农业生态系统-大气之间的二氧化碳和能量交换

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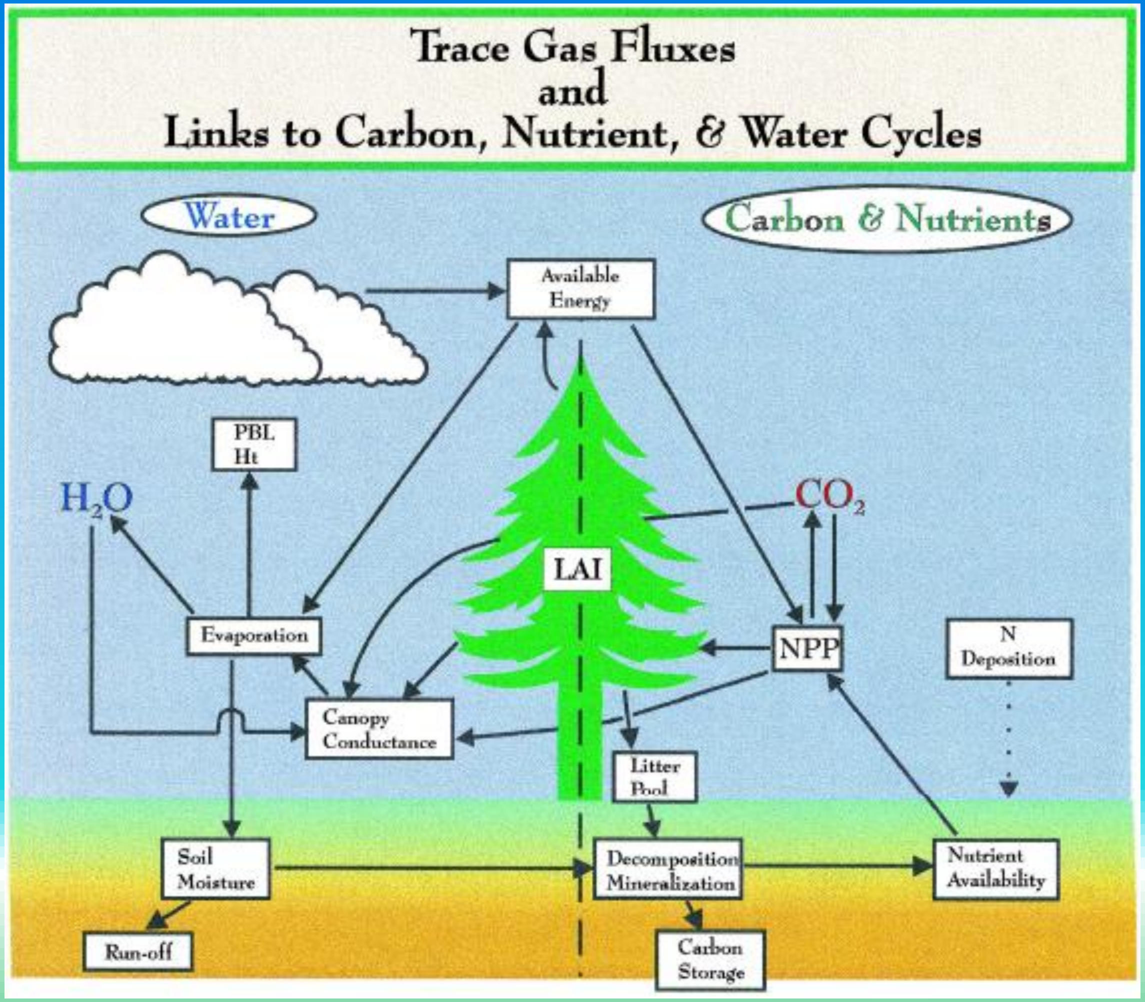
研究背景



Baldocchi & Meyers, 1998

研究背景

农业生态系统：

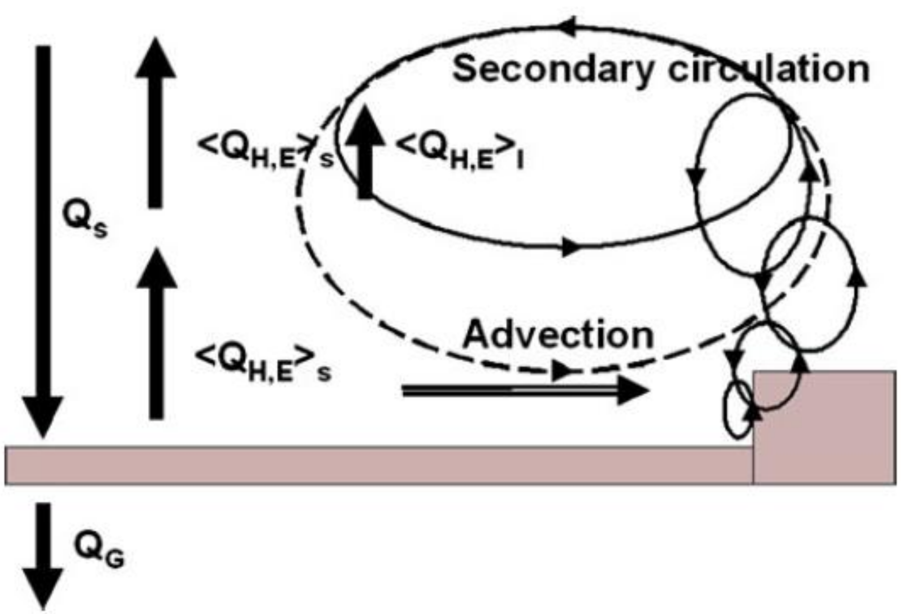
- •人类活动影响
- •非均匀下垫面
- •生长季节短，下垫面变化快

在CO_2和能量的地气交换研究上存在的问题：

- 能量平衡不闭合
- 通量观测的缺失值插补困难
- 平流的贡献未知

能量平衡的闭合
(Energy Blance Closure)

$$Res = -Q^{*} - (Q_G + Q_H + Q_E)$$



$$Q_{\mathrm{H}}^{\mathrm{EBC\text{-}HB}} = Q_{\mathrm{H}}^{\mathrm{EC}} + f_{\mathrm{HB}} Res,$$

$$Q_{\mathrm{E}}^{\mathrm{EBC\text{-}HB}} = Q_{\mathrm{E}}^{\mathrm{EC}} + (1 - f_{\mathrm{HB}}) Res,$$

$$f_{\mathrm{HB}} = \left(1 + \frac{C_1}{Bo^{\mathrm{EBC\text{-}HB}}}\right)^{-1} = \frac{Q_{\mathrm{H}}^{\mathrm{EBC\text{-}HB}}}{Q_{\mathrm{H}}^{\mathrm{EBC\text{-}HB}} + C_1 Q_{\mathrm{E}}^{\mathrm{EBC\text{-}HB}}},$$

$$C_1 = 0.61\bar{T}\frac{c_{\mathrm{p}}}{\lambda}$$

Foken et al., 2010

Charuchittipan et al., 2014

能量通量缺失值的插补
(Data Gap-filling)

- Penman-Monteith (PM) equation

$$Q_{\mathrm{E}}^{\mathrm{PM}} = \frac{s_{\mathrm{c}}(-R_{\mathrm{n}} - Q_{\mathrm{G}}) + \frac{\rho c_{\mathrm{p}}(e_{\mathrm{s}} - e_{\mathrm{a}})}{r_{\mathrm{a}}}}{s_{\mathrm{c}} + \gamma(1 + \frac{r_{\mathrm{s}}}{r_{\mathrm{a}}})}$$

Penman, 1948
Monteith, 1965

气孔阻力

FAO

KP

$$r_{\mathrm{s}} = \frac{r_{\mathrm{si}}}{\mathrm{LAI}_{\mathrm{active}}}$$

Allen et al., 1998

$$\frac{r_{\mathrm{s}}}{r_{\mathrm{a}}} = a\frac{r^*}{r_{\mathrm{a}}} + b$$

$$r^* = \frac{(s_{\mathrm{c}} + \gamma)\rho c_{\mathrm{p}}(e_{\mathrm{s}} - e_{\mathrm{a}})}{s_{\mathrm{c}}\gamma(-R_{\mathrm{n}} - Q_{\mathrm{G}})}$$

Katerji and Perrier (1983)

Katerji et al. 2011

CO_2通量缺失值的插补 (Data Gap-filling)

$$\mathrm{NEE} = \mathrm{GPP} + R_{\mathrm{eco}}$$

$$\mathrm{GPP} = \frac{\alpha R_{\mathrm{g}} \beta}{\alpha R_{\mathrm{g}} + \beta}$$

Michaelis and Menten, 1913

$$R_{\mathrm{eco}} = R_{\mathrm{ref}} e^{E_0 \left(\frac{1}{T_{\mathrm{ref}} - T_0} - \frac{1}{T - T_0} \right)}$$

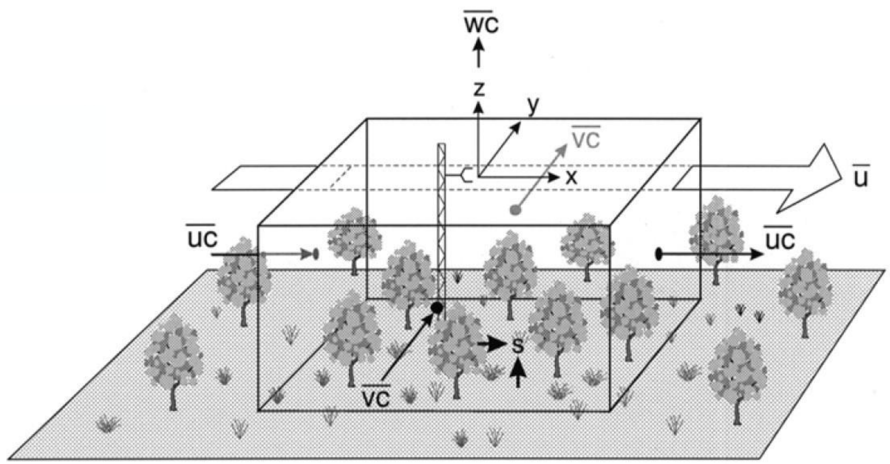
Lloyd and Taylor, 1994
Falge et al., 2001

$$\beta = \begin{cases} \beta_0 e^{-k_\beta (\mathrm{VPD} - \mathrm{VPD}_0)} & , \ \mathrm{VPD} > \mathrm{VPD}_0 \\ \beta_0 & , \ \mathrm{VPD} \leq \mathrm{VPD}_0 \end{cases}$$

Lasslop et al., 2010

平流的贡献

- 物质守恒方程



Finnigan *et al*., 2003

$$\overline{F_c} = \overline{F_c}(0) + \frac{1}{L^2}\int_0^L\int_0^L\int_0^h \overline{S_c}\,dz\,dx\,dy$$

$$= \frac{1}{L^2}\int_0^L\int_0^L\int_0^h \overline{c_d}\,\overline{\frac{\partial \chi_c}{\partial t}}\,dz\,dx\,dy$$

$$+\frac{1}{L^2}\int_0^L\int_0^L\int_0^h \left[\overline{u}\,\overline{c_d}\frac{\partial \overline{\chi_c}}{\partial x} + \overline{v}\,\overline{c_d}\frac{\partial \overline{\chi_c}}{\partial y} + \overline{w}\,\overline{c_d}\frac{\partial \overline{\chi_c}}{\partial z}\right] dz\,dx\,dy$$

$$+\frac{1}{L^2}\int_0^L\int_0^L\int_0^h \left[\frac{\partial \overline{c_d}\,\overline{u'\chi_c'}}{\partial x} + \frac{\partial \overline{c_d}\,\overline{v'\chi_c'}}{\partial y} + \frac{\partial \overline{c_d}\,\overline{w'\chi_c'}}{\partial z}\right] dz\,dx\,dy$$

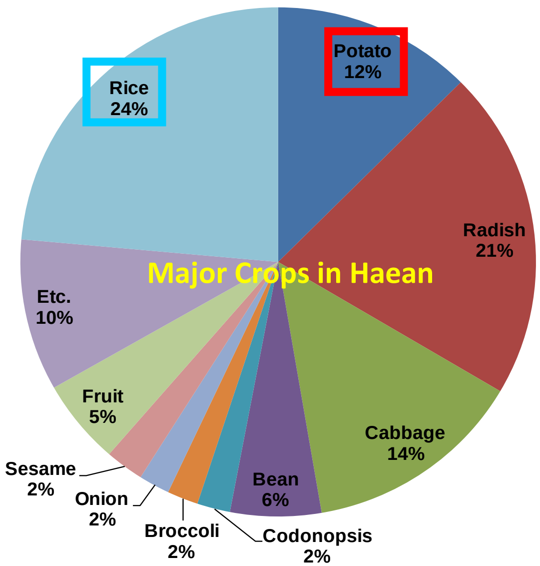
Leuning et al., 2008, 2010

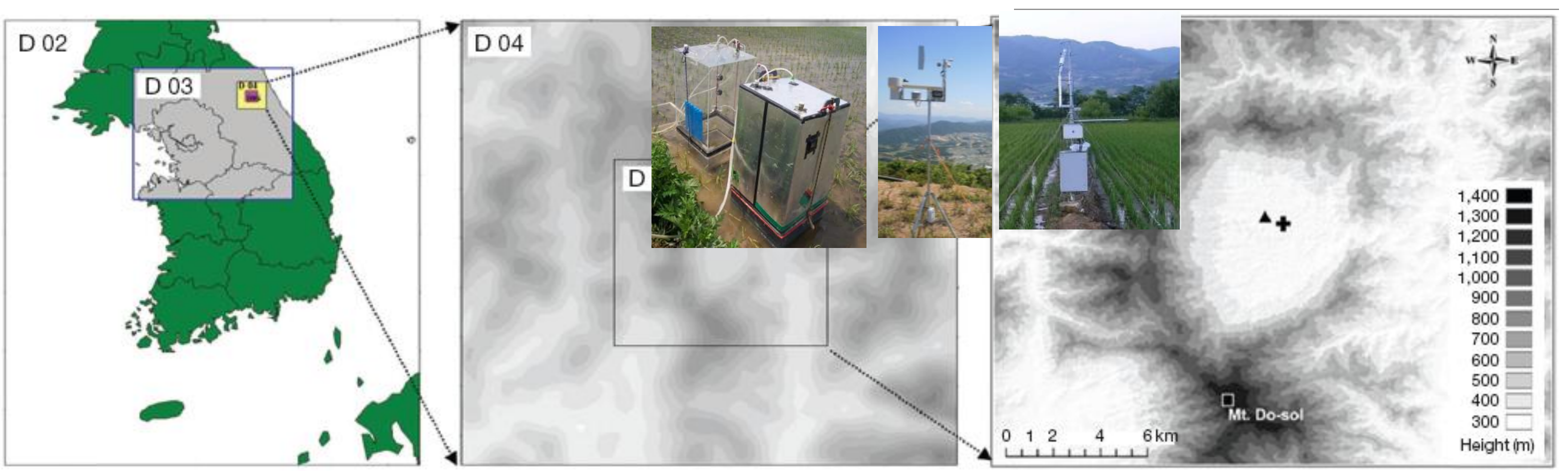
$F_c = F_s + F_{VT} + F_{HT} + F_{HA} + F_{VA}$

第一部分：能量交换

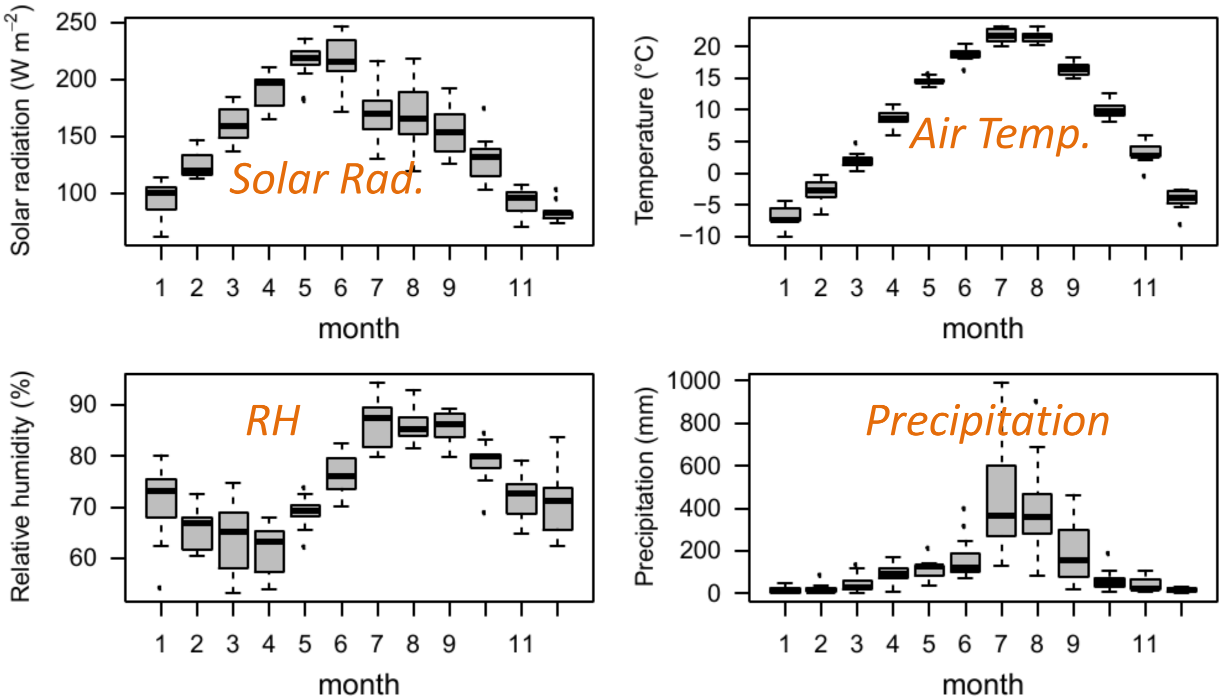
研究站点

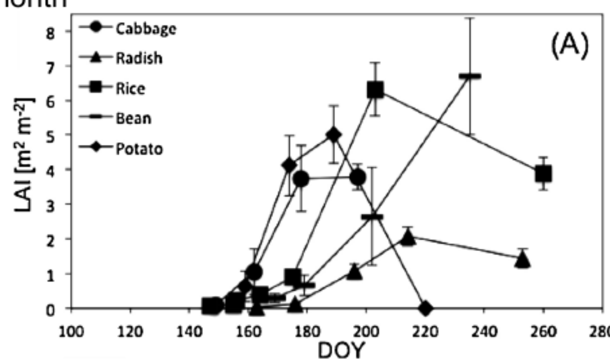
- TERRECO (Complex TERRain and ECOlogical Heterogeneity), 2009-2014
- 韩国亥安, 2009 – 2011
- 观测手段：
  - 涡度相关
  - 通量箱
  - 常规气象要素
  - 叶面积指数





气候条件与作物生长

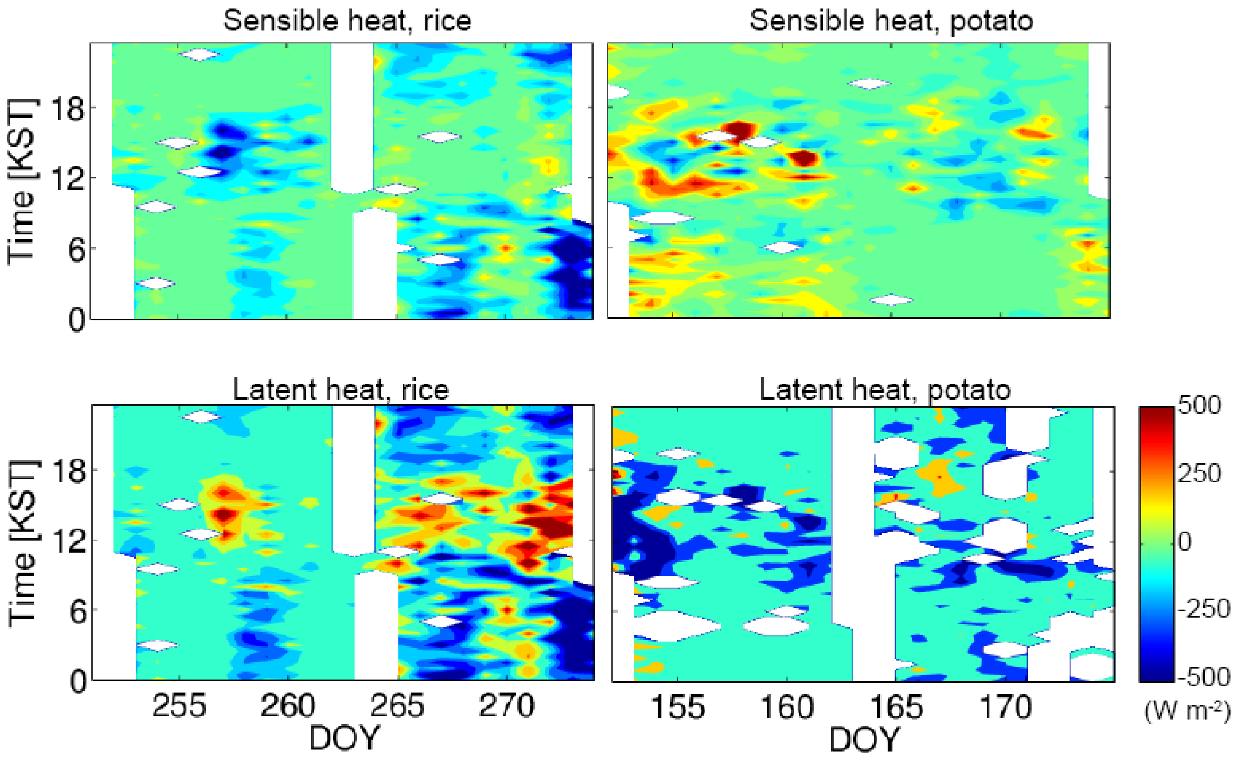




Lindner et al., 2014

次级环流(SC)

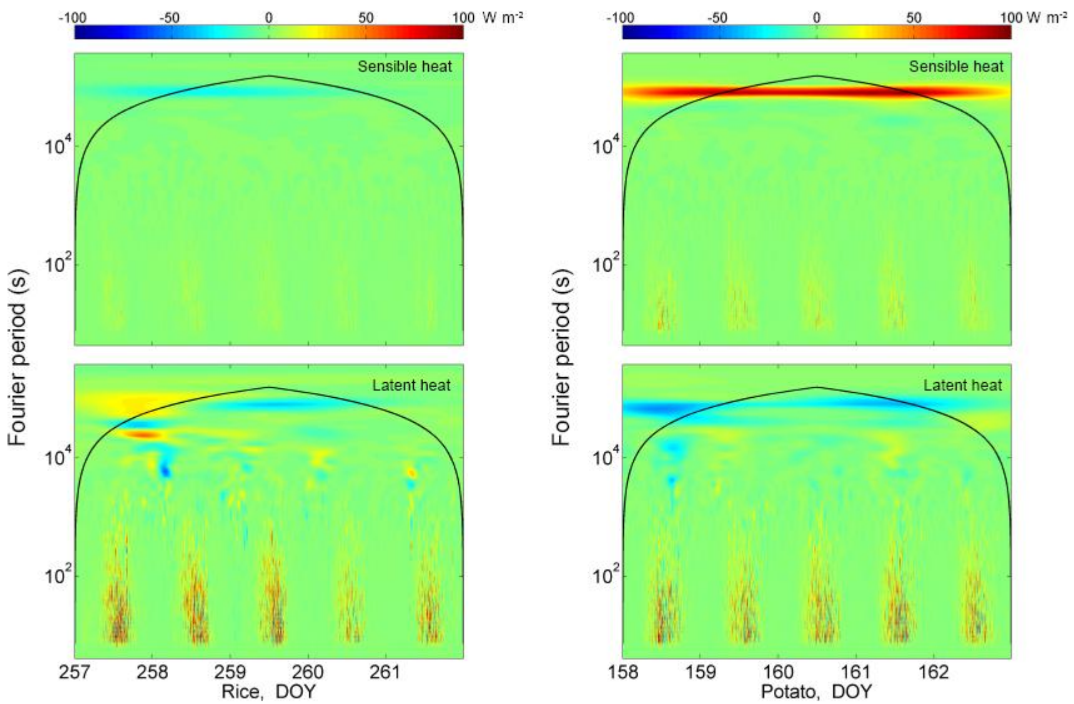
	水稻田	土豆田
EBC	88%	74%



Meso-scale movement

次级环流(SC)

	水稻田	土豆田
EBC	88%	74%



Meso-scale movement

能量通量的修正

Charuchittipan et al., 2014

$$Q_{\mathrm{H}}^{\text{EBC-HB}} = Q_{\mathrm{H}}^{\mathrm{EC}} + f_{\mathrm{HB}} Res,$$

$$Q_{\mathrm{E}}^{\text{EBC-HB}} = Q_{\mathrm{E}}^{\mathrm{EC}} + (1 - f_{\mathrm{HB}}) Res,$$

$$f_{\mathrm{HB}} = \left(1 + \frac{C_1}{Bo^{\text{EBC-HB}}}\right)^{-1} = \frac{Q_{\mathrm{H}}^{\text{EBC-HB}}}{Q_{\mathrm{H}}^{\text{EBC-HB}} + C_1 Q_{\mathrm{E}}^{\text{EBC-HB}}},$$

$$C_1 = 0.61 \bar{T} \frac{c_{\mathrm{p}}}{\lambda}$$

本研究

$$f_{\mathrm{HB}} = 0.5 + \frac{C_2}{Res},$$

$$Q_{\mathrm{H}}^{\text{EBC-HB}} = Q_{\mathrm{H}}^{\mathrm{EC}} + 0.5 Res + C_2$$

$$Q_{\mathrm{E}}^{\text{EBC-HB}} = Q_{\mathrm{E}}^{\mathrm{EC}} + 0.5 Res - C_2$$

$$C_2 = \frac{\sqrt{(Q_{\mathrm{H}}^{\mathrm{EC}} + C_1 Q_{\mathrm{E}}^{\mathrm{EC}} - Res + C_1 Res)^2 + 4(1 - C_1) Q_{\mathrm{H}}^{\mathrm{EC}} Res} - Q_{\mathrm{H}}^{\mathrm{EC}} - C_1 Q_{\mathrm{E}}^{\mathrm{EC}}}{2(1 - C_1)}$$

Zhao et al., 2016

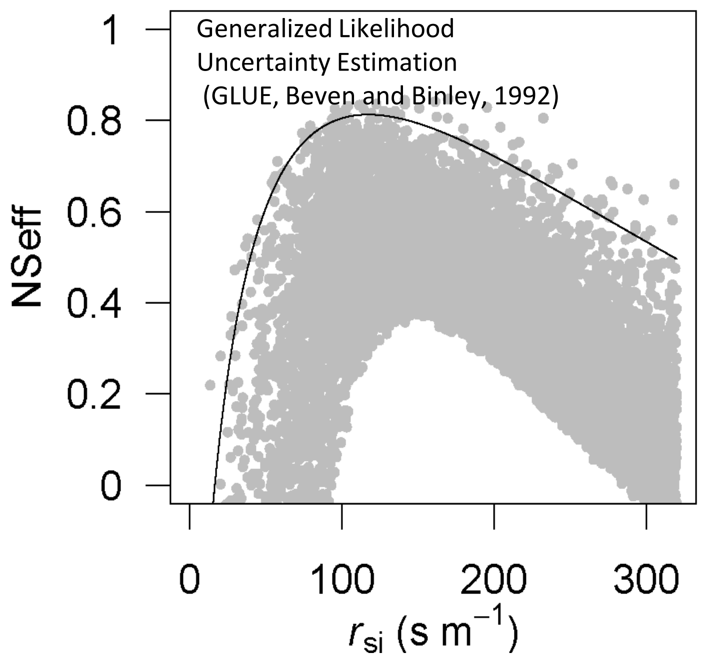
PM-FAO

$$Q_{\mathrm{E}}^{\mathrm{PM}} = \frac{s_{\mathrm{c}}(-R_{\mathrm{n}} - Q_{\mathrm{G}}) + \frac{\rho c_{\mathrm{p}}(e_{\mathrm{s}} - e_{\mathrm{a}})}{r_{\mathrm{a}}}}{s_{\mathrm{c}} + \gamma(1 + \frac{r_{\mathrm{s}}}{r_{\mathrm{a}}})}$$

Penman, 1948
Monteith, 1965

$$r_{\mathrm{s}} = \frac{r_{\mathrm{si}}}{\mathrm{LAI_{active}}}$$

Allen et al., 1998



- r_{si}文献值: 70 to 80 s m^{-1}
  Potato: NSeff = 0.75
  Rice: Nseff = 0.80

- 本研究的优化值:
  Potato: 117 s m^{-1} (NSeff = 0.81)
  Rice: 38 s m^{-1} (NSeff = 0.91)

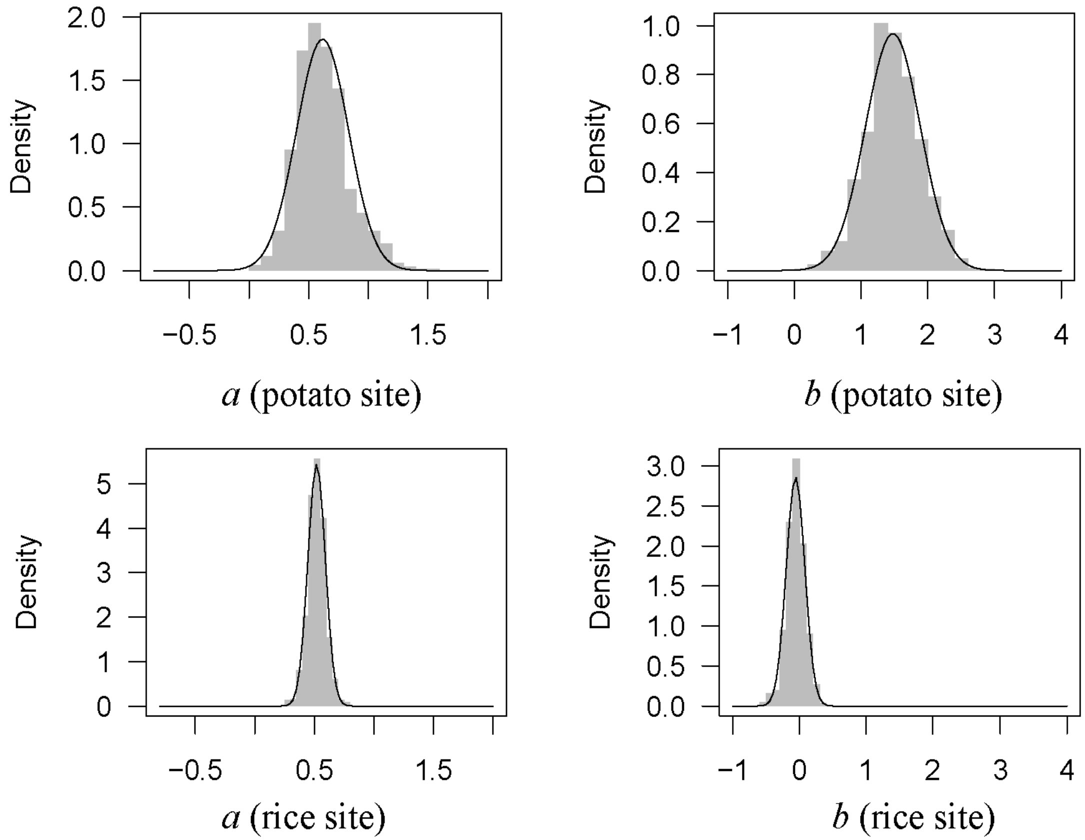
Zhao et al., 2016

PM-KP

$$\frac{r_s}{r_a} = a\frac{r^*}{r_a} + b \qquad r^* = \frac{(s_c + \gamma)\rho c_p (e_s - e_a)}{s_c \gamma (-R_n - Q_G)}$$

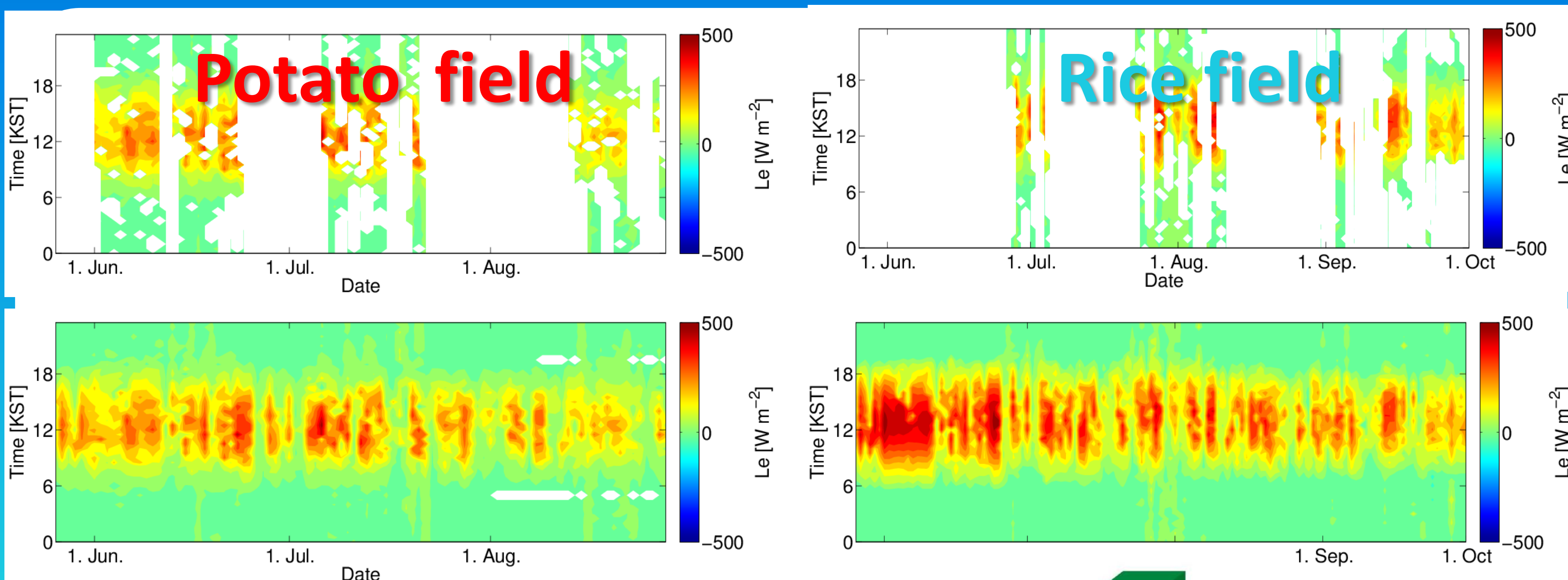
Katerji and Perrier, 1983

Katerji et al. 2011

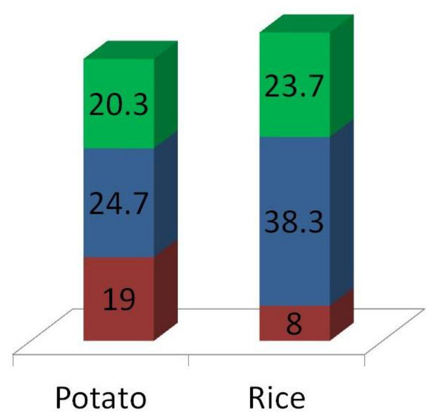


Zhao et al., 2016

能量收支

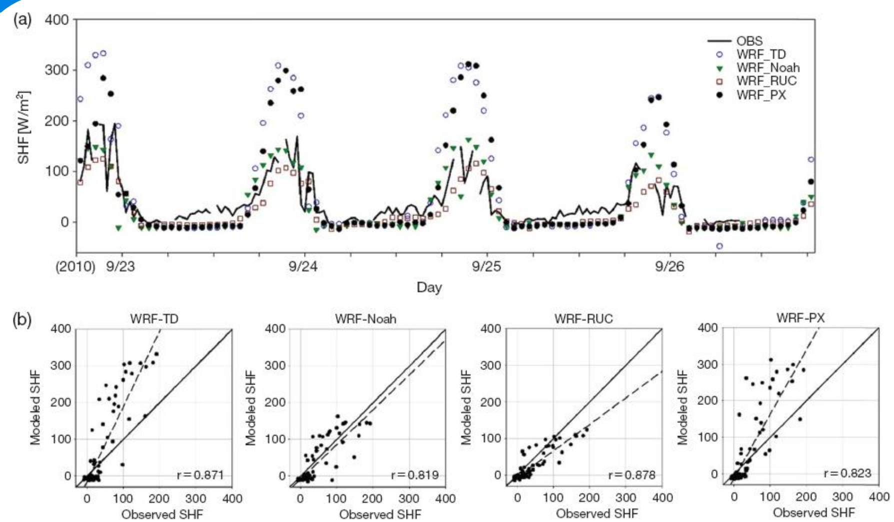


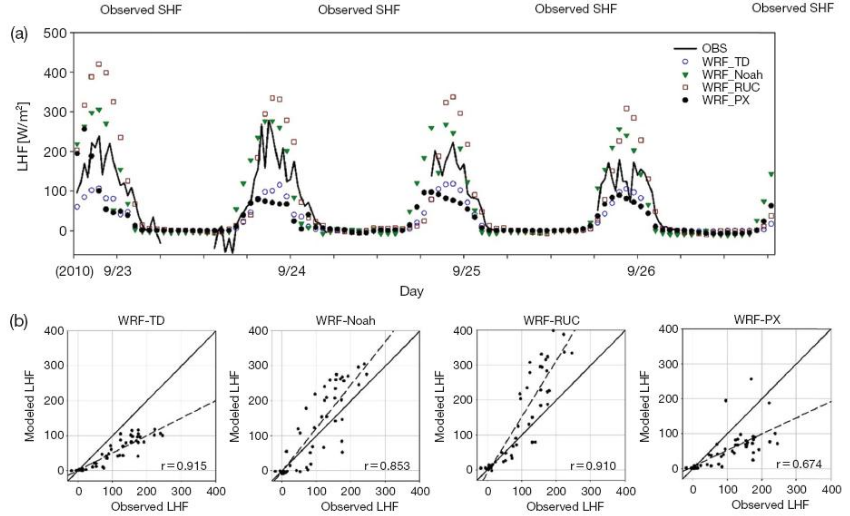
Transpiration
Evaporation
Sensible heat
(in W m^{-2})

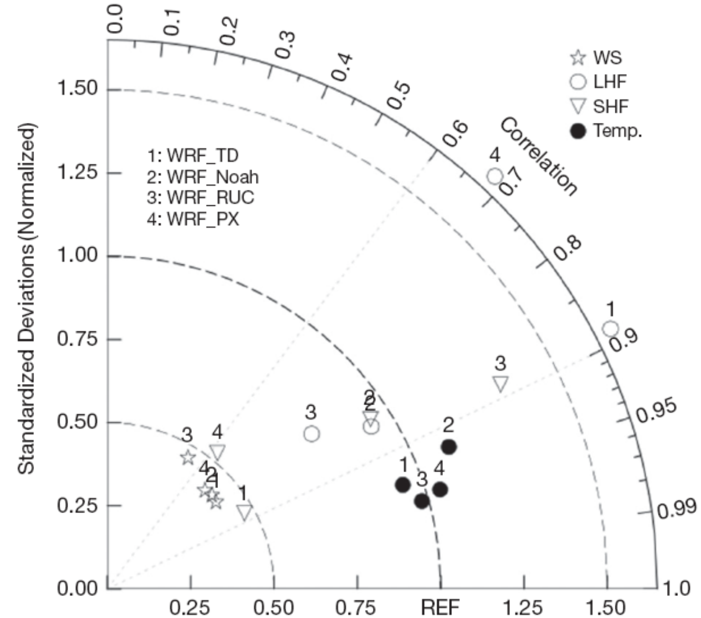


WRF-LSM

Weather Research and Forecasting – Land Surface Model







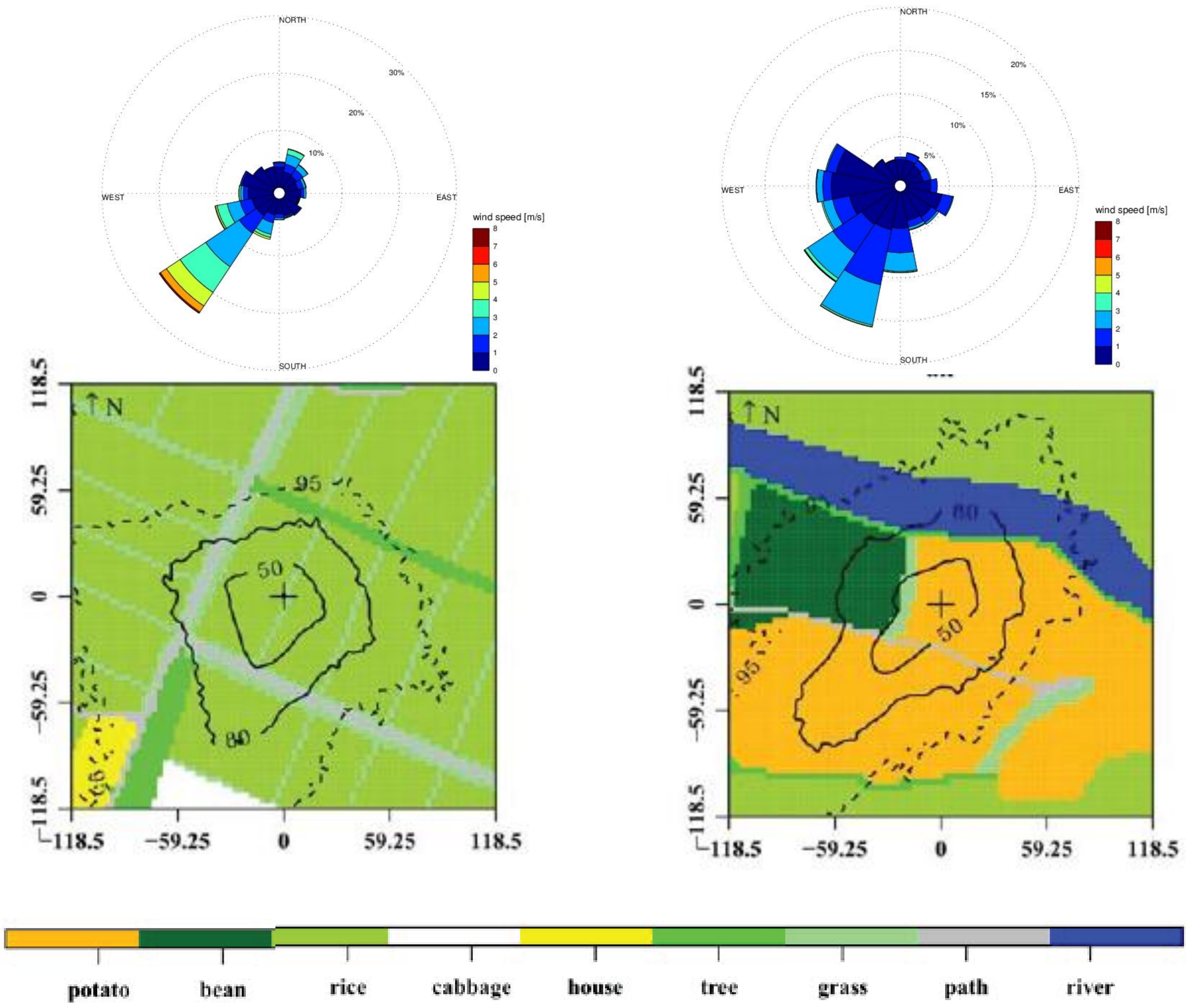
Lee et al., 2016

小结

- 次级环流的影响在农田生态系统的能量收支中是存在的，其贡献可用来修正能量平衡
- 针对站点优化的r_{si}（FAO方法）和a，b值（KP方法）以提高PM方程计算的准确性
- PM-KP方法应用于水稻田的结果优于土豆田

第二部分：CO_2交换

Footprint



Göckede et al. , 2004, 2006, 2008

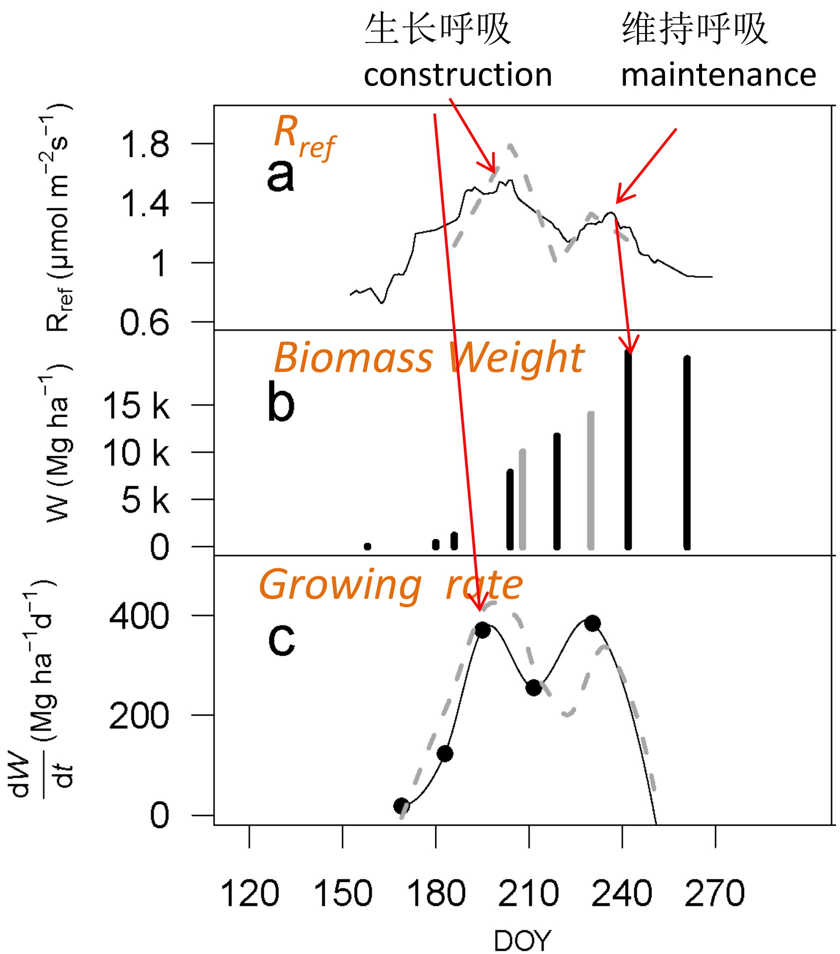
Zhao et al., 2011

CO_2的呼吸排放：呼吸方程

$$R_{\mathrm{eco}} = R_{\mathrm{ref}} e^{E_0\left(\frac{1}{T_{\mathrm{ref}}-T_0} - \frac{1}{T-T_0}\right)}$$

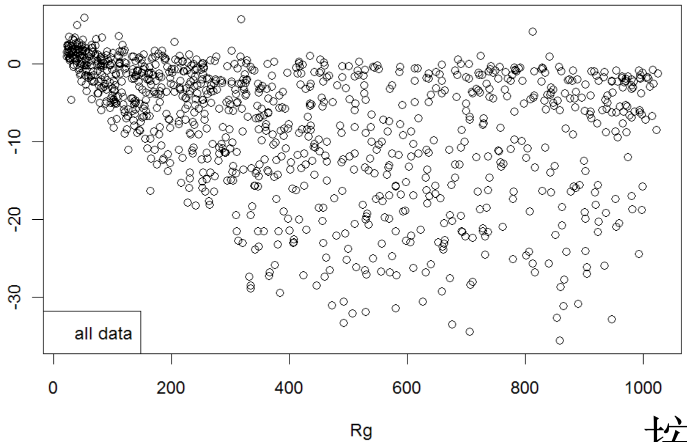
生物量响应？

$$R_{\mathrm{plant}} = a\frac{\mathrm{d}W}{\mathrm{d}t} + bW$$

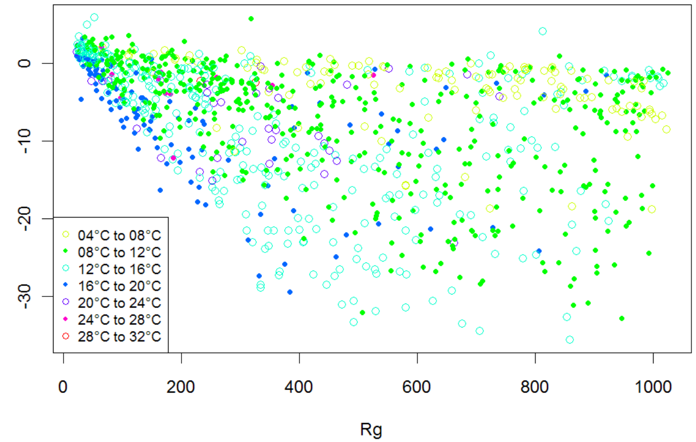


CO_2 的光合吸收：光响应方程

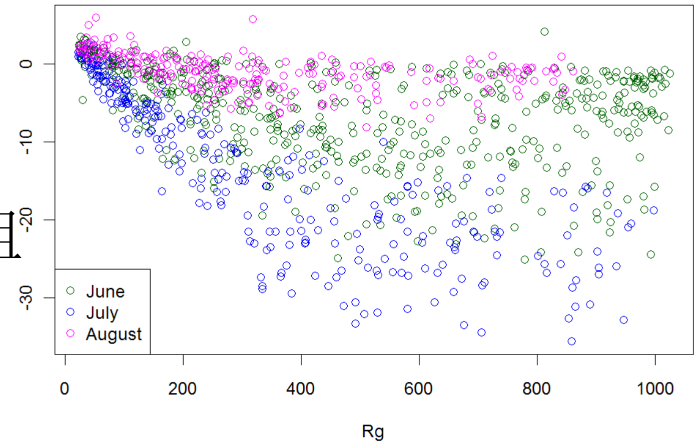
$$\mathrm{GPP} = \frac{\alpha R_{\mathrm{g}} \beta}{\alpha R_{\mathrm{g}} + \beta}$$



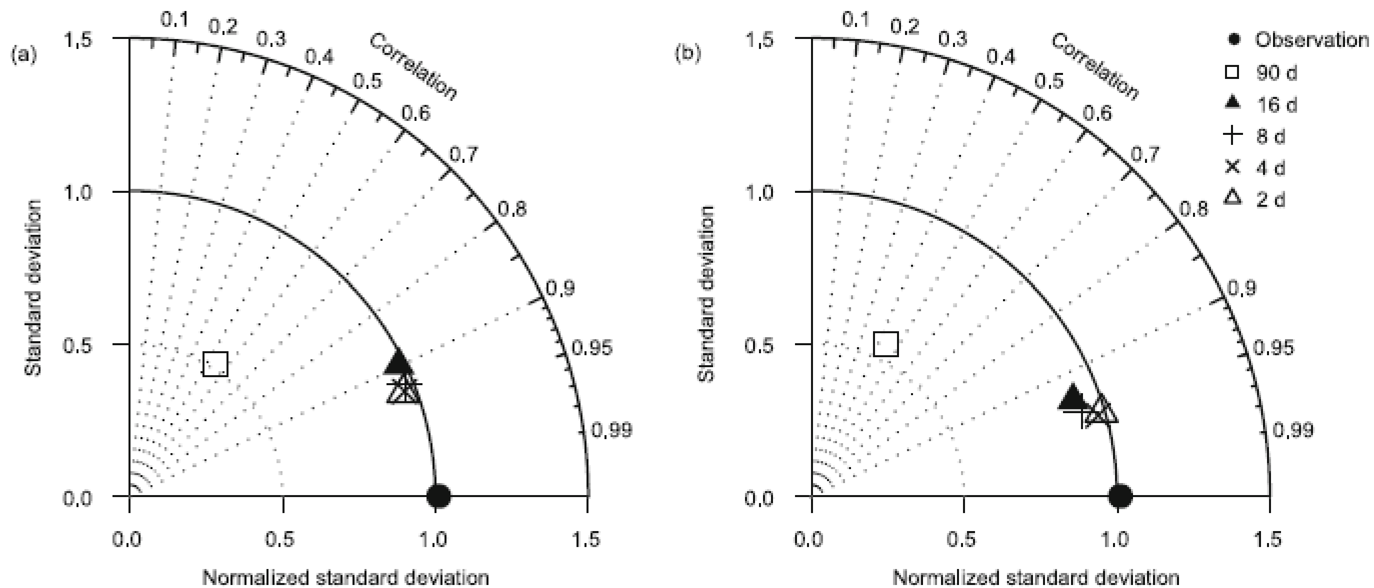
按温度分组



按时间分组



光响应方程：按时间分组



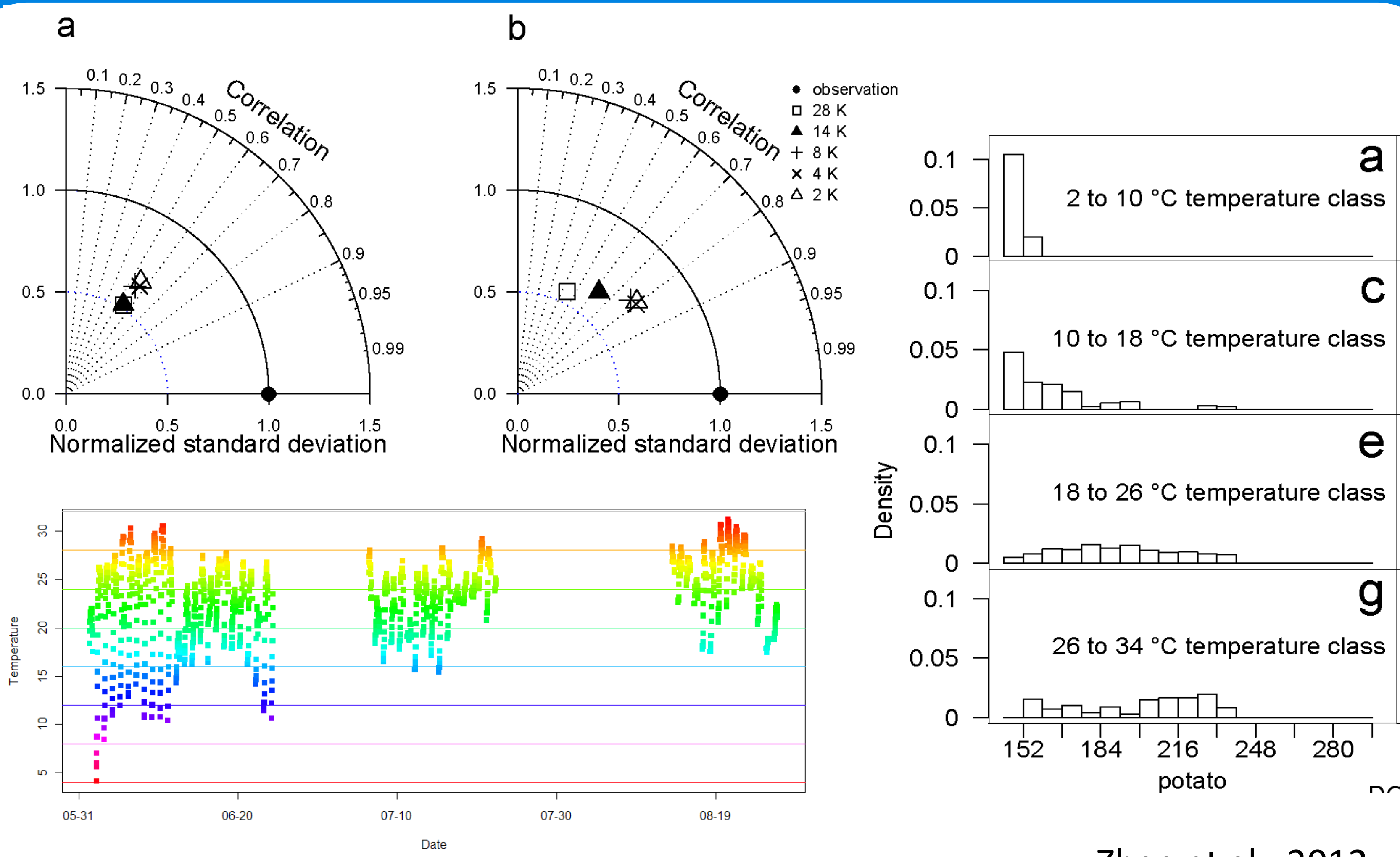
Potato: 2 days

Rice: 4 days

经验值：△LAI ~ 0.5

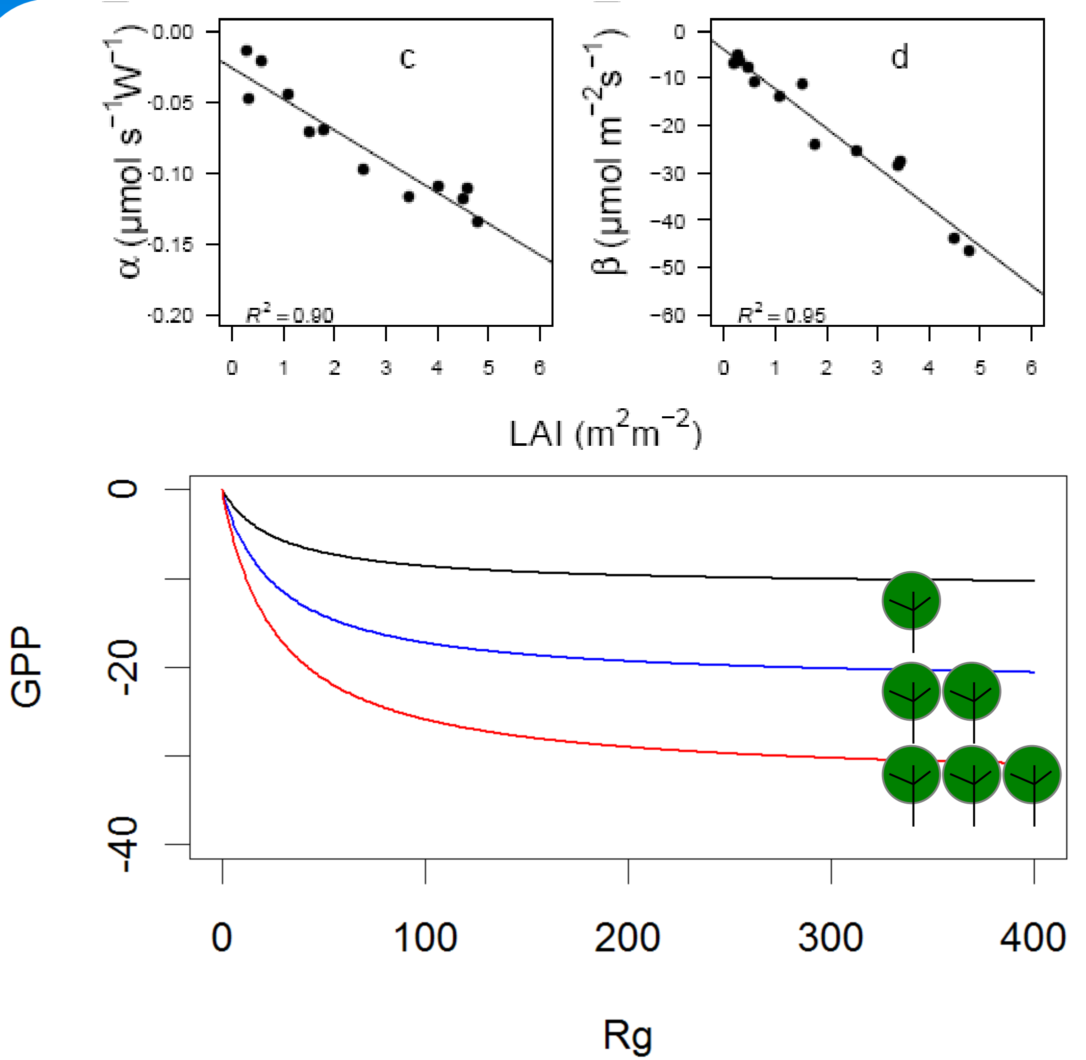
Zhao et al., 2012

光响应方程：按温度分组



Zhao et al., 2012

GPP - (R_g,LAI)



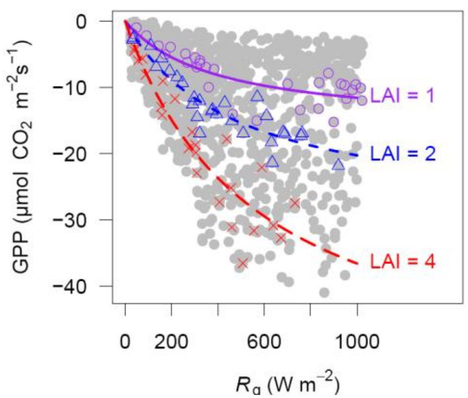
$$GPP = \frac{\alpha R_g \beta}{\alpha R_g + \beta}$$

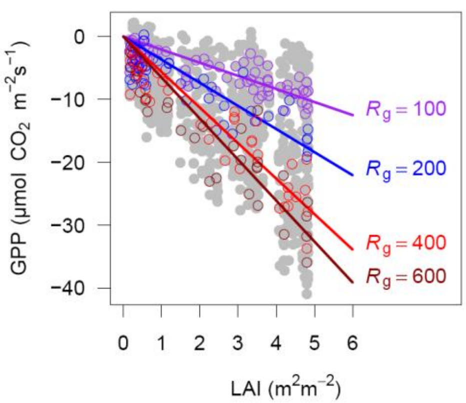
$$\frac{GPP}{LAI} = \frac{\frac{\alpha}{LAI} R_g \frac{\beta}{LAI}}{\frac{\alpha}{LAI} R_g + \frac{\beta}{LAI}}$$

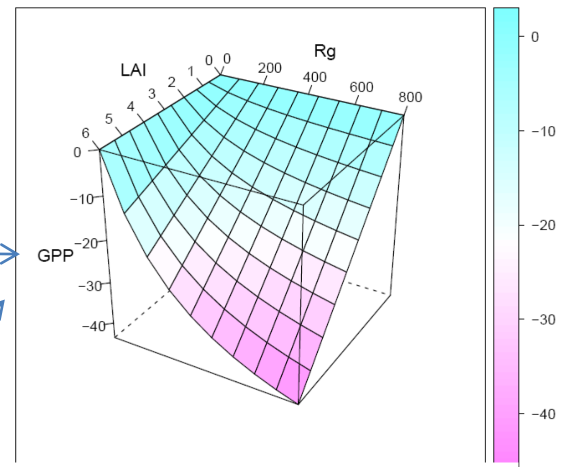
$$\mathrm{GPP} = \mathrm{LAI_{act}} \frac{\alpha' R_g \beta'}{\alpha' R_g + \beta'}$$

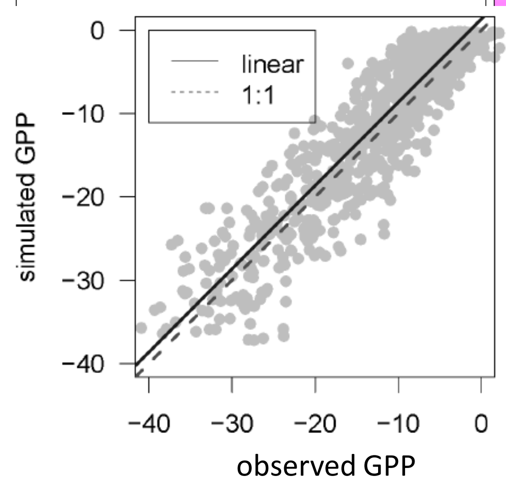
GPP - (R_g,LAI)

$$\mathrm{GPP} = \mathrm{LAI}_{\mathrm{act}} \frac{\alpha' R_{\mathrm{g}} \beta'}{\alpha' R_{\mathrm{g}} + \beta'}$$









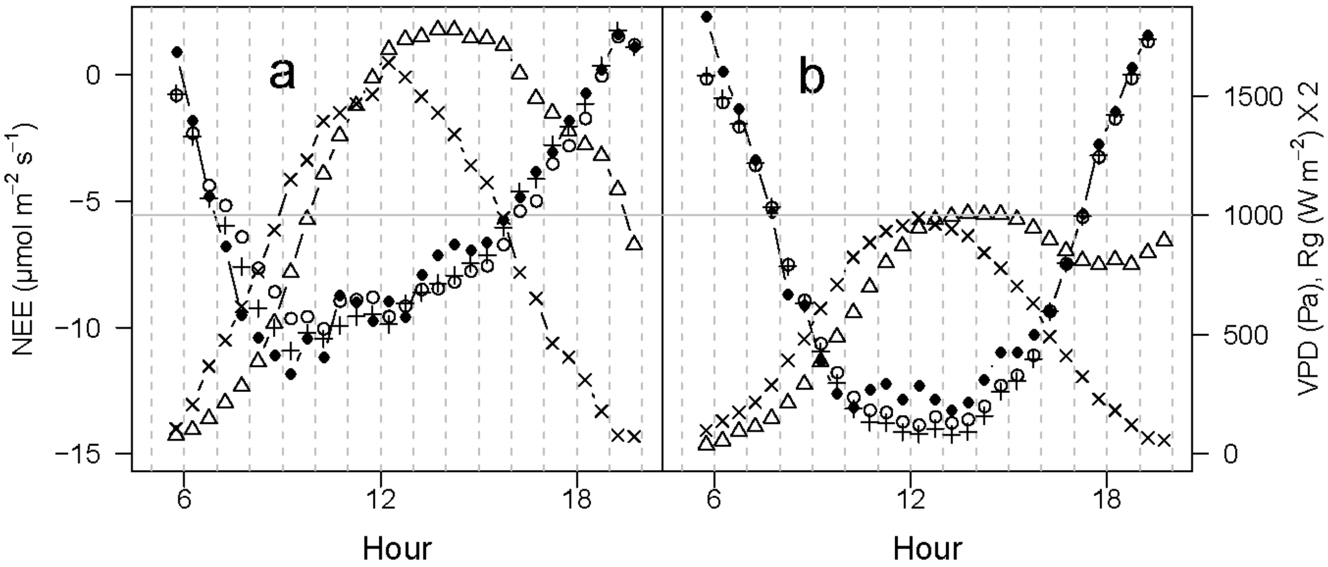
R^2: 0.87 – 0.95

R^2: 0.85

Zhao et al., 2016

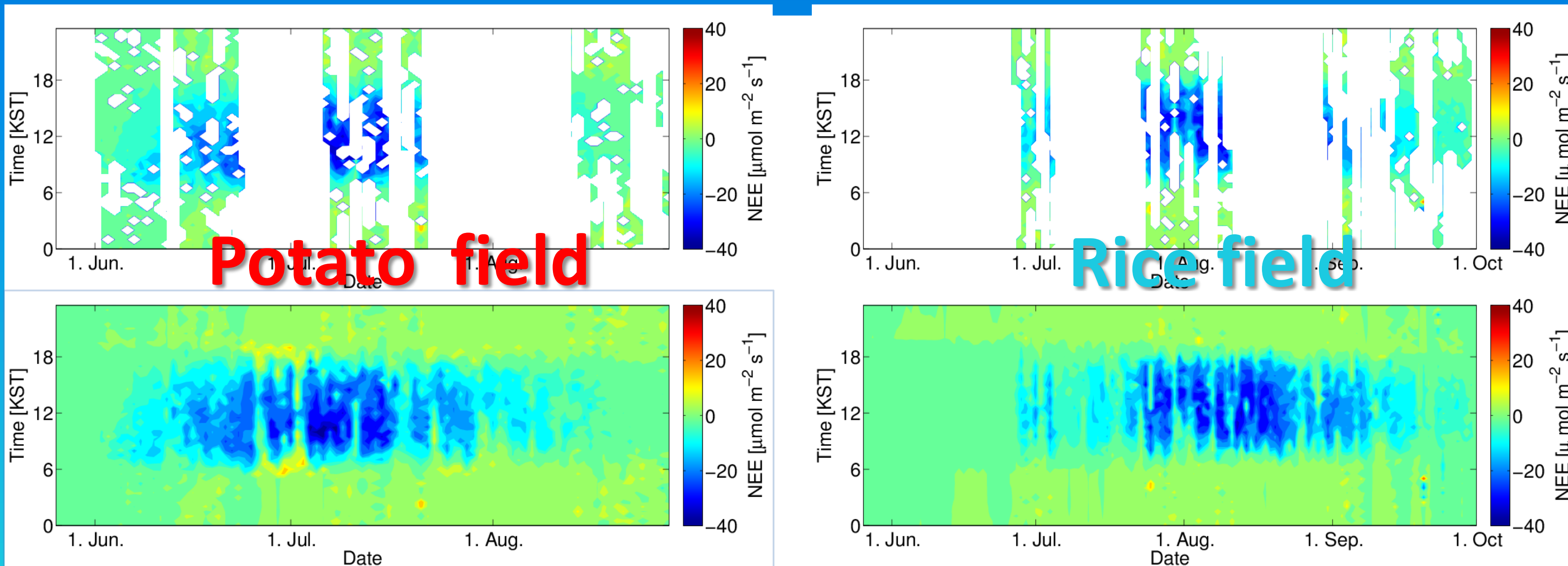
蒸气压差 VPD 的影响

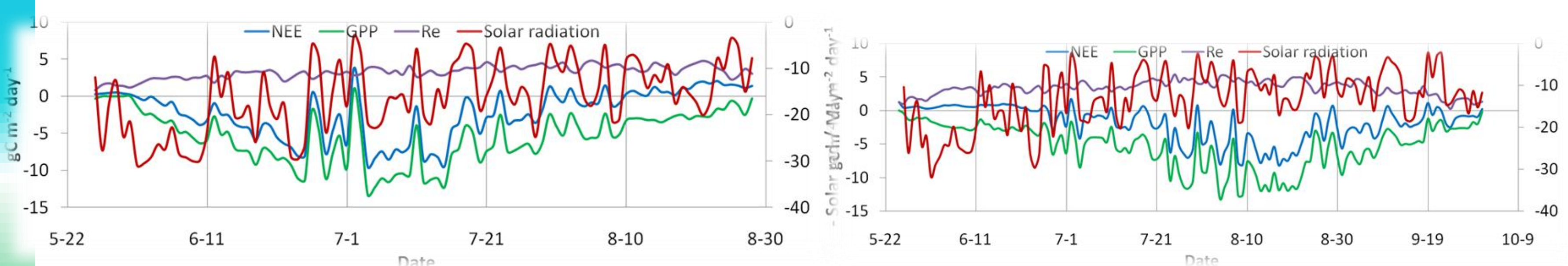
$$\beta = \begin{cases} \beta_0 e^{-k_\beta(\mathrm{VPD}-\mathrm{VPD}_0)} & , \mathrm{VPD} > \mathrm{VPD}_0 \\ \beta_0 & , \mathrm{VPD} \le \mathrm{VPD}_0 \end{cases}$$



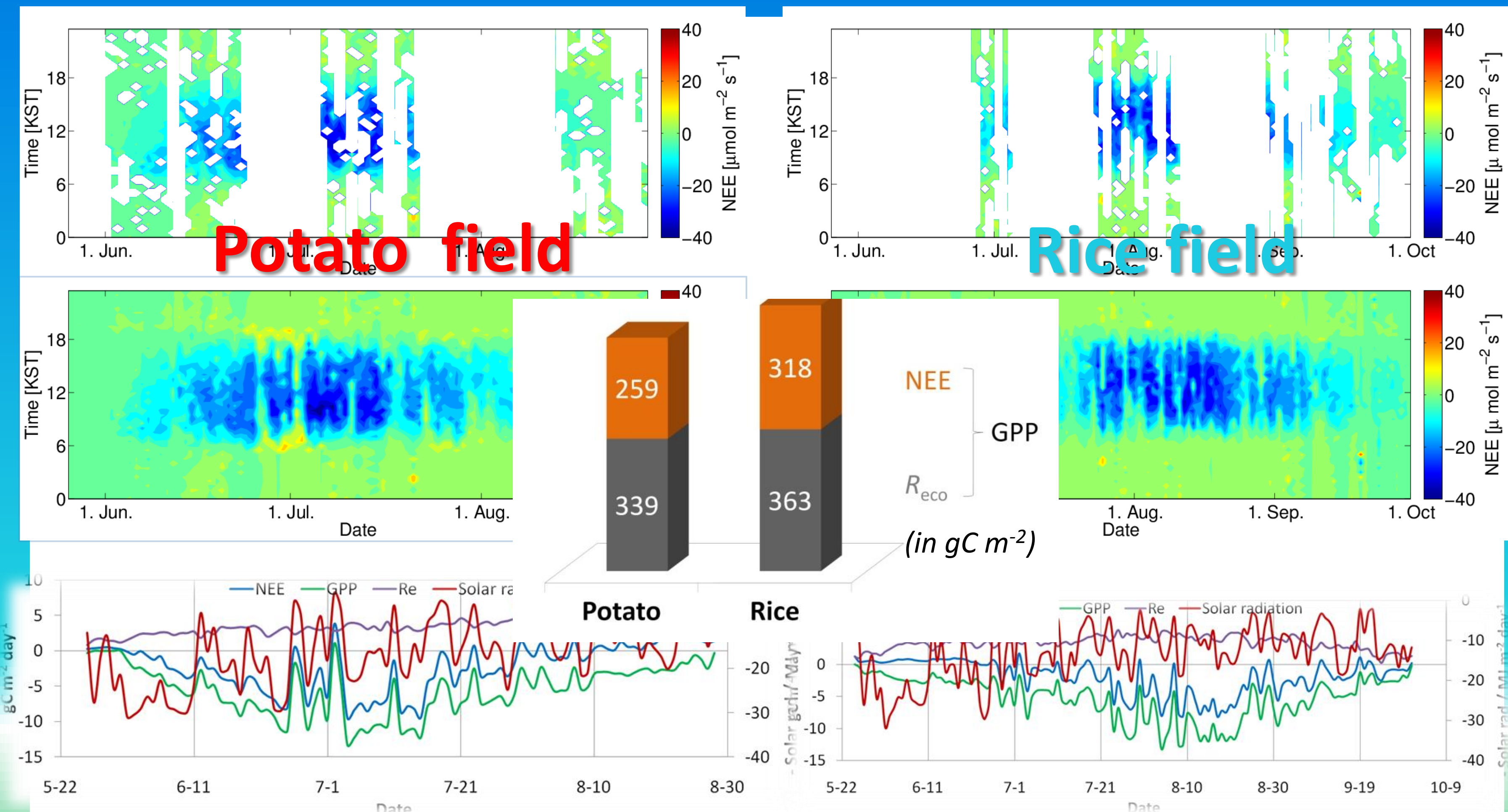
夏季风前　　　　夏季风

CO_2 收支


Potato field
Rice field
Time [KST]
NEE [μmol m^{-2} s^{-1}]
Date
1. Jun.
1. Jul.
1. Aug.
1. Sep.
1. Oct


NEE
GPP
Re
Solar radiation
gC m^{-2} day^{-1}
Solar rad / MJ m^{-2} day^{-1}
Date
5-22
6-11
7-1
7-21
8-10
8-30
9-19
10-9

CO_2 收支



Potato field
Rice field
Time [KST]
NEE [μmol m^{-2} s^{-1}]
1. Jun.
1. Jul.
1. Aug.
1. Sep.
1. Oct
Date
259
339
318
363
NEE
GPP
R_{eco}
(in gC m^{-2})
Potato
Rice
NEE
GPP
Re
Solar radiation
5-22
6-11
7-1
7-21
8-10
8-30
9-19
10-9

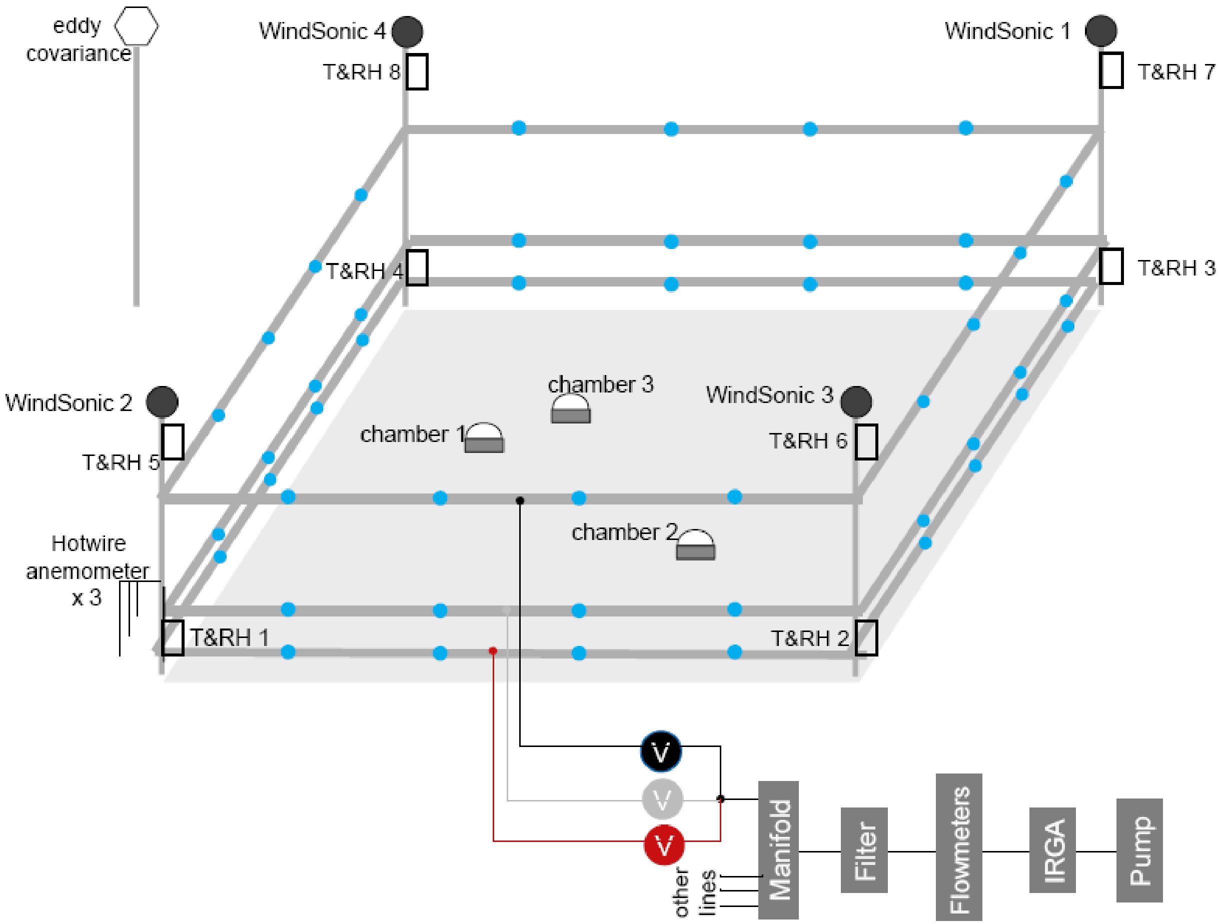
小结

- 农作物的快速生长对呼吸方程的影响
- 按时间分组拟合的方法明显提高了光响应方程的准确性
- 按温度分组拟合的方法作用有限
- 改进的光-叶面积指数响应方程有助于连续长时间的缺失值插补

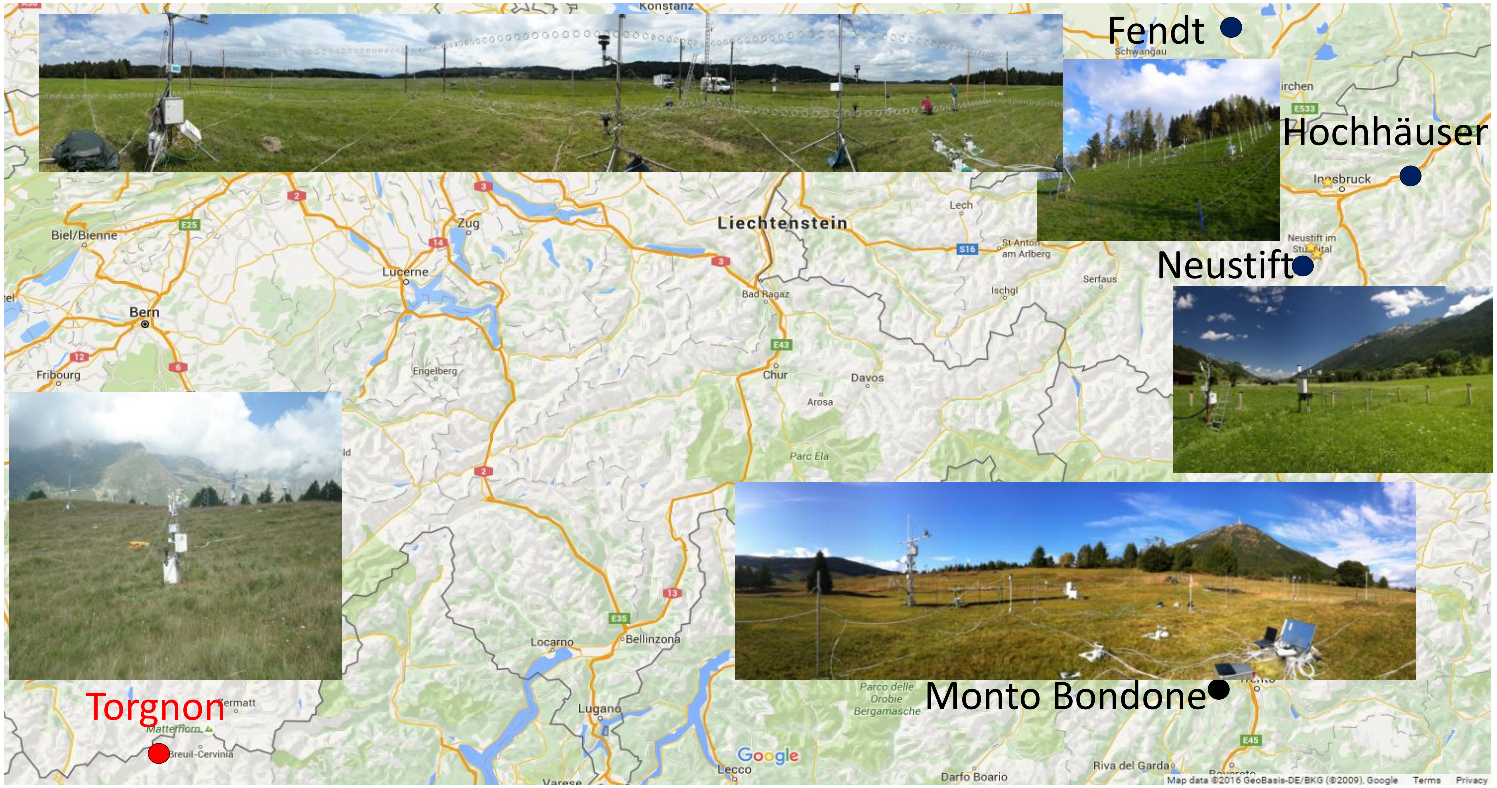
第三部分：平流贡献

平流观测

$F_c = F_s + F_{VT} + F_{HT} + F_{HA} + F_{VA}$

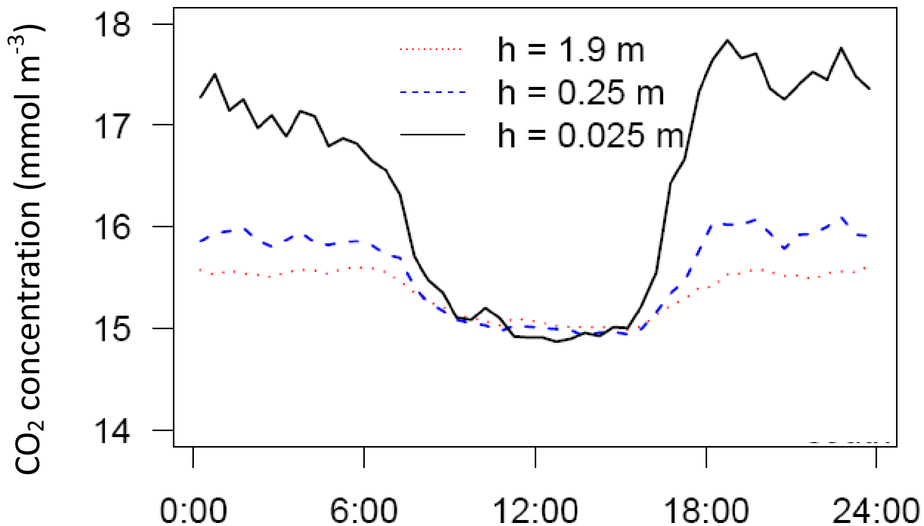


观测站点

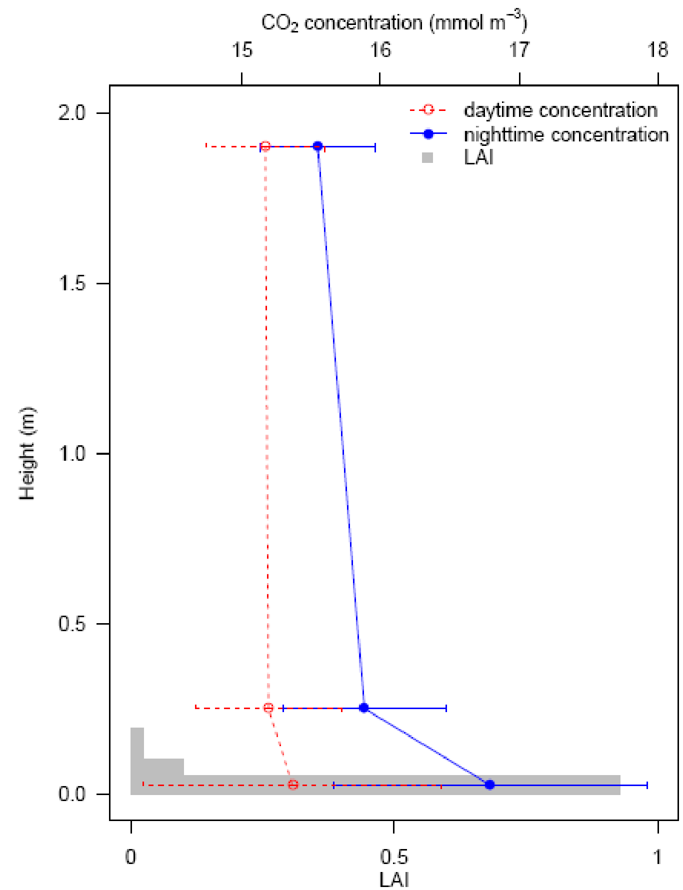


Fendt
Hochhäuser
Neustift
Torgnon
Monto Bondone
Liechtenstein
Bern
Lucerne
Zug
Chur
Davos
Innsbruck
Locarno
Bellinzona
Lugano
Fribourg
Biel/Bienne
Google

CO_2 浓度

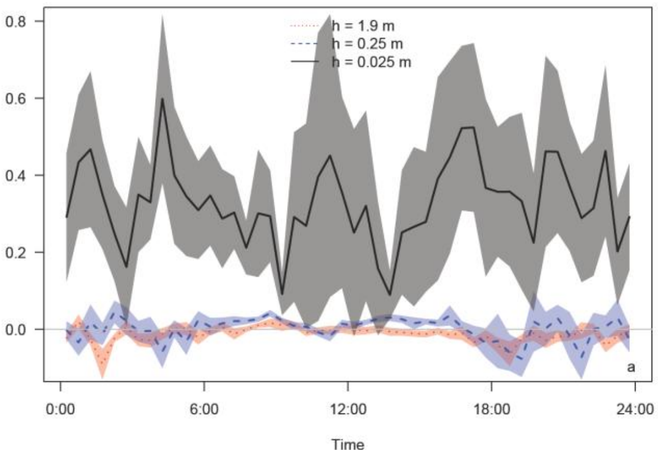


Diurnal variation

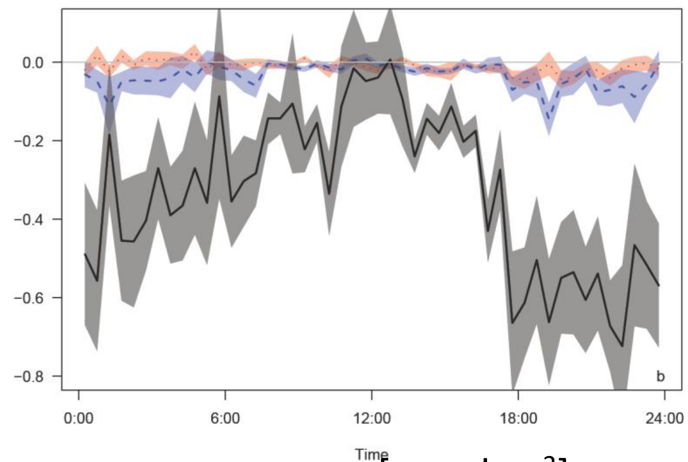


Vertical profile

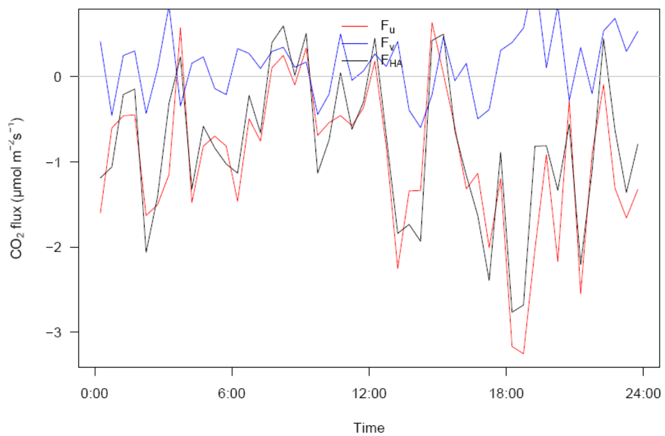
水平平流

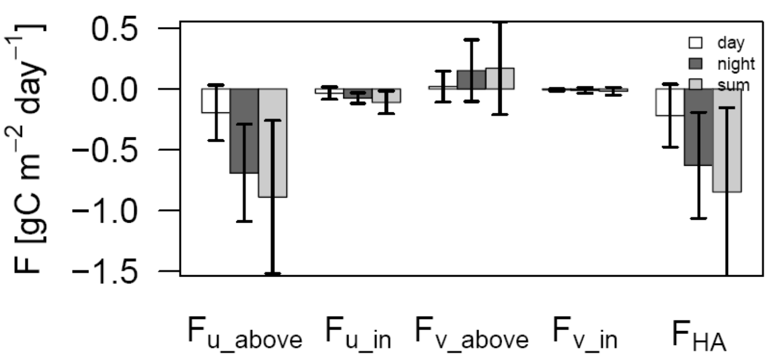


$c_{east} - c_{west}$ [mmol m^{-3}]

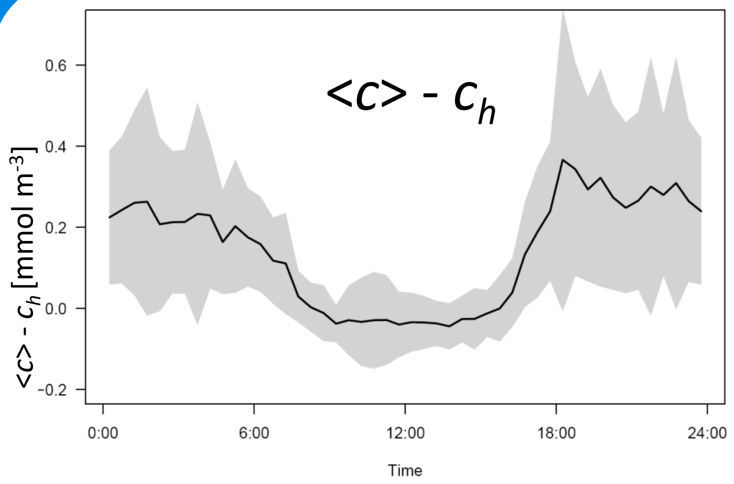


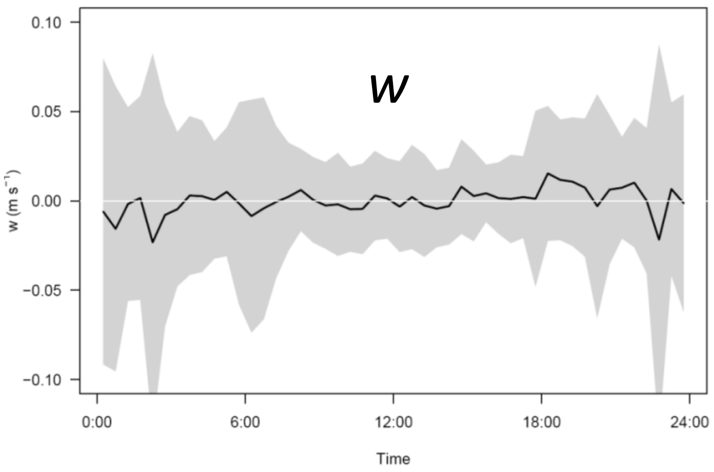
$c_{north} - c_{south}$[mmol m^{-3}]

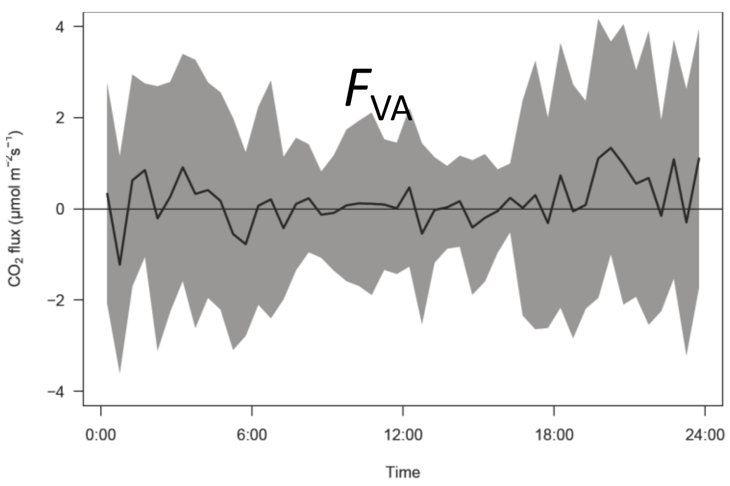


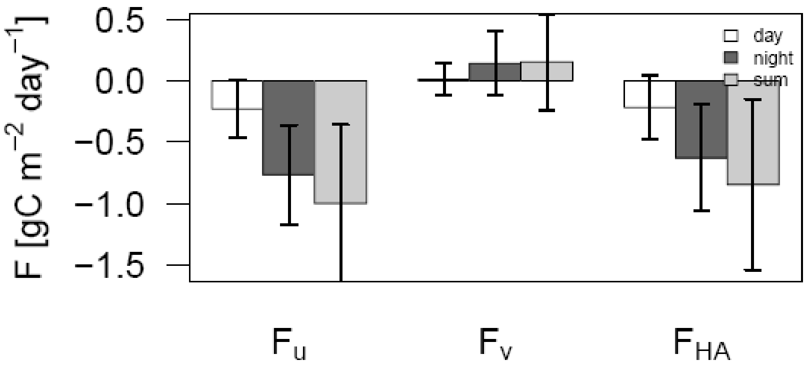


垂直平流

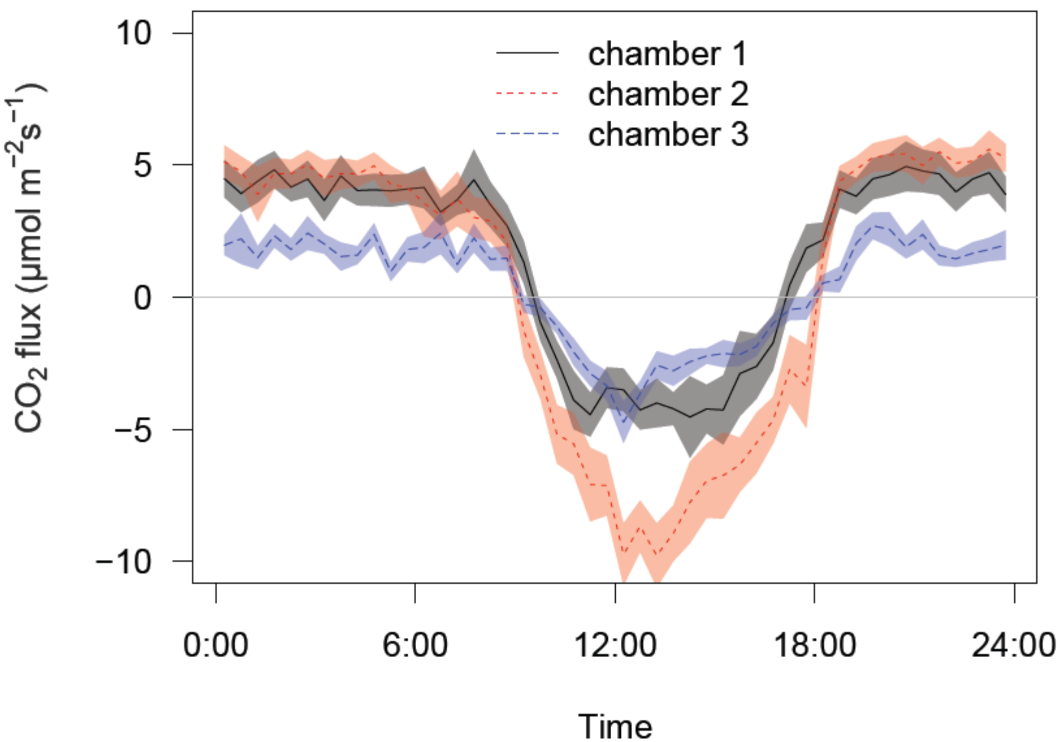

<c> - c_h
<c> - c_h [mmol m^{-3}]
0.6
0.4
0.2
0.0
-0.2
0:00
6:00
12:00
18:00
24:00
Time


w
w (m s^{-1})
0.10
0.05
0.00
−0.05
−0.10
0:00
6:00
12:00
18:00
24:00
Time


F_{VA}
CO_2 flux (µmol m^{-2}s^{-1})
4
2
0
−2
−4
0:00
6:00
12:00
18:00
24:00
Time

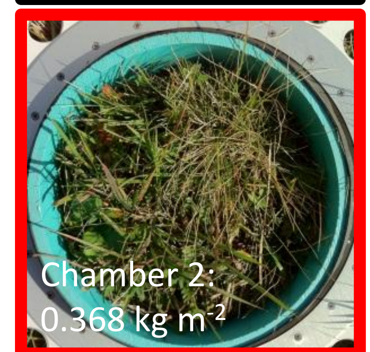

F [gC m^{-2} day^{-1}]
0.5
0.0
−0.5
−1.0
−1.5
day
night
sum
F_u
F_v
F_{HA}

通量箱

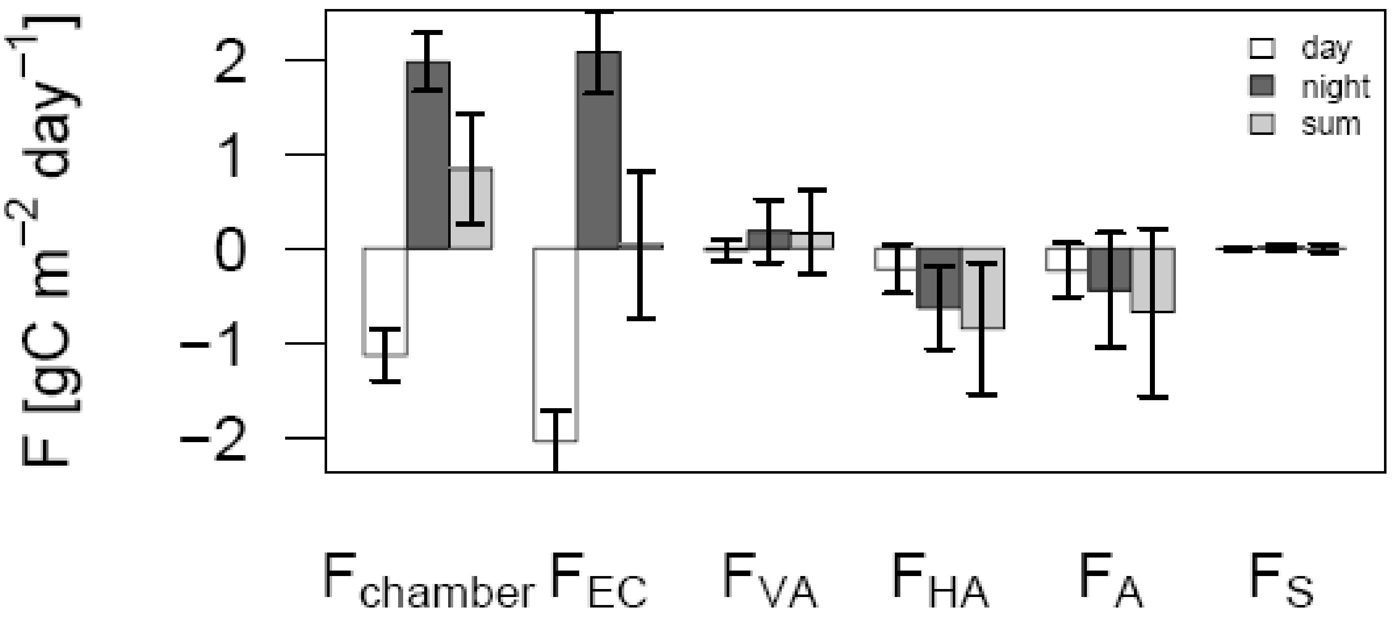


Dominant vegetation types:

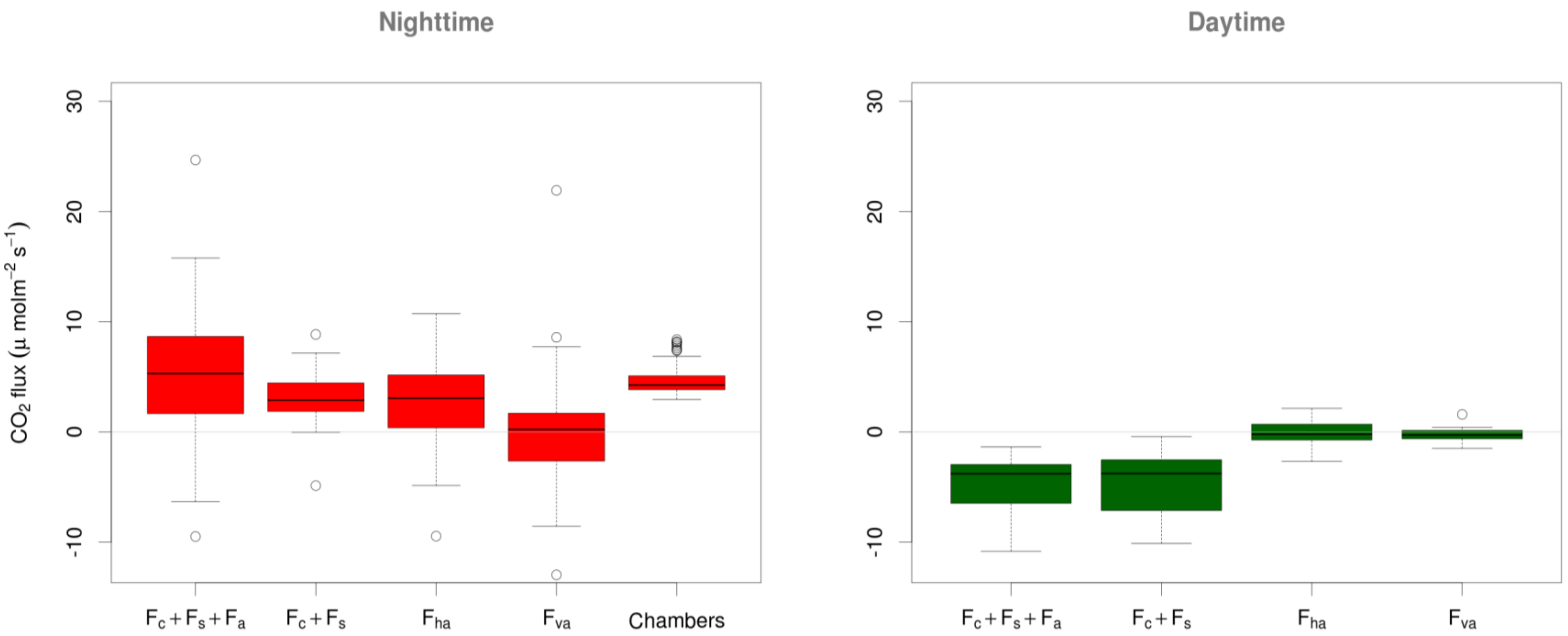
- *Festuca rubra* (L.) 25%
- *Nardus stricta* (L.) 13%
- *Trifolium sp.* (L.) 14%



各项通量汇总



Torgnon

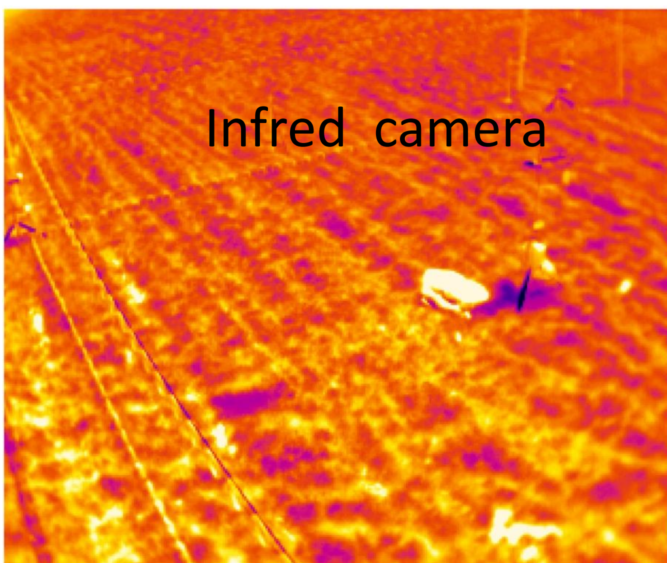


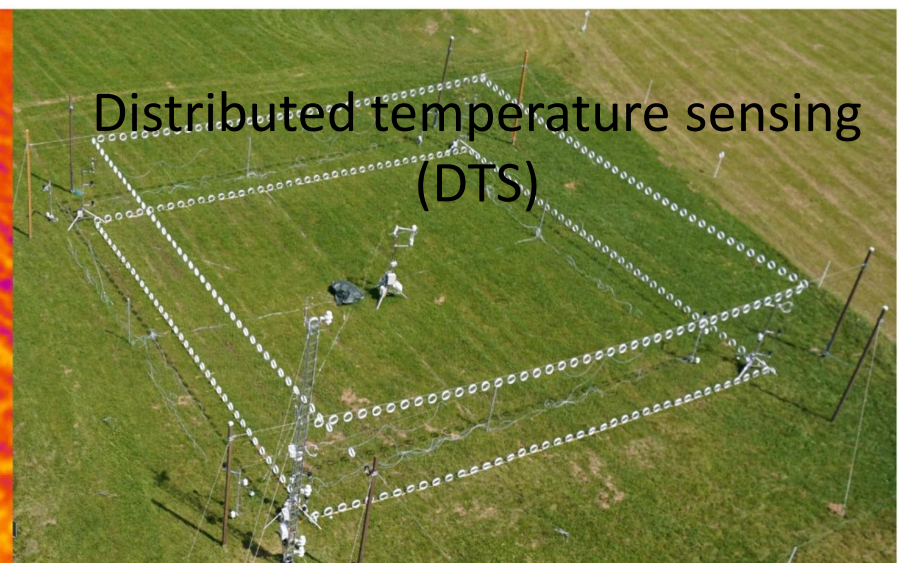
Nighttime
Daytime
CO_2 flux (μ molm^{-2} s^{-1})
30
20
10
0
-10
$F_c+F_s+F_a$
F_c+F_s
F_{ha}
F_{va}
Chambers

Fendt

Multi-Scale Observation and Modelling of Energy and Matter Exchange in the Atmospheric Boundary-Layer (ScaleX Campaigns)

Kevin Wolz[1], Claire Brenner[2], Frederik De Roo[1],
Bianca Adler[3], Stefan Emeis[1], Norbert Kalthof[3], Matthias Mauder[1], Klaus Schäfer[1], Georg Wohlfahrt[4], Peng Zhao[4]
Matthias Zeeman[1] (1) KIT/IMK–IFU (2) BOKU (Vienna, Austria) (3) KIT/IMK–TRO (4) U of Innsbruck (Innsbruck, Austria)





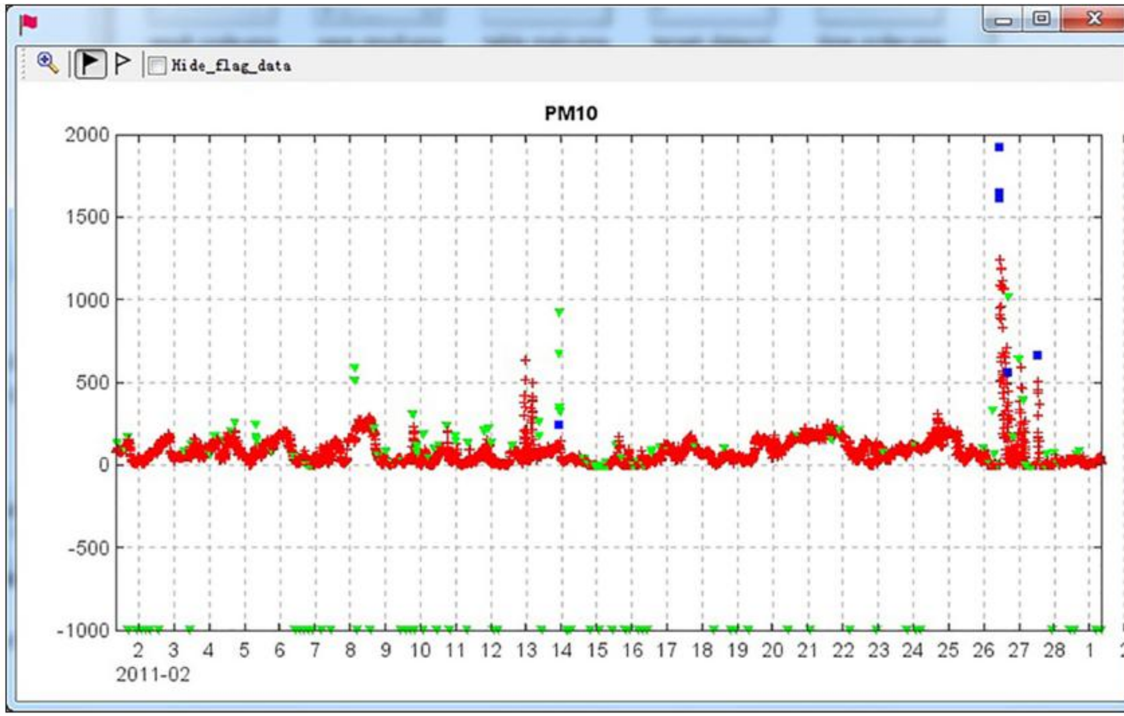
小结

- 通量箱：NEE在草场空间的不均匀性
- 水平平流：冠层内贡献可以忽略，冠层以上昼夜均有明显贡献
- 垂直平流：白天可忽略，夜间有明显贡献
- 不同地势下，平流的贡献亦有不同

Take-Home Messages

OutlierFlag

单机版



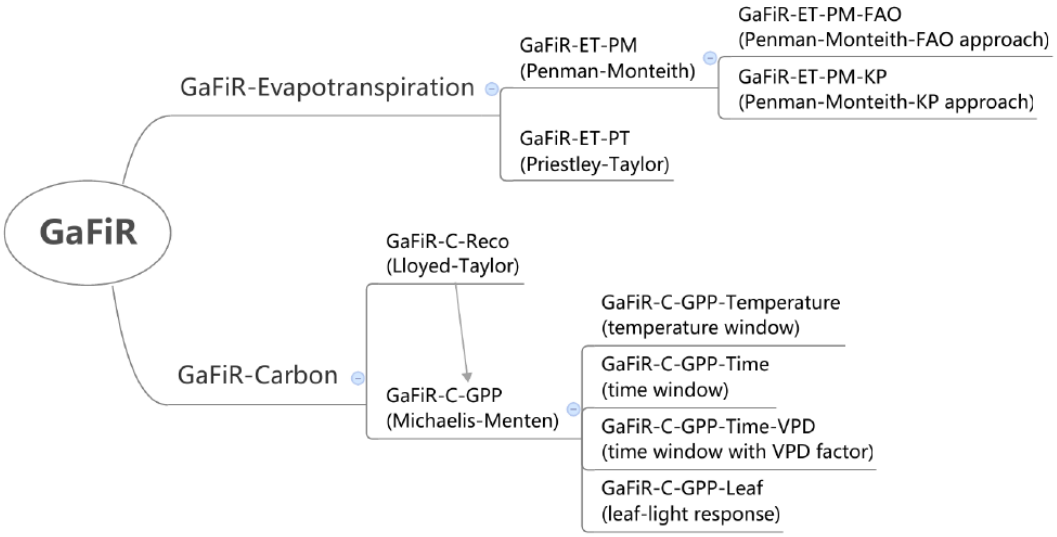
Huang et al., 2016

Take-Home Messages

- Gap-Filling R package GaFiR

GaFiR

单机版



Zhao et al., 2014

Take-Home Messages

EddyPoster (eddy covariance data post processor)

Home | SunSetter | WindRoser | PairViewer | TimeFiller | OutlierMarkerLite | OutlierMarker | Hovmöller | PlanarFitter | GapFiller | TaylorPlotter

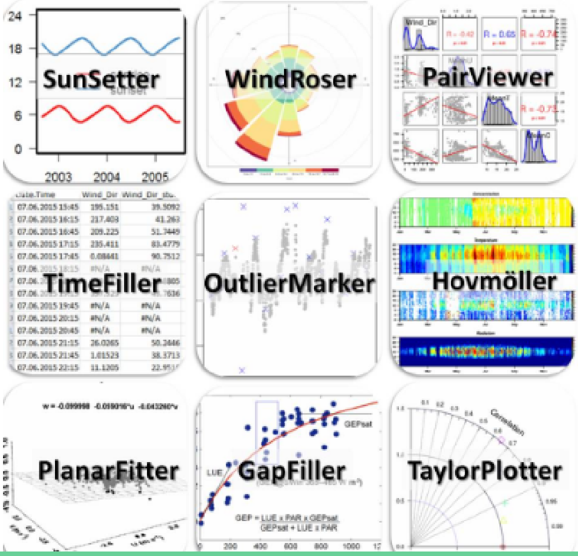
About

EddyPoster is a web-based interface for processing scientific data. Although it is originated from my PhD work of post processing eddy covariance data, users are free to apply it to other topics of interest, such as plotting any time series, plotting windrose diagrams, completing a time series, viewing pair-wise correlations, or find outliers in datasets.

EddyPoster is composed of several tools, including:

- **WindRoser**, which plots windroses,
- e correlations between multiple variables in a friendly way,
- ise and sunset time at a given location,
- ne series with NA to get complete time stamps within a given range,
- iers in (a) time series of eddy-covariance data, with **OutlierMarkerLite** as a simplified version for general
- ller diagram for given variables,
- e planar fit coefficients,
- and GPP data with esttimated values,
- or diagram for comparison between models and observations, and
- oming soon.

EddyPoster



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- 德国拜罗伊特大学植物生态系Prof. John Tenhunen负责的TERRECO项目组
- 奥地利因斯布鲁克大学生态学院Dr. Georg Wohlfahrt生态气象研究组
- 韩国江原大学环境科学系
- 德国卡尔斯鲁厄理工学院气候与气象研究院
- 华南植物园
- 德国联合研究会 DFG
- 奥地利科学基金 FWF
- 韩国研究基金会 KRF

谢谢！

Gap-filling strategy for CO_2 flux

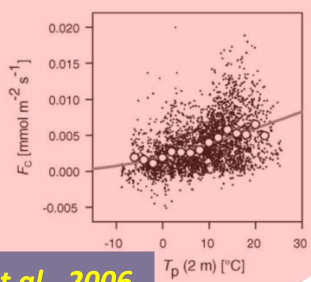
	Nighttime	Daytime
Ecosystem respiration (R_{eco})	Measured with gaps	gaps
Net ecosystem exchange (NEE)	$NEE = R_{eco}$	Measured with gaps
Gross primary production (GPP)	0	$GPP = NEE - R_{eco}$

Lloyd and Taylor, 1994

Michaelis and Menten, 1913
Falge et al., 2001

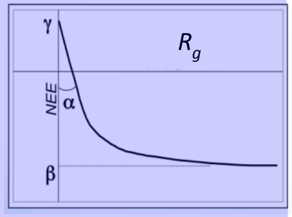
$$R_{eco} = R_{ref} e^{E_0\left(\frac{1}{T_{ref}-T_0} - \frac{1}{T-T_0}\right)}$$

T_{ref}: reference temperature, 10 °C
R_{ref}: R_{eco} at T_{ref}
E_0: temperature sensitivity
T: air temperature
T_0: constant value, -46.02 °C



Ruppert et al., 2006

$$NEE = \frac{\alpha R_g \beta}{\alpha R_g + \beta} + R_{eco}$$



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

$$GPP = \frac{\alpha R_g \beta}{\alpha R_g + \beta}$$

R_g: global radiation
α: initial slope
β: saturated NEE

seasonal temperature VPD