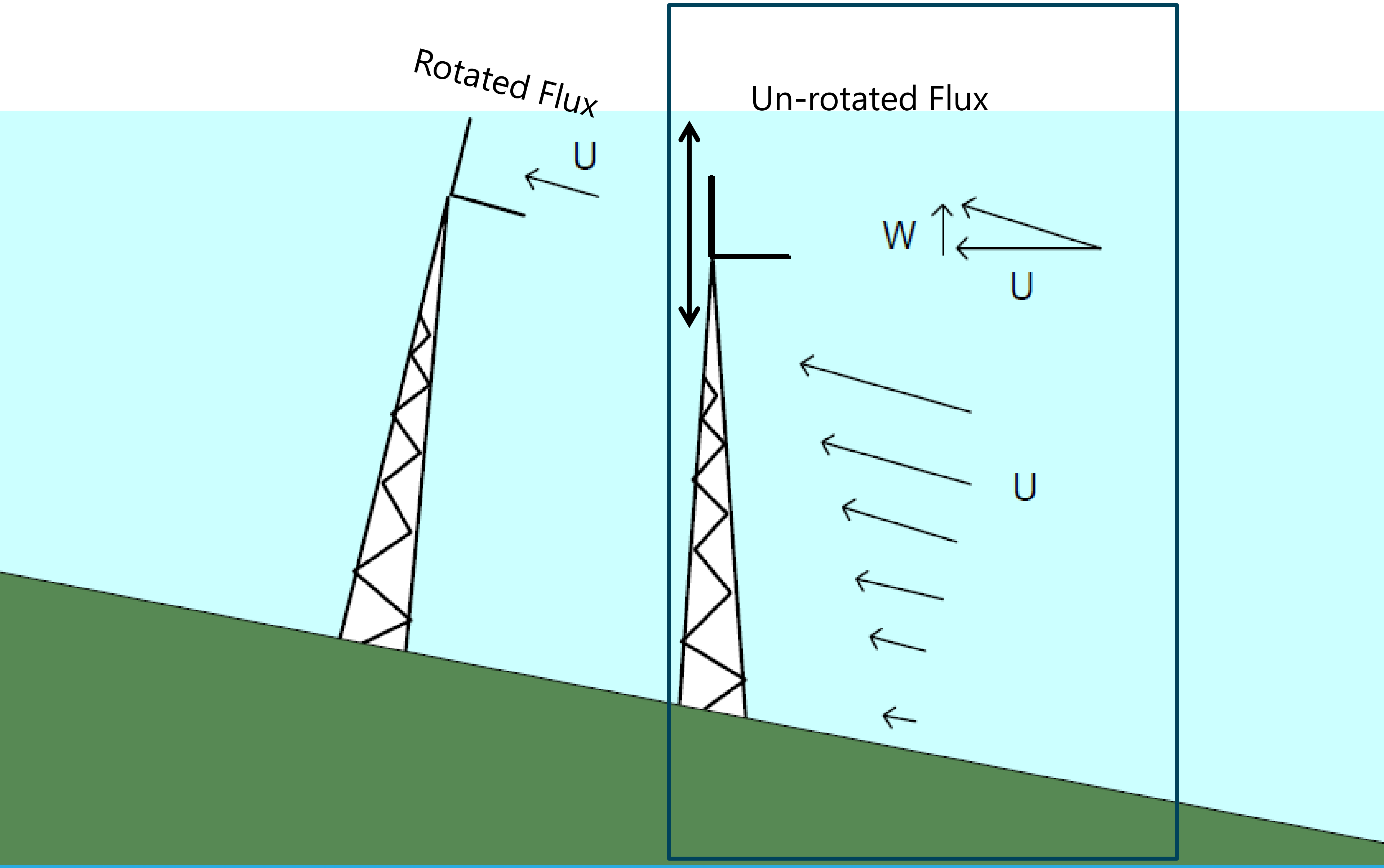
$$\sin\theta = \frac{w}{\left(u^2 + v^2 + w^2\right)^{1/2}}$$

Coordinate rotation； 坐标旋转

$$\overline{w'c'} = \overline{W'C'} \cdot \cos\theta - \overline{U'C'} \cdot \sin\theta \cdot \cos\varepsilon - \overline{V'C'} \cdot \sin\theta \cdot \sin\varepsilon$$

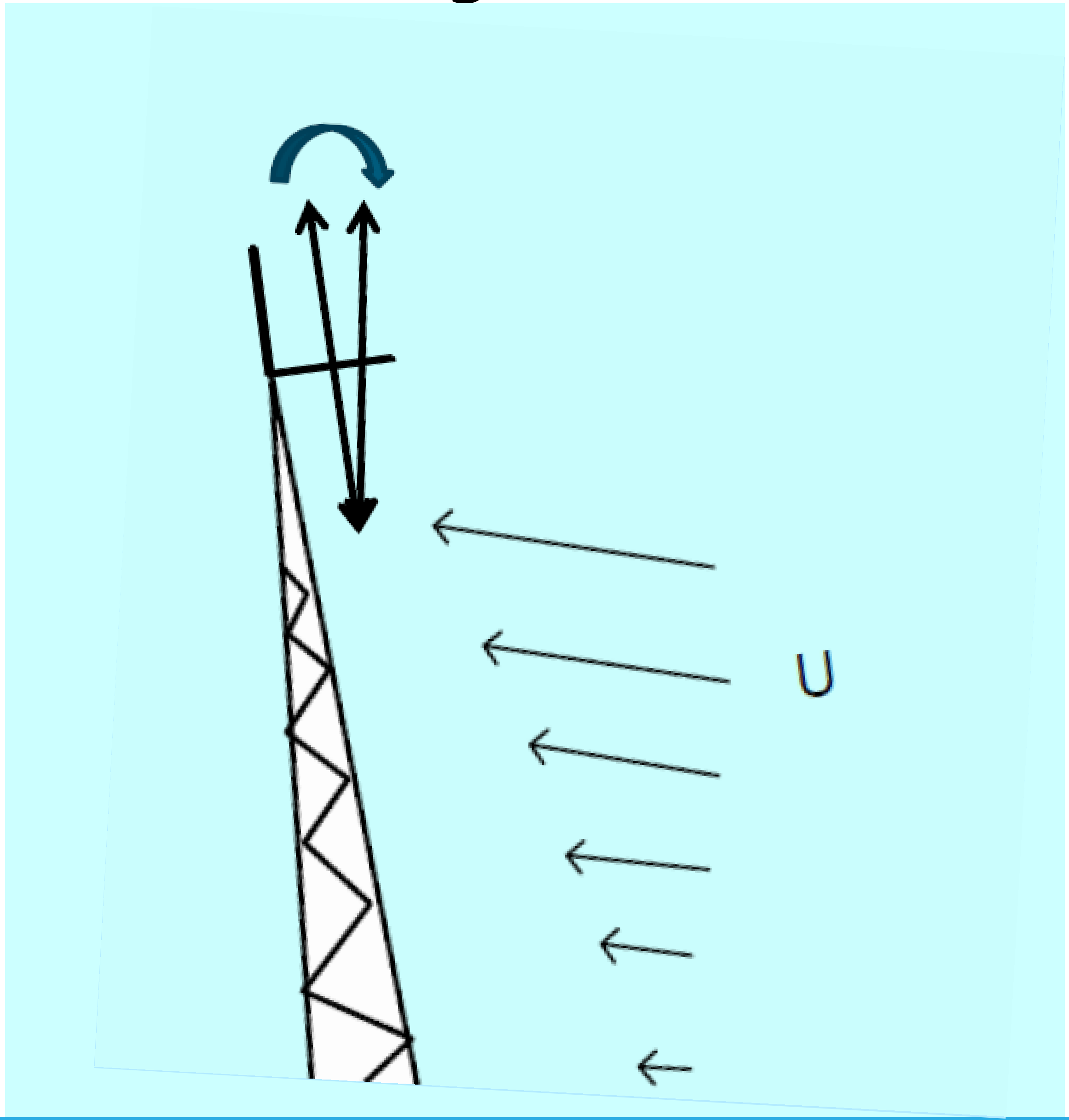
If the sonic is perfectly leveled along with the ground surface, then no coordinate rotation is needed!

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.



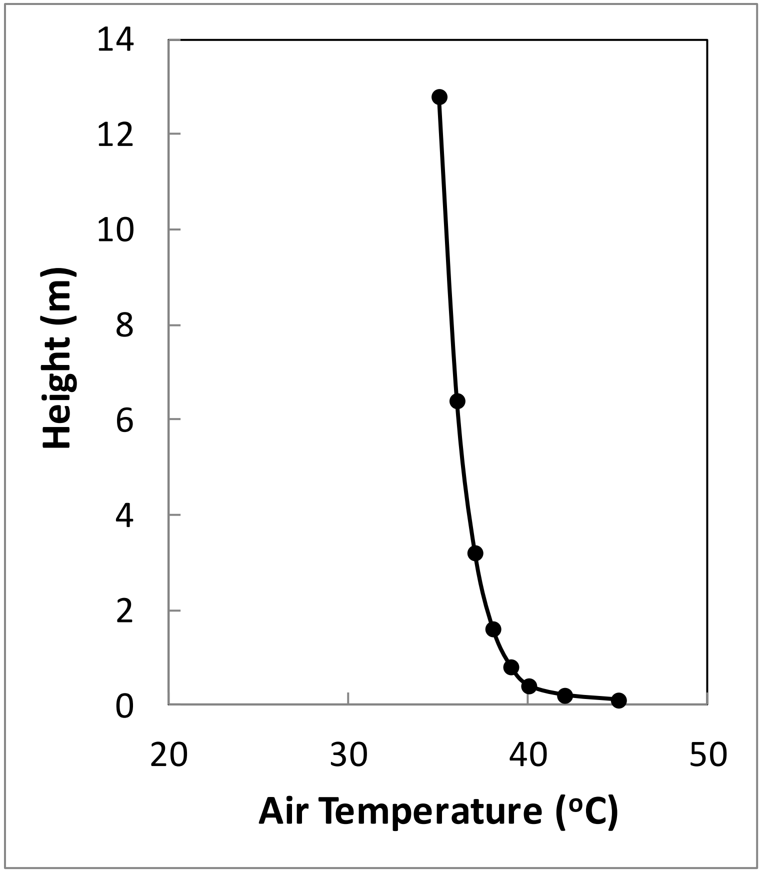
Courtesy of Prof. Baldocchi

Data Processing: Coordinate rotation



Courtesy of Prof. Baldocchi

WPL；密度订正：因为感热



Imagine a situation: over a dry parking lot

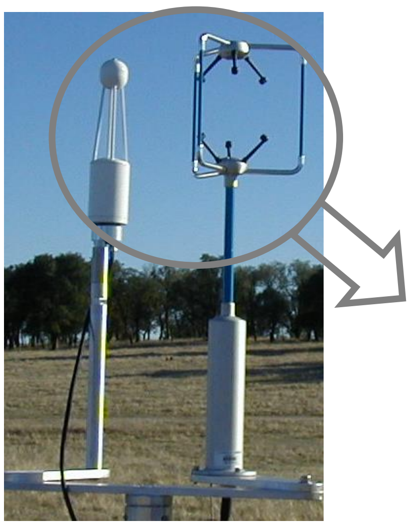
No CO_2 flux

Hot, dry summer afternoon

WPL；密度订正：因为感热

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

s is mixing ratio (g CO_2 per g air). 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' –

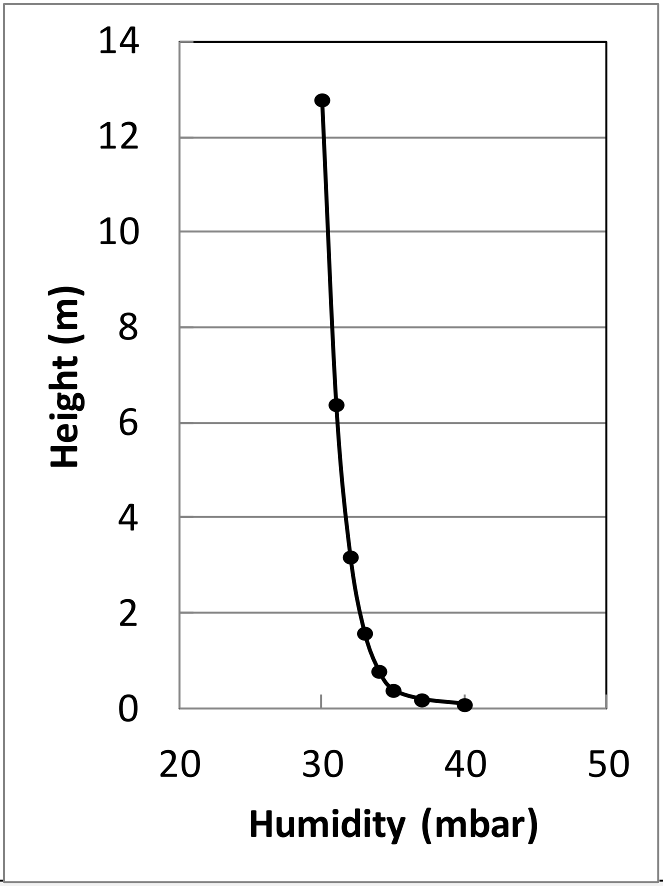
$\overline{w'CO_2'} < 0$, CO2 uptake?

Imagine a situation: over a dry parking lot

No CO_2 flux

Hot, dry summer afternoon

WPL；密度订正：因为潜热

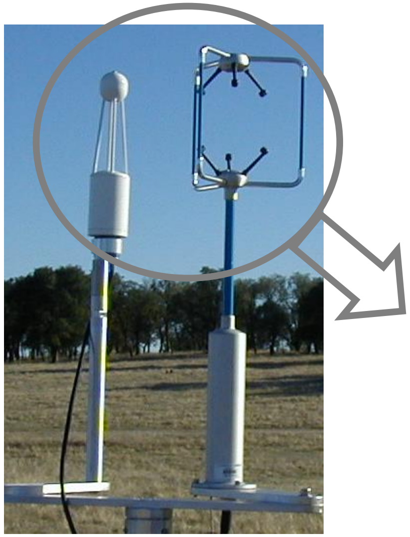


Imagine a situation: over a wet parking lot

No CO_2 flux

Hot summer afternoon

WPL；密度订正：因为潜热



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

密度订正(WPL)公式

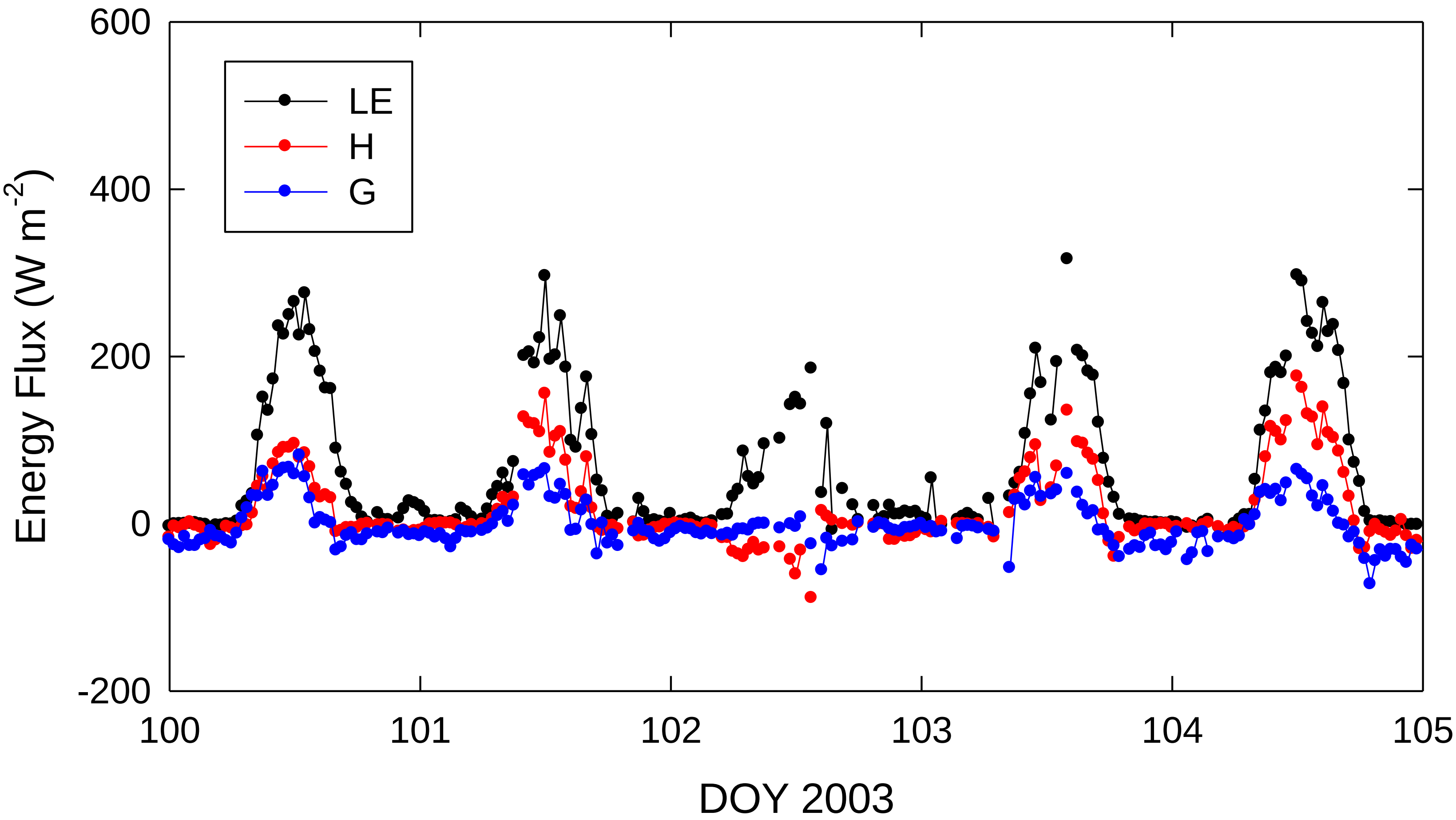
Webb, Pearman, Leuning Algorithm:
Correction for Density Fluctuations when using OpenPath Sensors

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

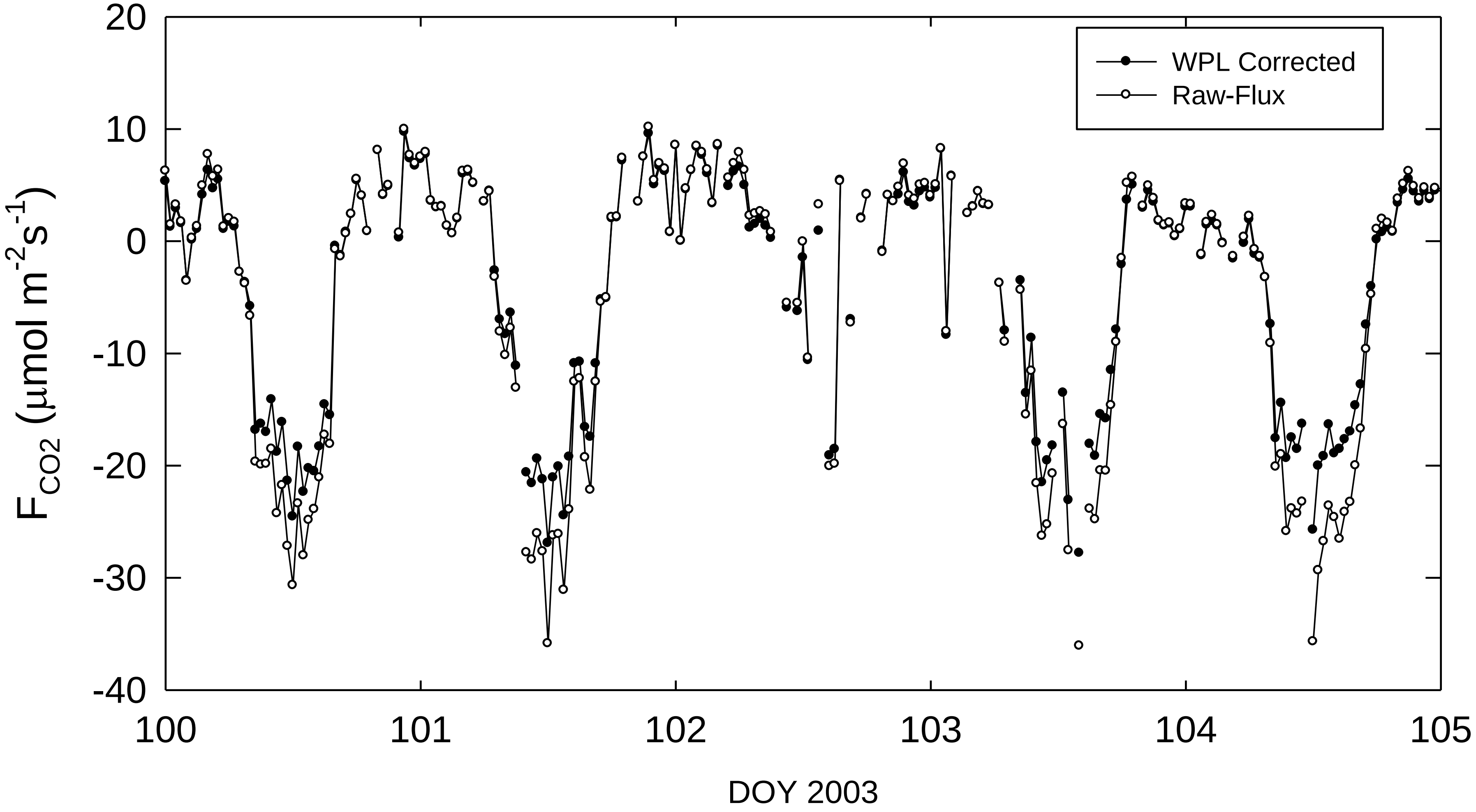
Webb et al., 1980

Magnitude of the density correction

Magnitude of the density correction



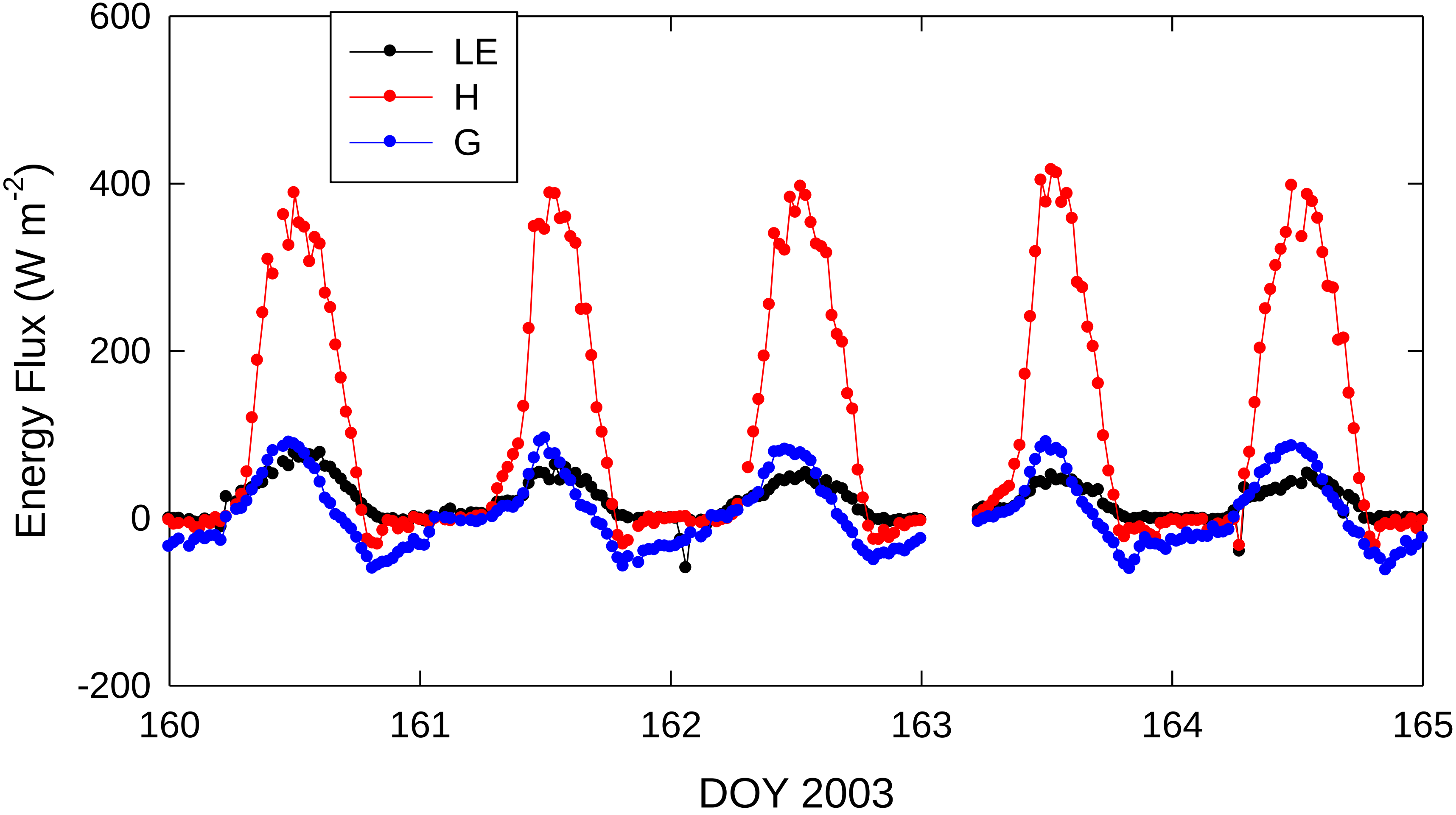
California grassland 2003, growing season



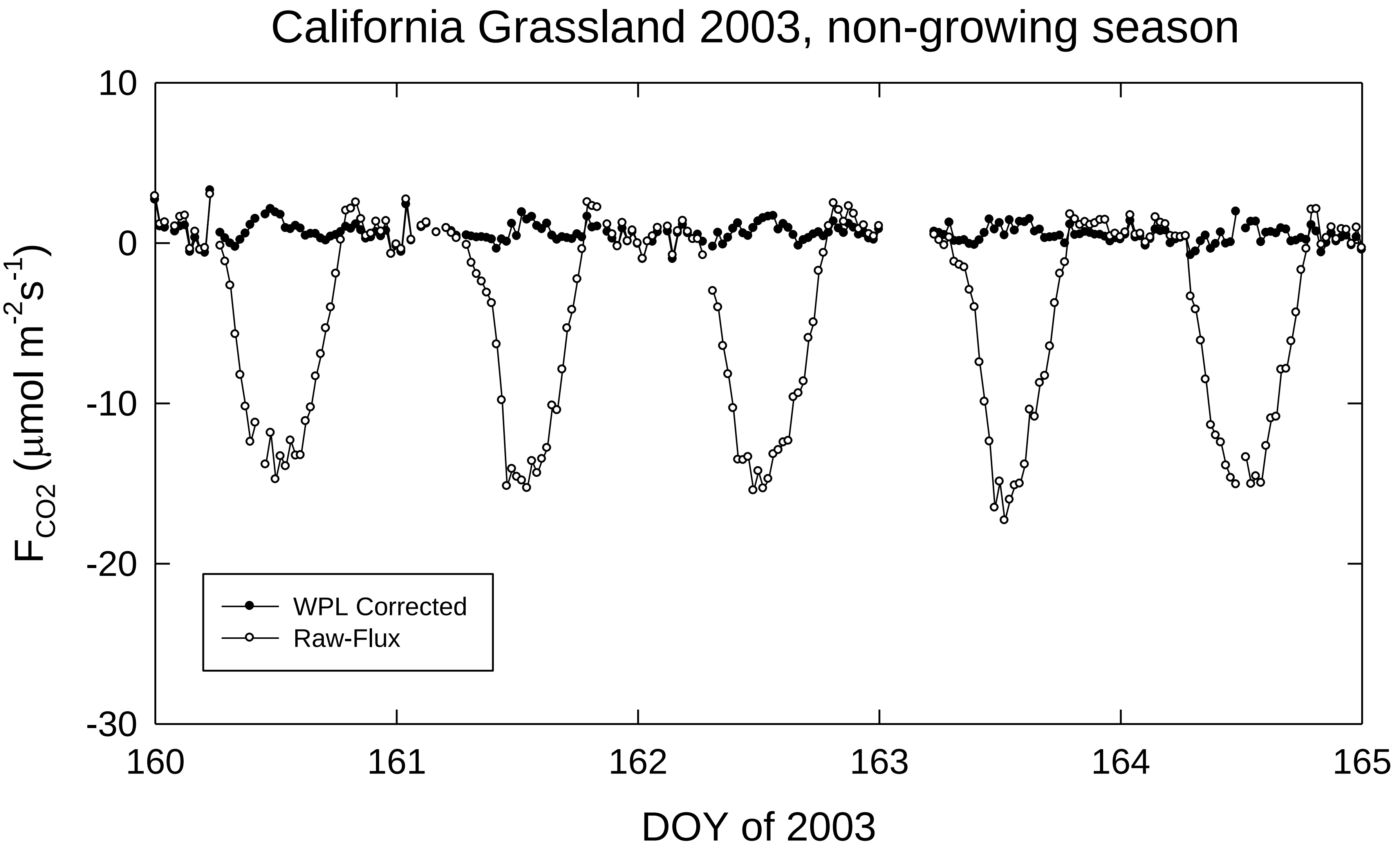
LI-COR®

Magnitude of the density correction

Magnitude of the density correction



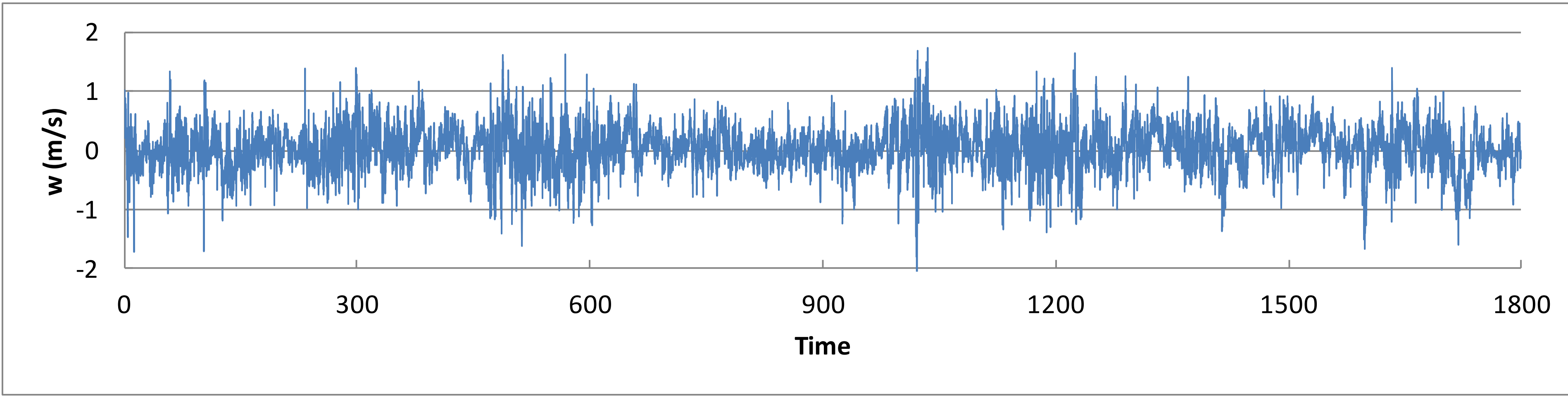
Magnitude of the density correction

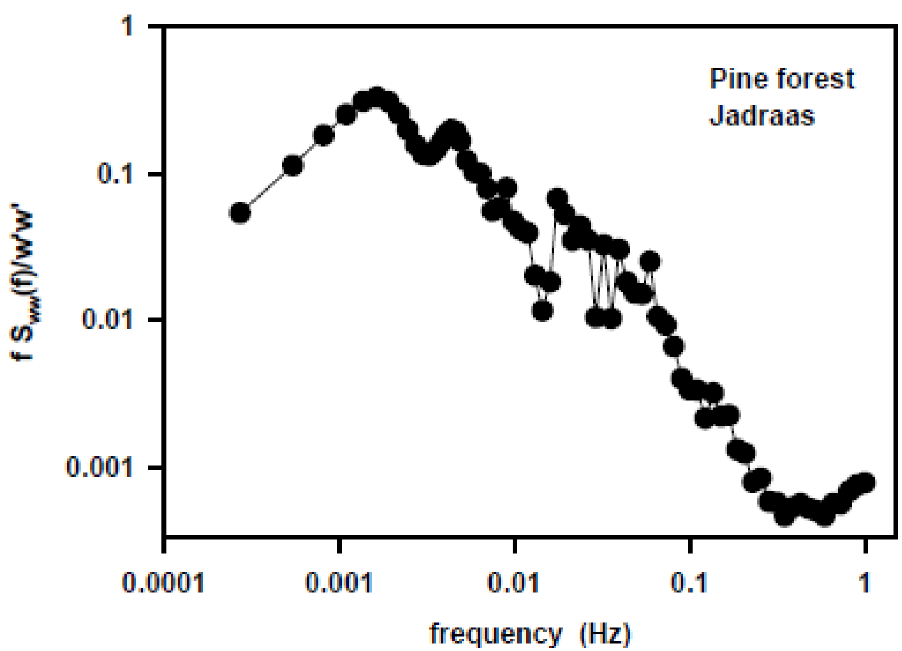


Final density correction equation (WPL)

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

Power Spectra Analysis；波谱分析





Kinetic Energy， 动能

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

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

Mean Kinetic energy (MKE，平均动能)

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

Turbulence Kinetic energy (TKE，湍流动能)

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

湍流动能的来源

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

$$\frac{\partial e}{\partial t} = -\overline{u'w'}\frac{\partial \overline{U}}{\partial z} + \frac{g}{T}\overline{\theta' w'} - \frac{\partial}{\partial z}\left(\overline{e'w'} + \frac{1}{\rho}\overline{p'w'}\right) - \varepsilon$$

I II III IV V

I: Mechanical or shear production or loss term

II. Buoyancy production or consumption term

III. Turbulent transport term by eddies

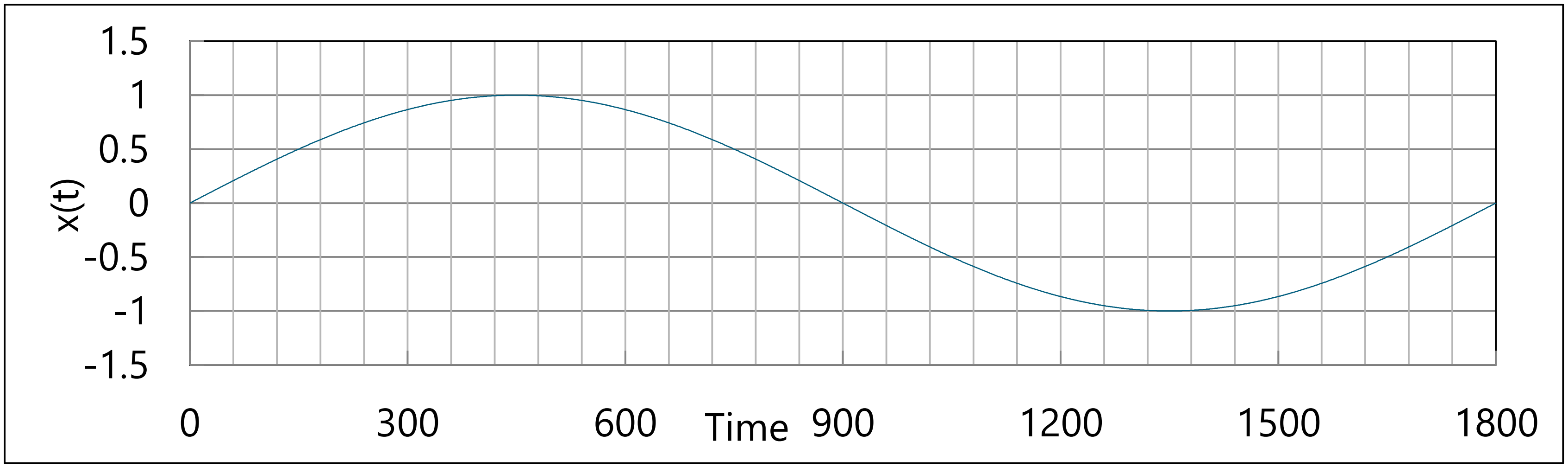
IV. Pressure correlation term, how TKE is redistributed by pressure perturbation

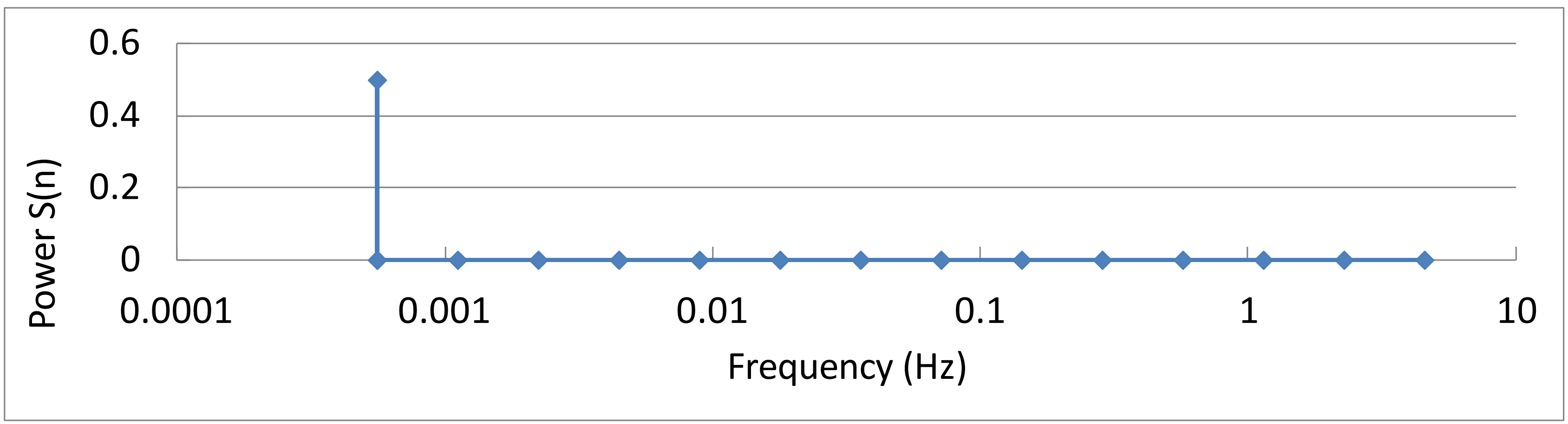
V. Viscous dissipation term, conversion of TKE to heat

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

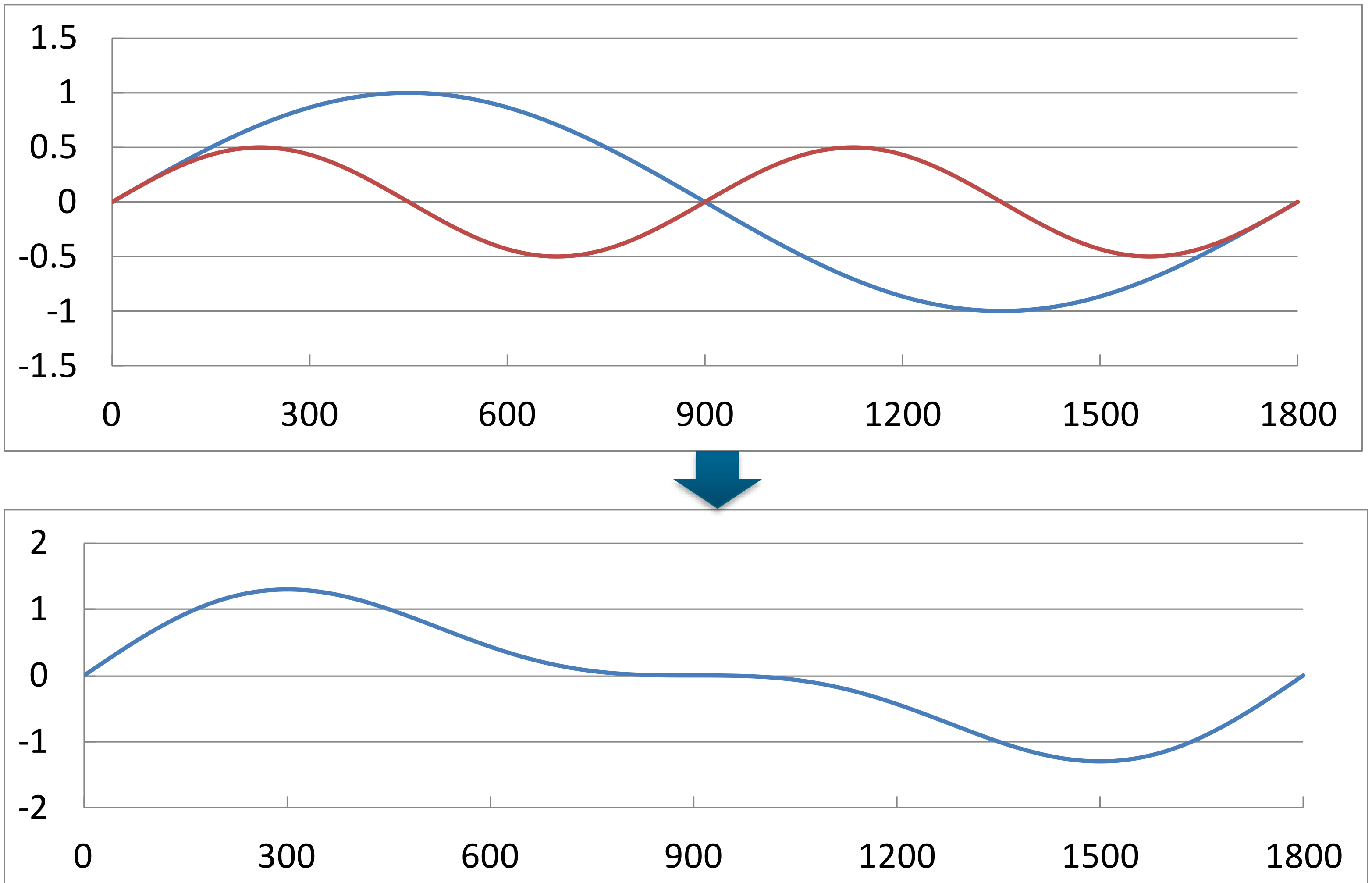
$$x(k) = \sin\left(\frac{2\pi}{1800} k\Delta t\right)$$

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

Period =15 min=900 s

Frequency=1/900=0.001111 Hz

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



Period =30 min=1800 s

Frequency=1/1800=0.000556 Hz

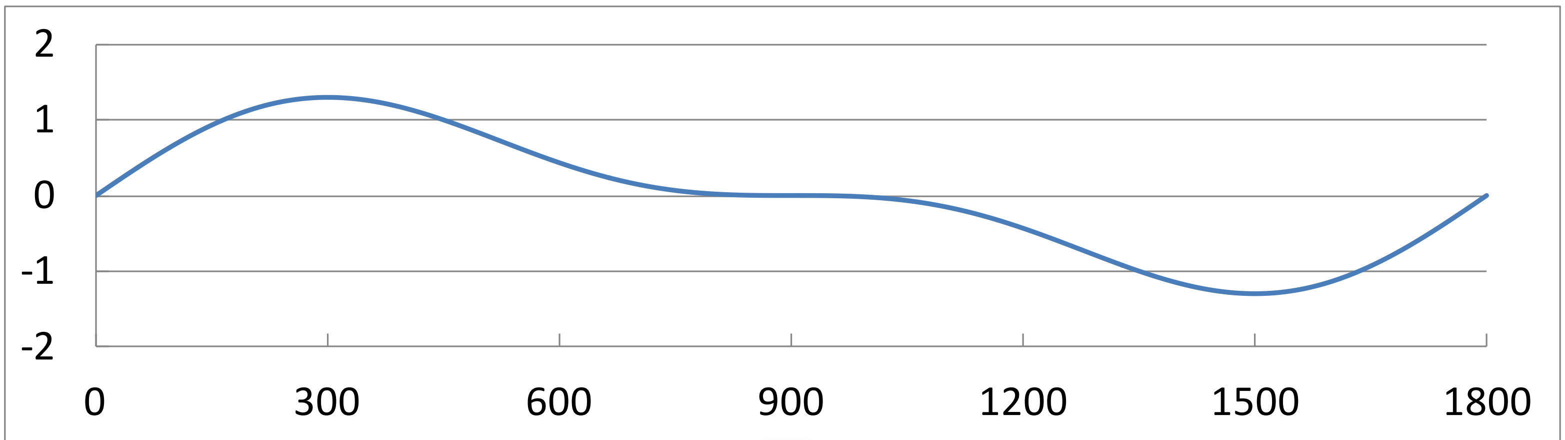
$$x(k) = \sin\left(\frac{2\pi}{1800}k\Delta t\right)$$

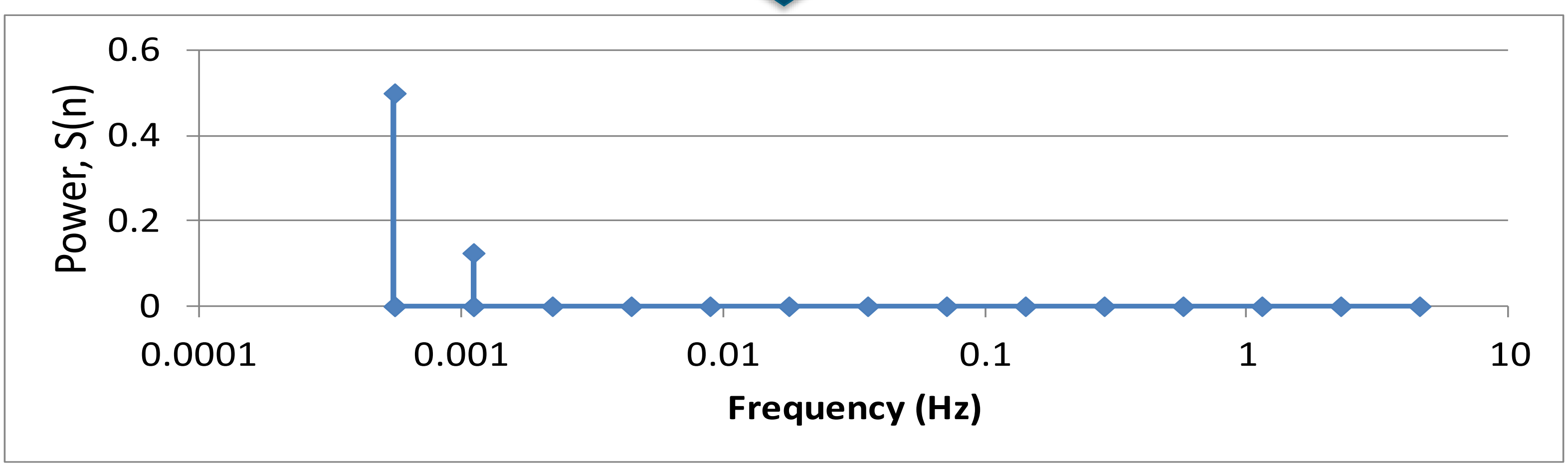
k=0, 1,2,3, N-1

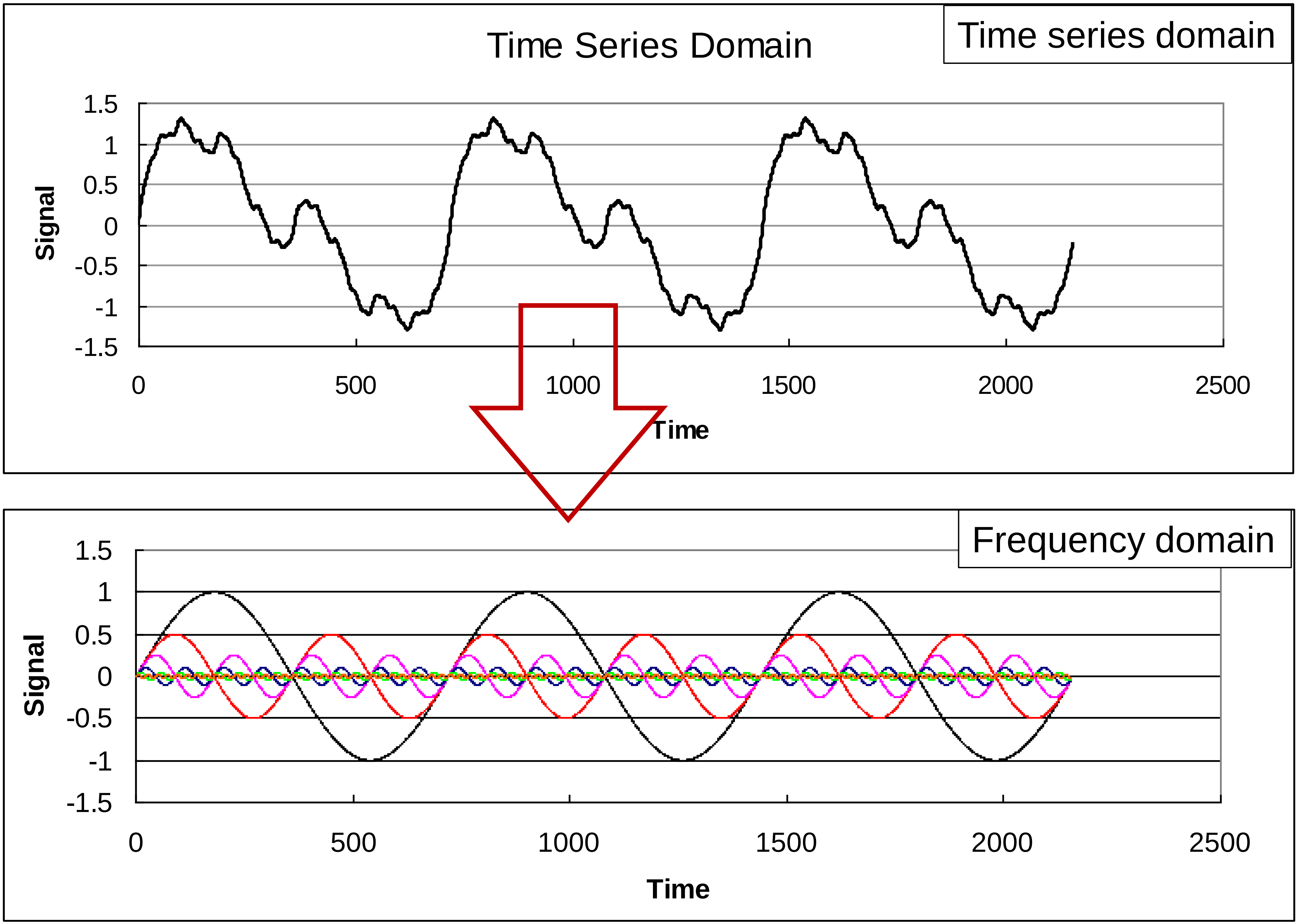
Period =15 min=900 s

Frequency=1/900=0.001111 Hz

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







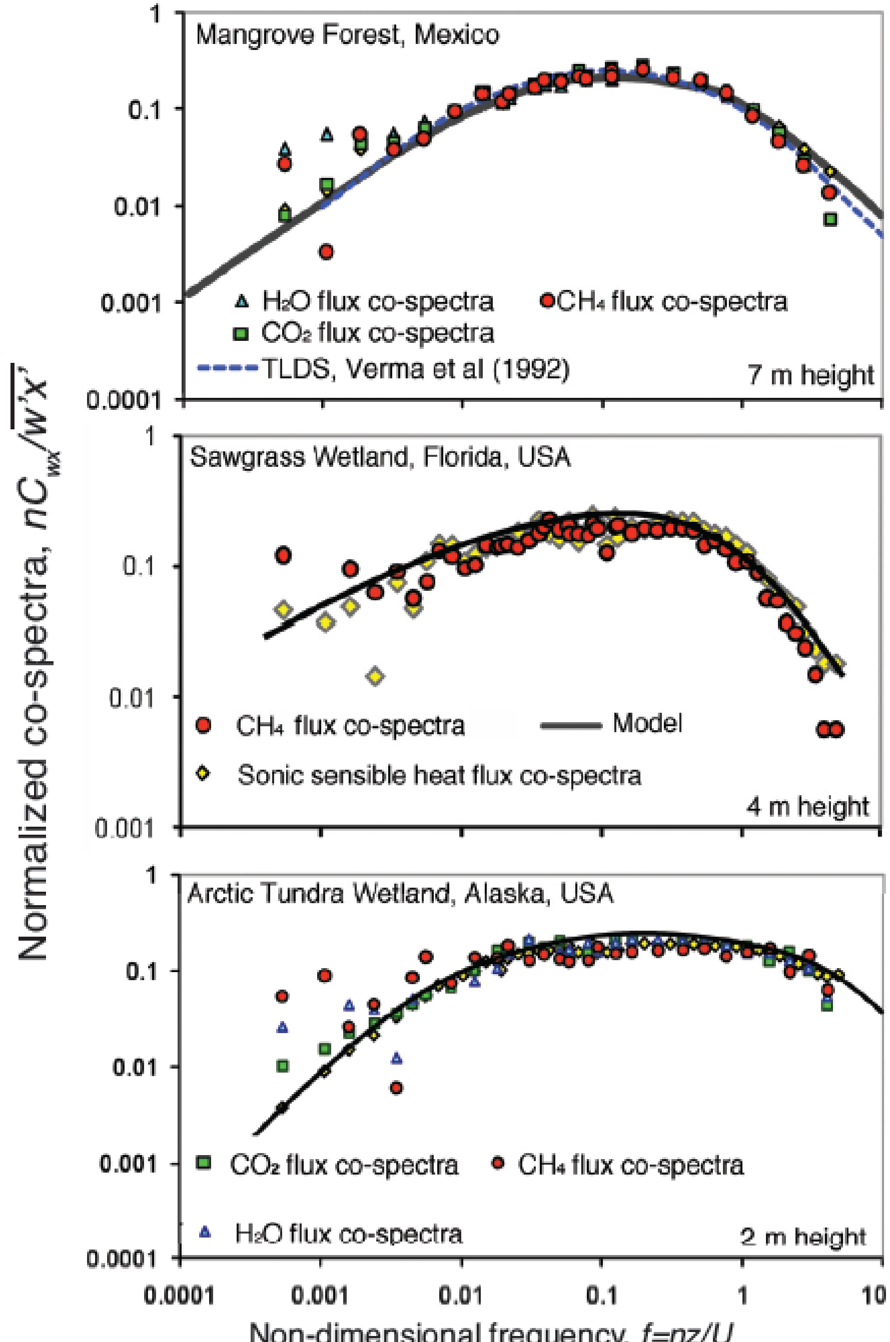
Time Series Domain
Time series domain
Signal
1.5
1
0.5
0
-0.5
-1
-1.5
0
500
1000
1500
2000
2500
Time
Frequency domain
Signal
1.5
1
0.5
0
-0.5
-1
-1.5
0
500
1000
1500
2000
2500
Time

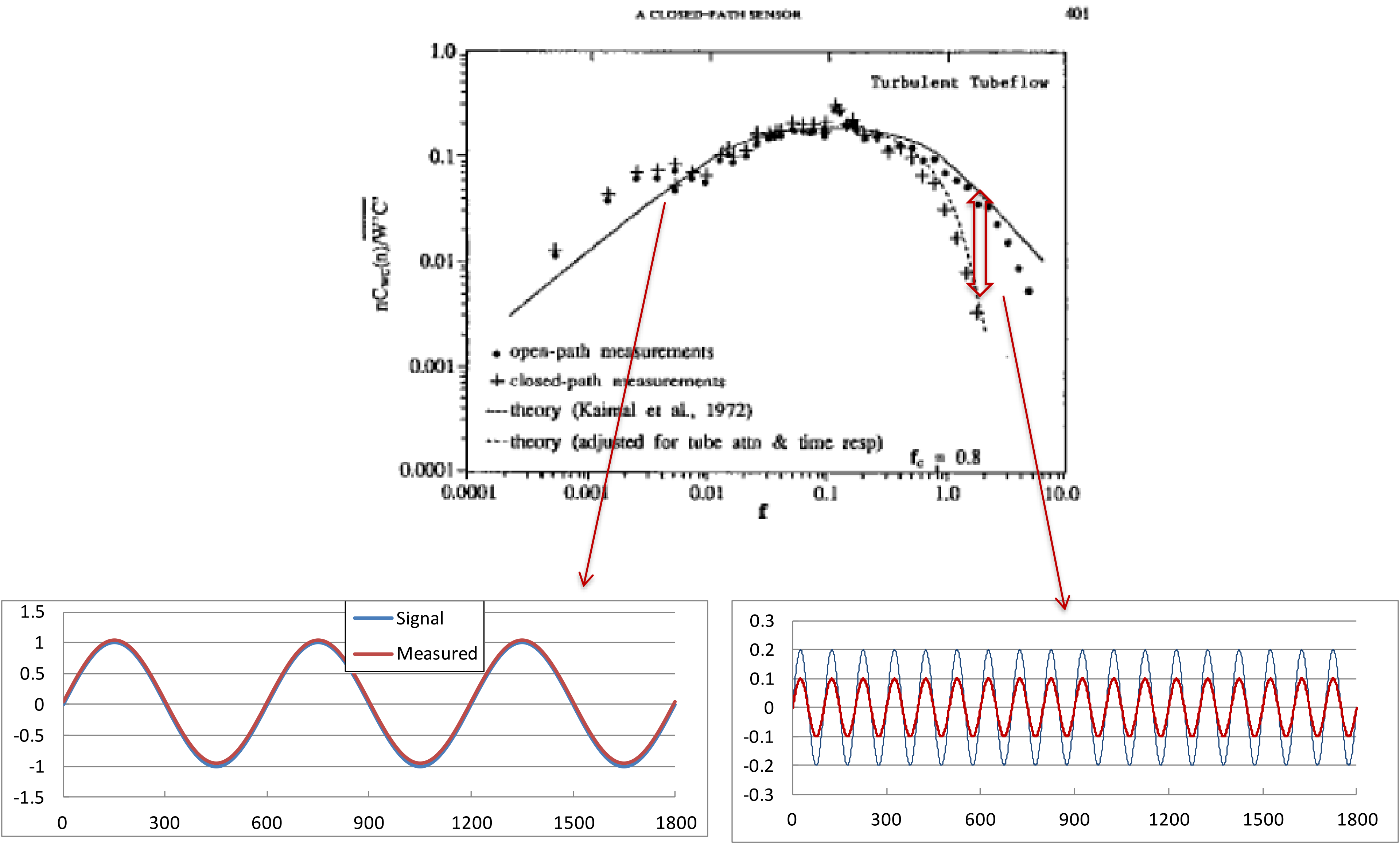
Mathematically

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

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

Spectra Analysis



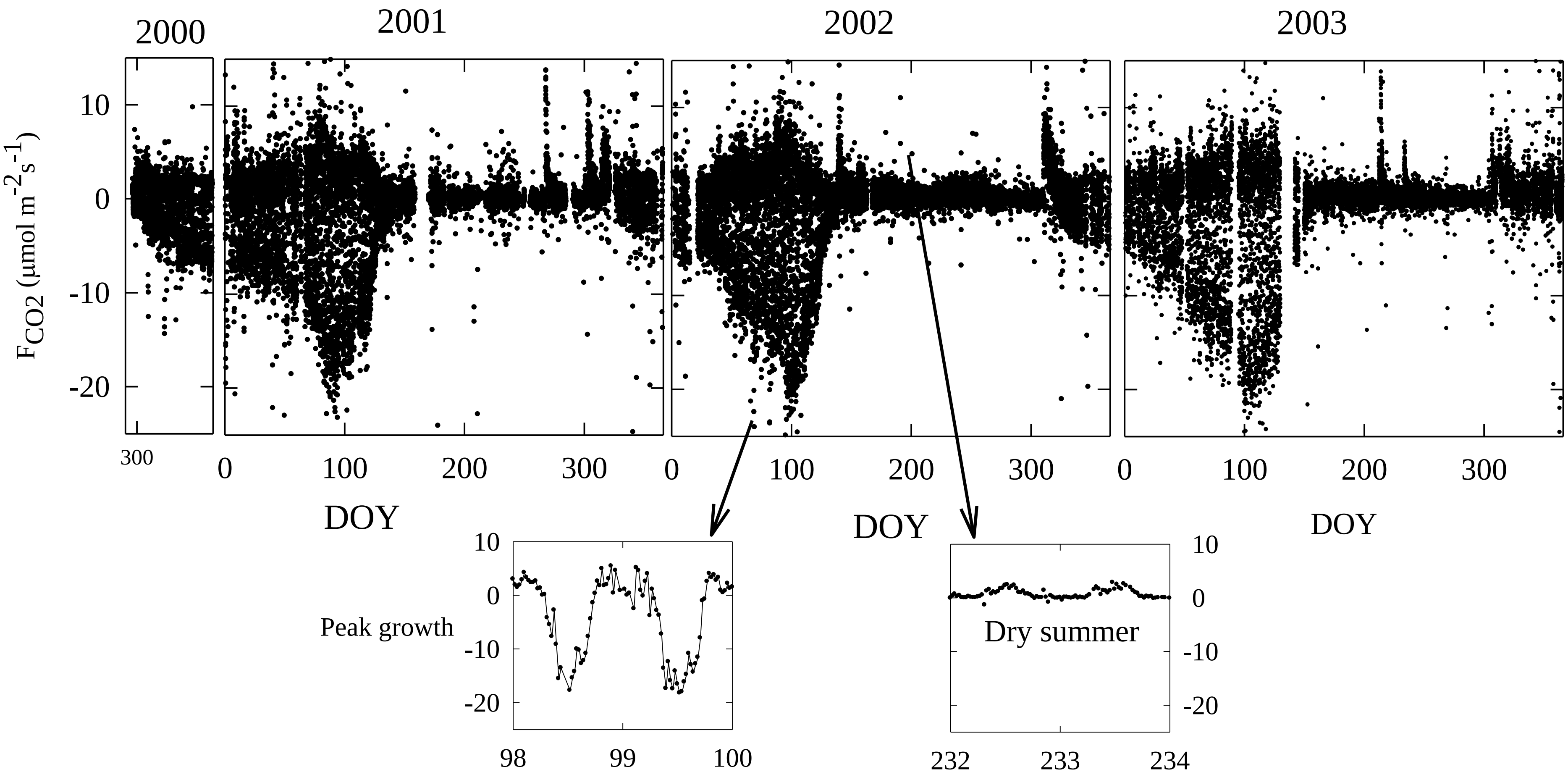


Suyker and Verma, 1993 BLM

Flux Data QA/QC； 质量控制

- *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
- Stationarity test
- other criteria

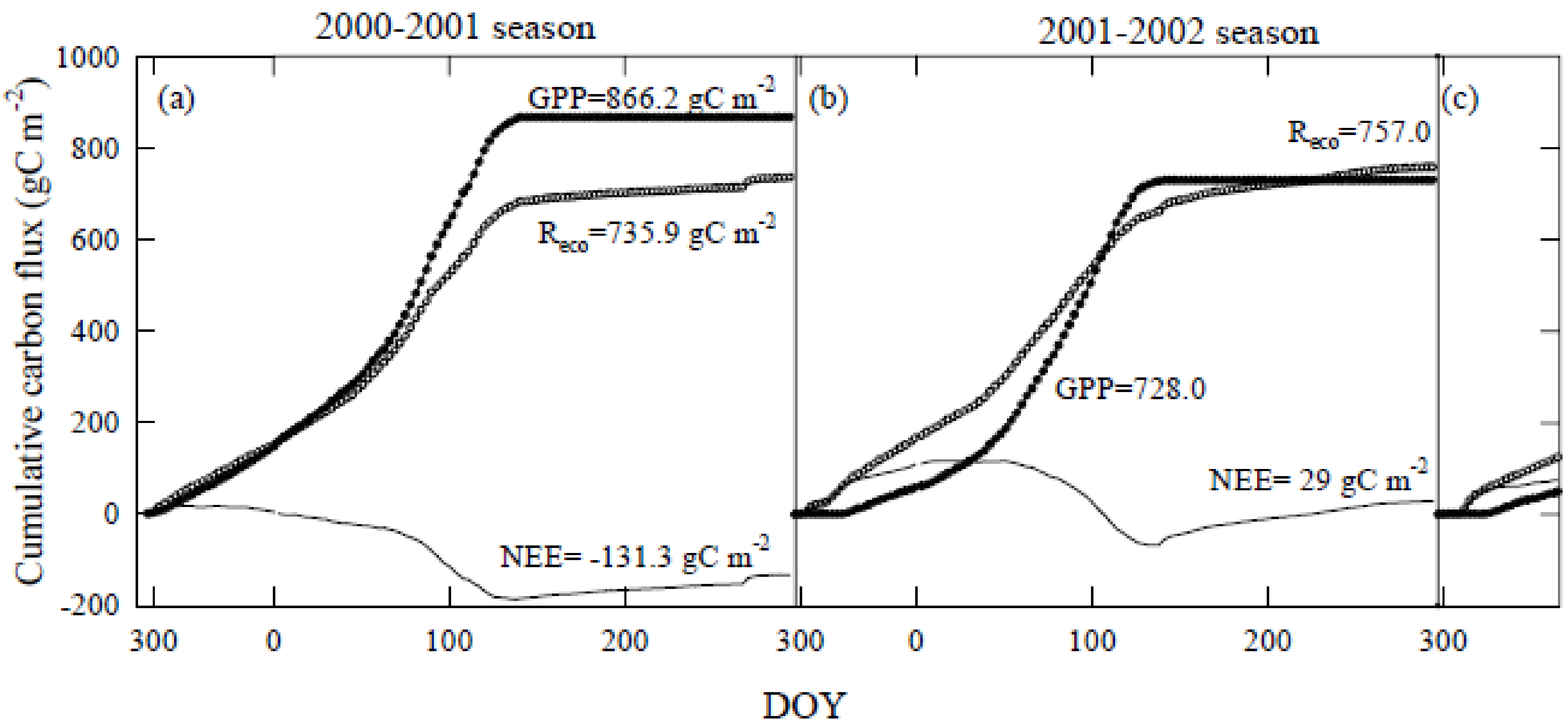
Example of long-term flux data (2000-2003)
California grassland



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； 优势

- direct measure of the flux density, 直接测量
- *in situ*, 原位观测
- No disturbance on the system, 没有干扰
- Quasi-continuous, 连续测量
- Represents a large upwind area, 大面积平均
- Others， 其他

EC Method 的 局 限 性

- Low U*, air stratification， 夜间湍流很弱
- Energy imbalance， 能量不闭合
- Horizontal advection due to complex terrain， 复杂地形
- Cannot be used for a small plot， 不能用在小的样地。

References； 参考文献:

Aubinet, M., et al., 2000. Estimates of the annual net carbon and water exchange of European forests: the EUROFLUX methodology, *Advances of Ecological Research*. 113-174

Aubinet M., Vesala T., Papale D., 2012. Eddy Covariance: A practical guide to measurement and data analysis. Springer,

Baldocchi D. D., Hicks B.B., Meyers T.P., 1988, Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods, *Ecology*, 69, 1331–1340,

Baldocchi, D. D., et al., 2001a, FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities, *Bulletin of American Meteorology Society*, 82, 2415–2434,

Baldocchi, D. D. (2003), Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future, review, *Global Change Biology*, 9, 479-492,

Falge, E., et al., 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agricultural and Forest Meteorology*, 107(1), 43-69.

Falge, E., et al., 2001. Gap filling strategies for long term energy flux data sets. *Agricultural and Forest Meteorology*, 107(1), 71-77.

Kaimal, J.C. and J.J. Finnigan. 1994. Atmospheric Boundary Layer Flows: Their Structure and Measurement. Oxford University Press, Oxford, UK. 289 pp

References； 参考文献:

Lee X, Massman W, Law B (2004) Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, Dordrecht, 250 pp.

Lenschow, DH. 1995. Micrometeorological techniques for measuring biosphere atmosphere trace gas exchange. In: Biogenic Trace Gases: Measuring Emissions from Soil and Water. Eds. P.A. Matson and R.C. Harriss. Blackwell Sci. Pub. Pp 126-163.

Moore, C. 1986. Frequency response corrections for eddy covariance systems. *Boundary Layer Meteorology*. 37, 17-35.

Stull R.B., 1994. An introduction to Boundary Layer Meteorology. Kluwer Academic Publishers.

Webb, E.K., G. Pearman and R. Leuning. 1980. Correction of flux measurements for density effects due to heat and water vapor transfer, *Quarterly Journal of Royal Meteorological society*, 106, 85-100.

Wilson, K. et al., 2002. Energy balance closure at FLUXNET sites. *Agricultural and Forest Meteorology*, 113(1-4): 223-243.

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

Thank you !

Any questions ?