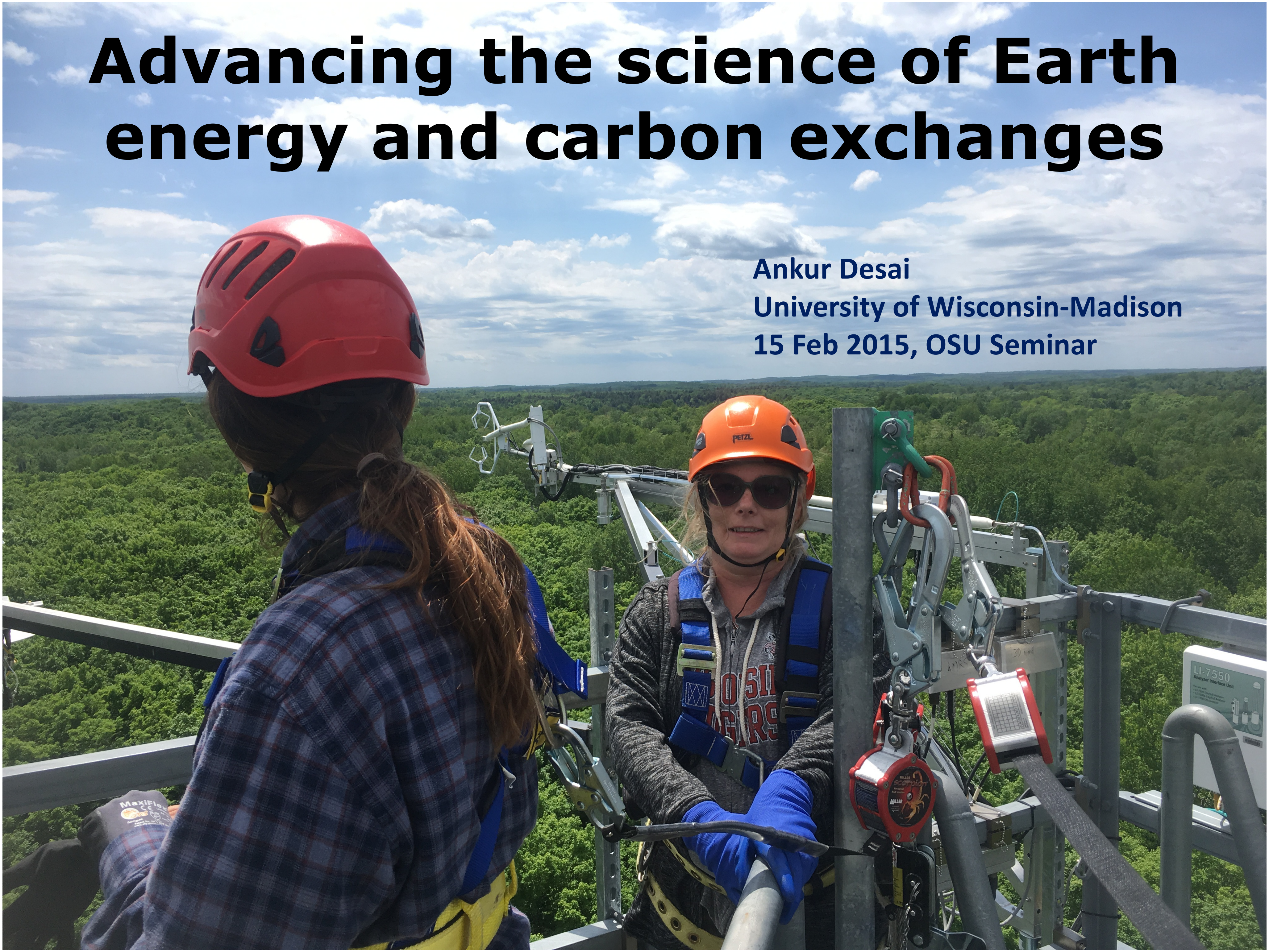
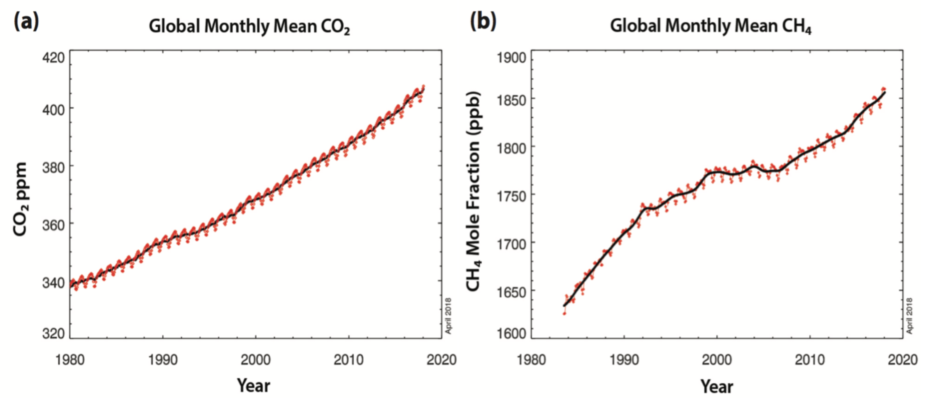
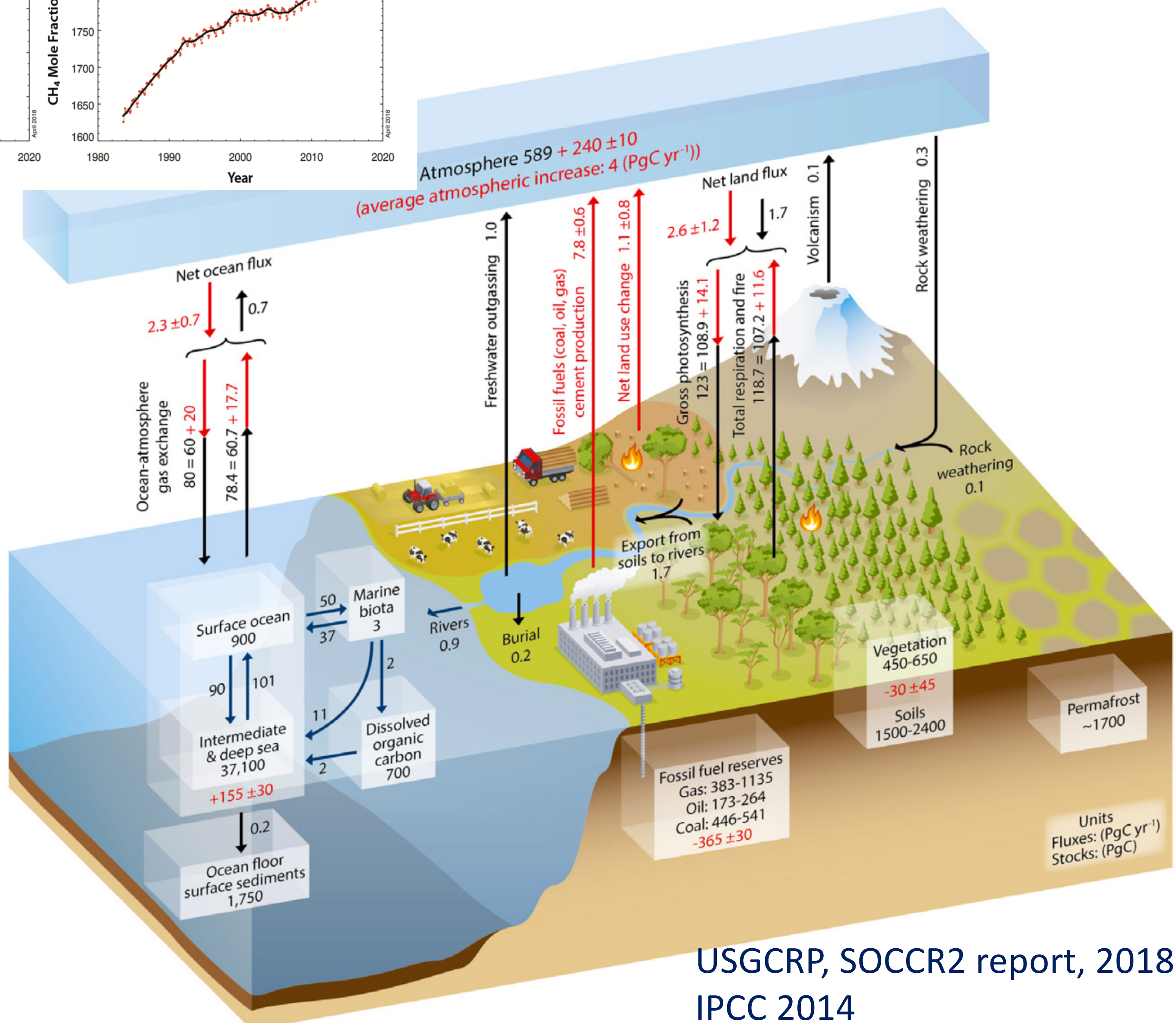
Advancing the science of Earth energy and carbon exchanges

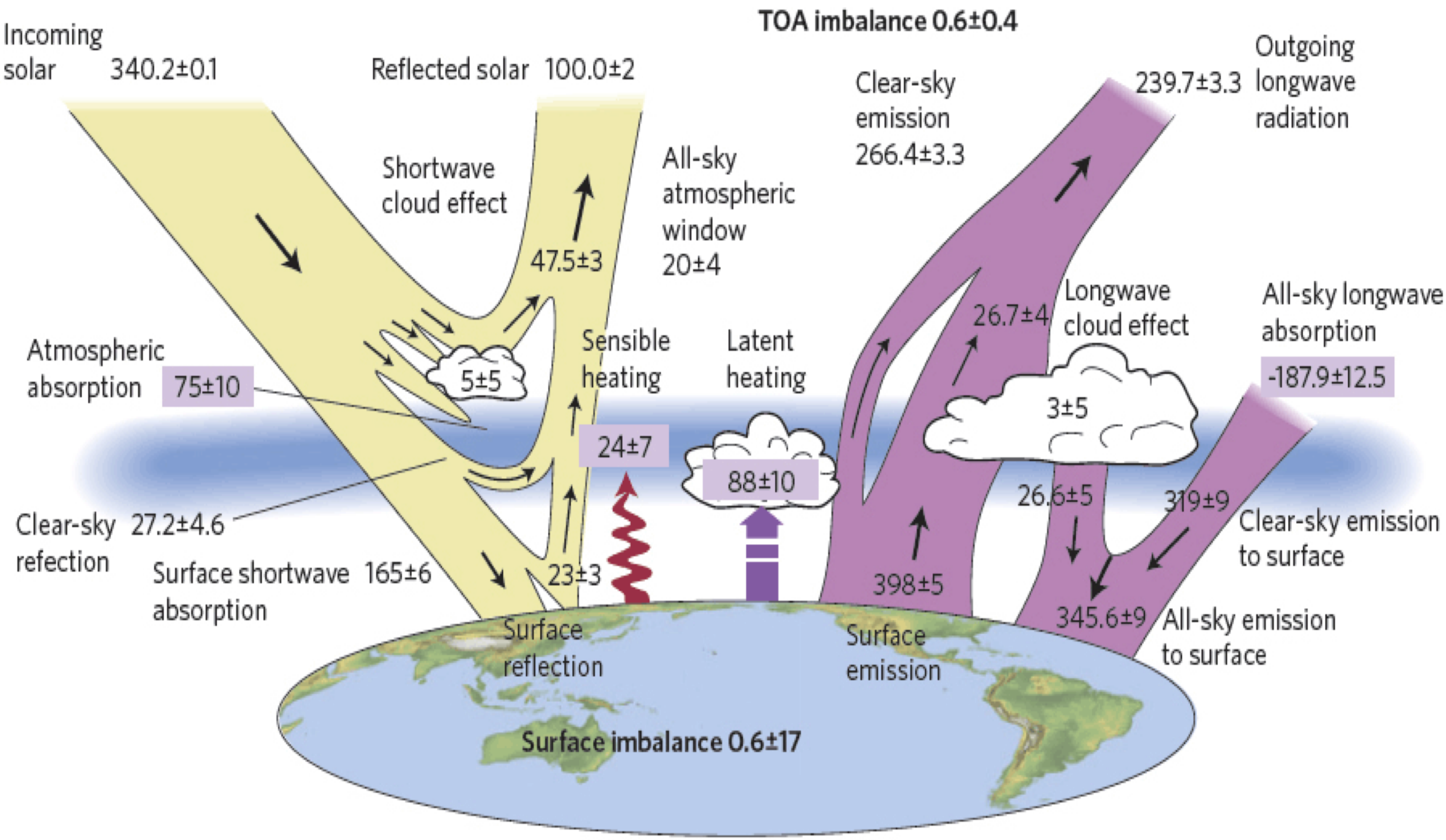
Ankur Desai
University of Wisconsin-Madison
15 Feb 2015, OSU Seminar







USGCRP, SOCCR2 report, 2018
IPCC 2014



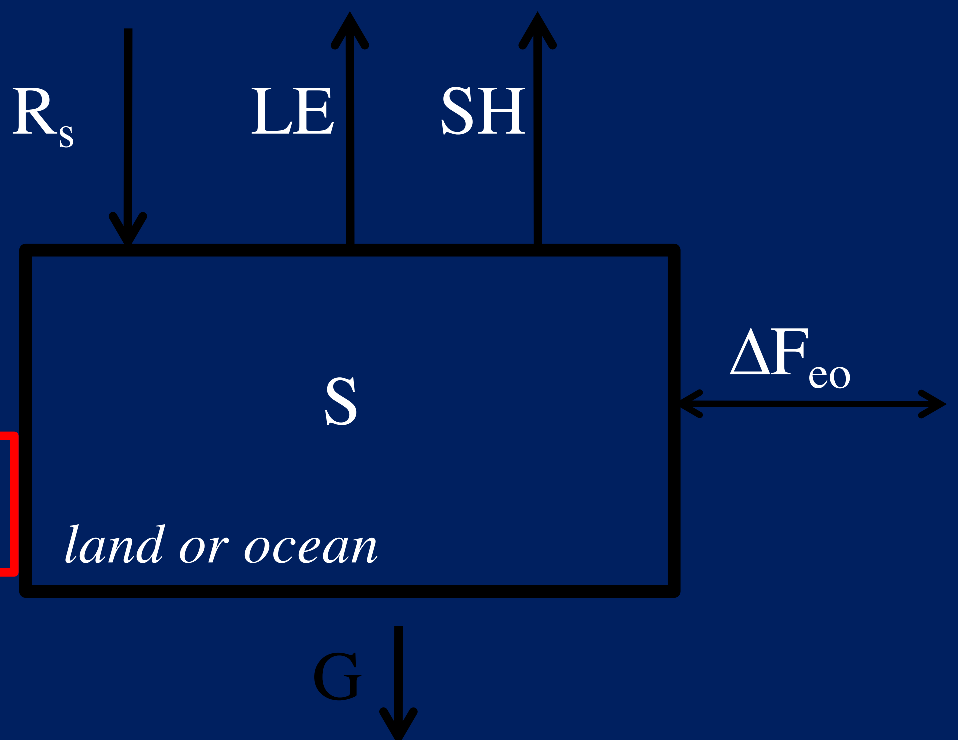
Stephens et al., 2012, Nature Geosci

Energy Balance of a Surface

- R_N = Net Radiation =
  - Shortwave_in – Shortwave_out + Longwave_in – Longwave_out
- S = Storage = d(Surface Energy)/dt = dE_s/dt
- G = Ground heat flux
- LE = Latent heat flux
- SH = Sensible heat flux
- ΔF_{eo} = Lateral transport

BALANCE EQUATION

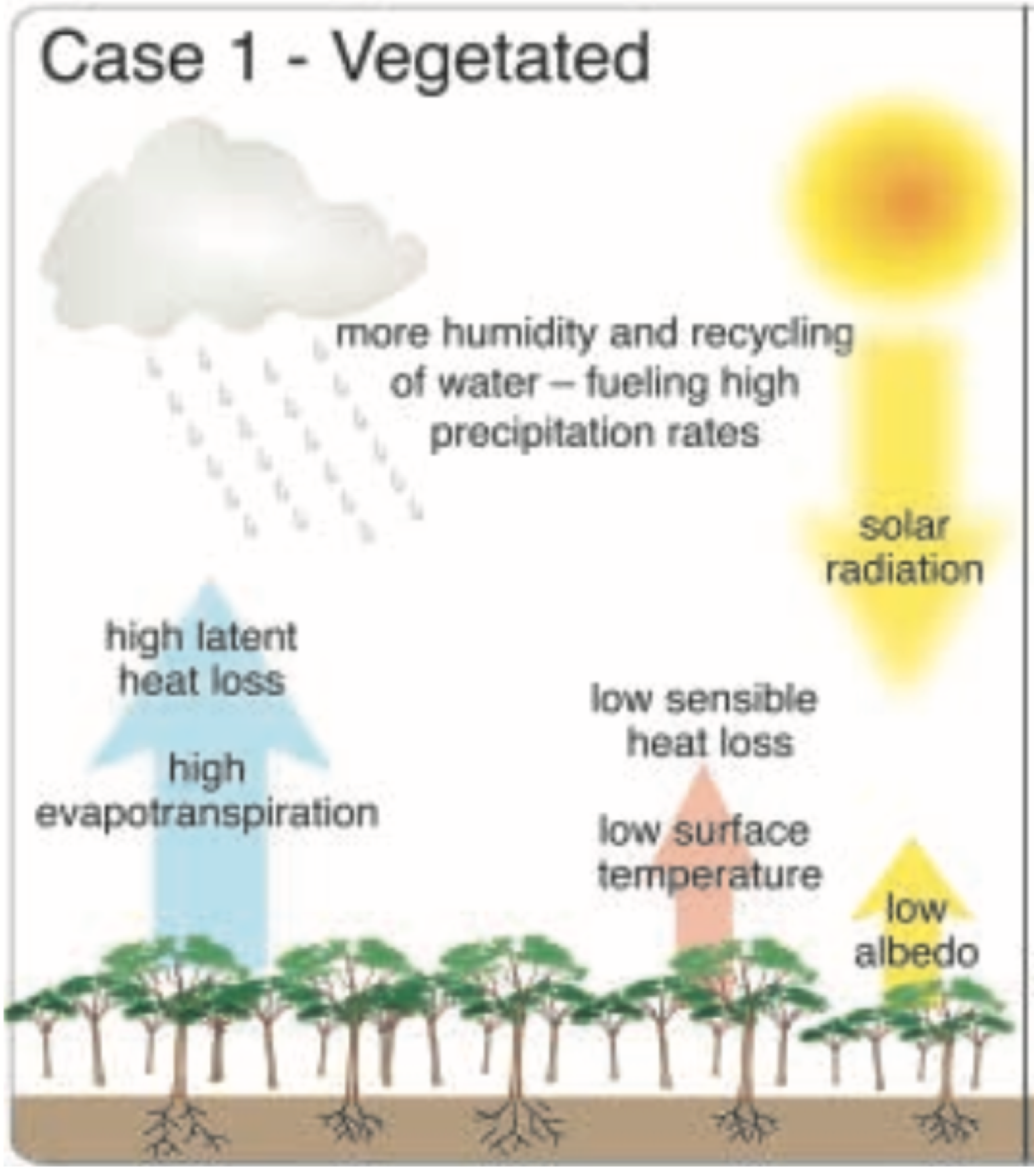
$$R_N - G = LE + SH + S + \Delta F_{eo}$$



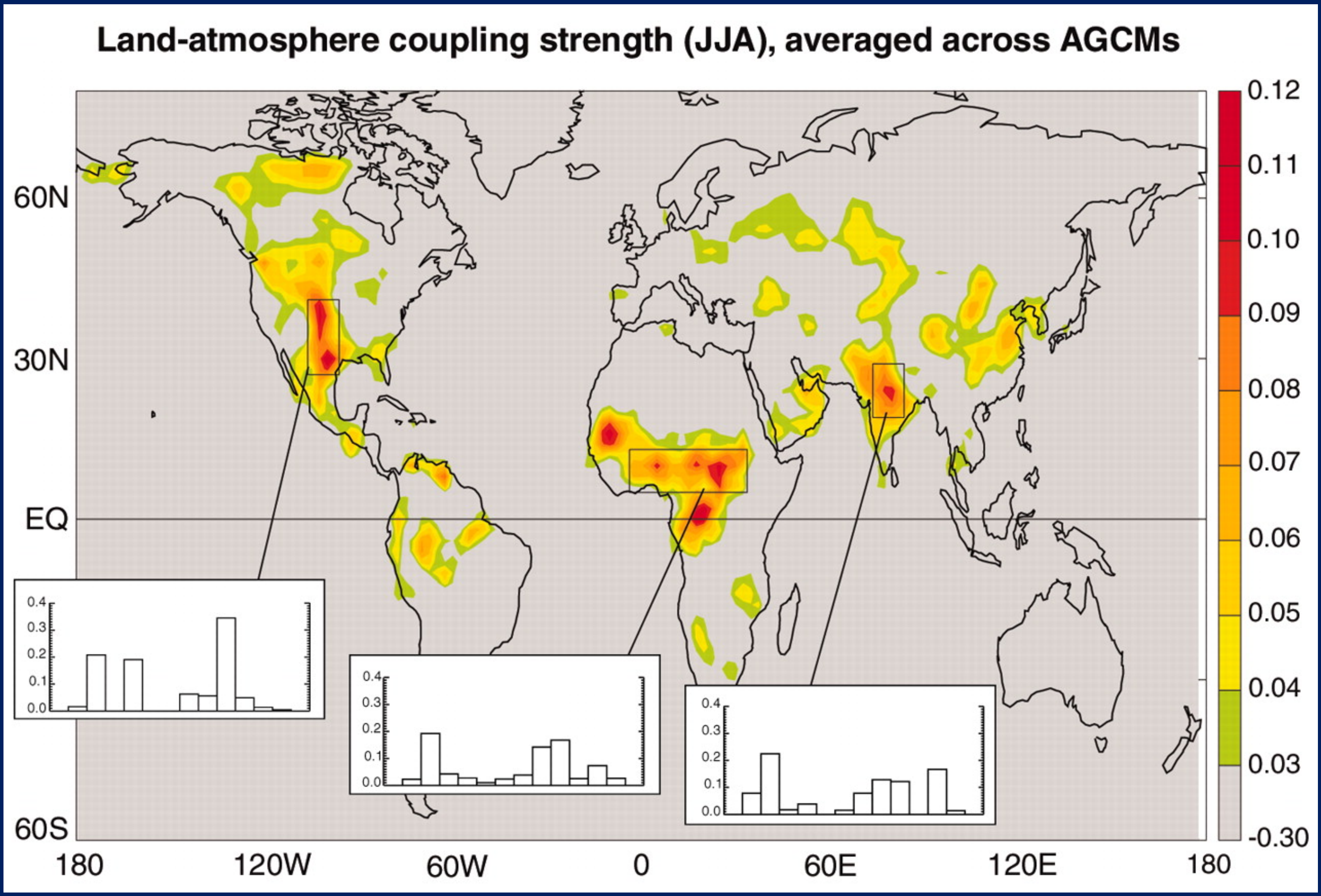
Green surprise? How terrestrial ecosystems could affect earth's climate

Jonathan A Foley[1], Marcos Heil Costa[2], Christine Delire[1], Navin Ramankutty[1], and Peter Snyder[1]

Frontiers in Ecology, 2003

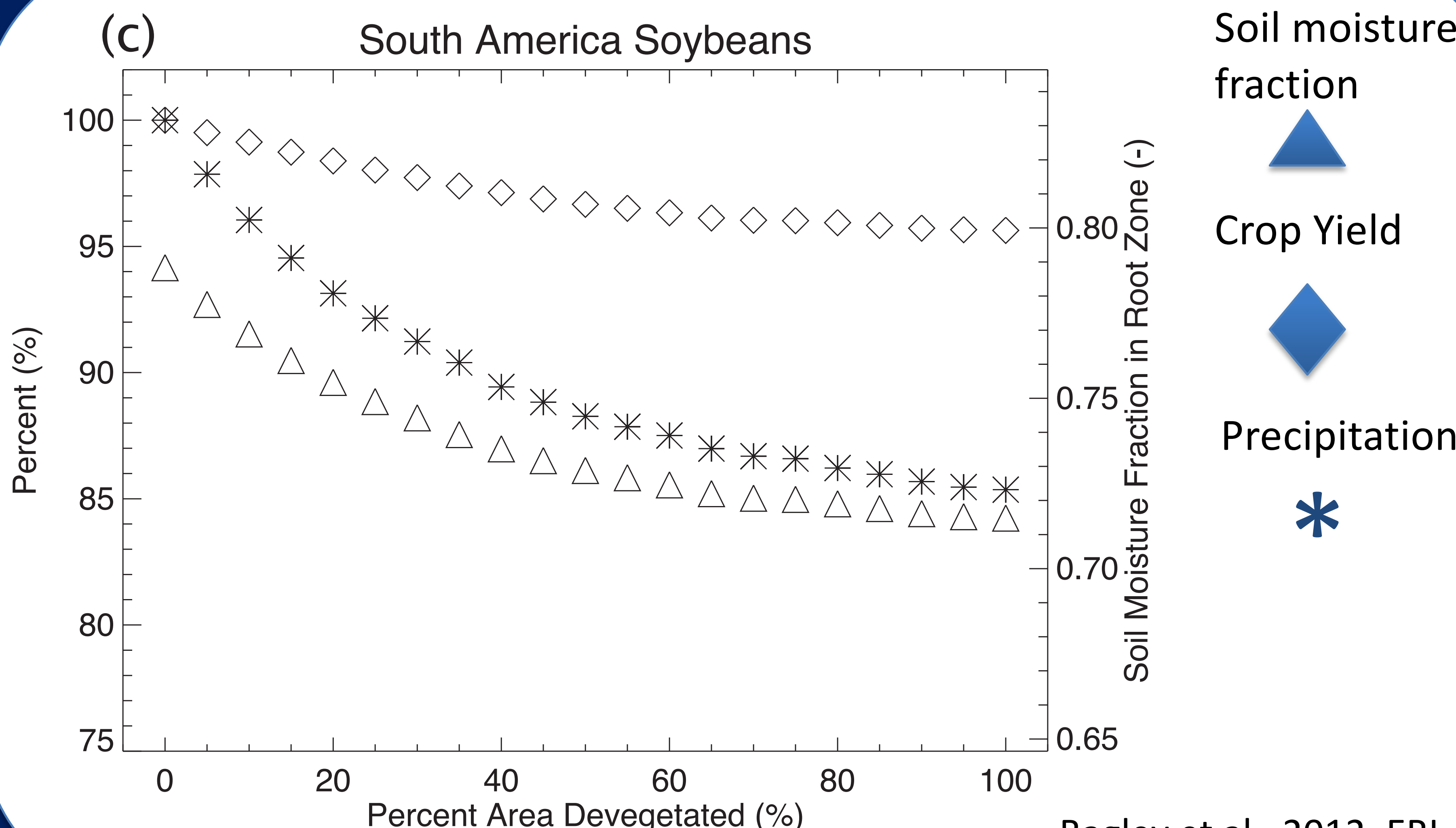


Koster et al., 2004

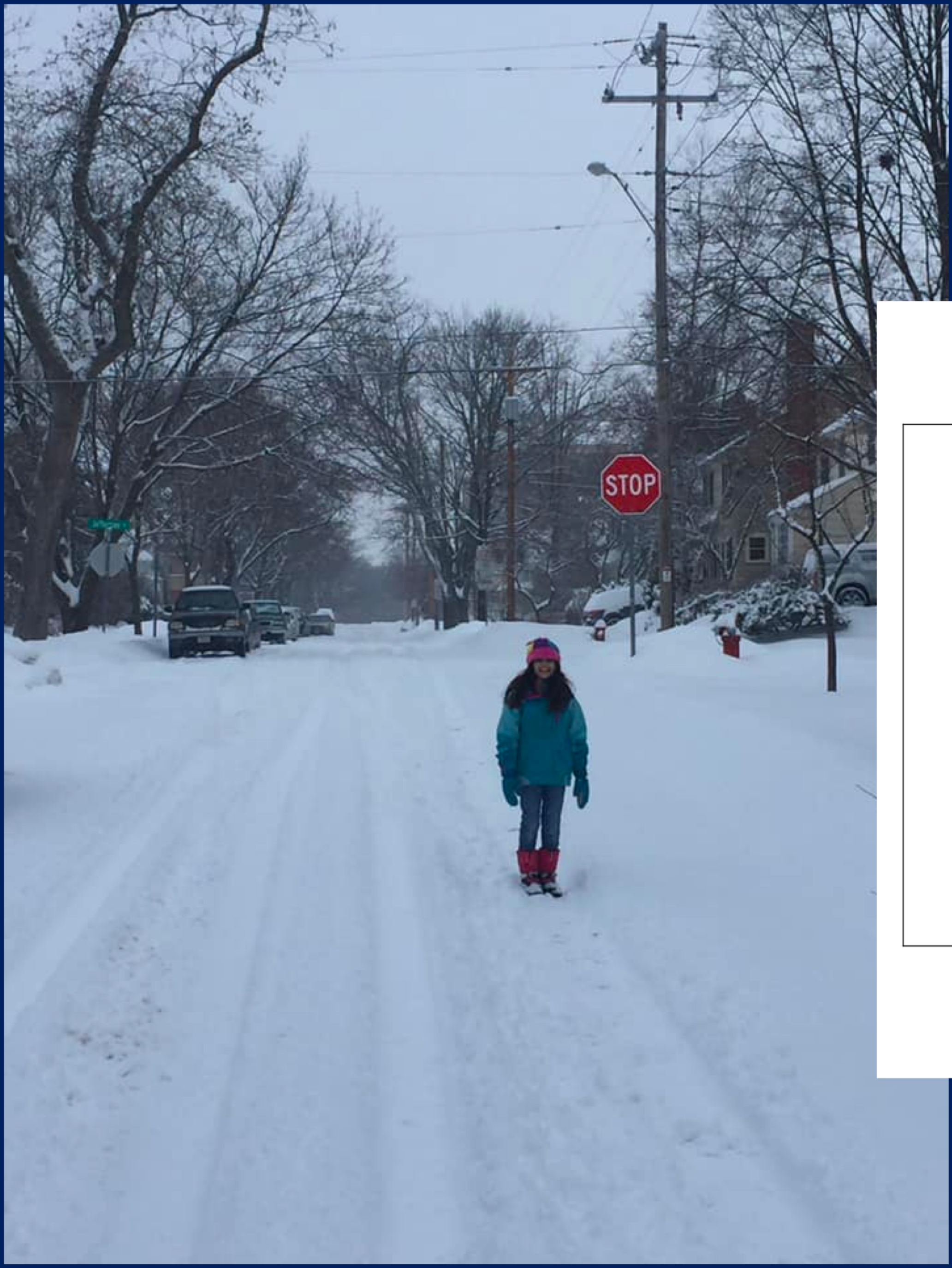


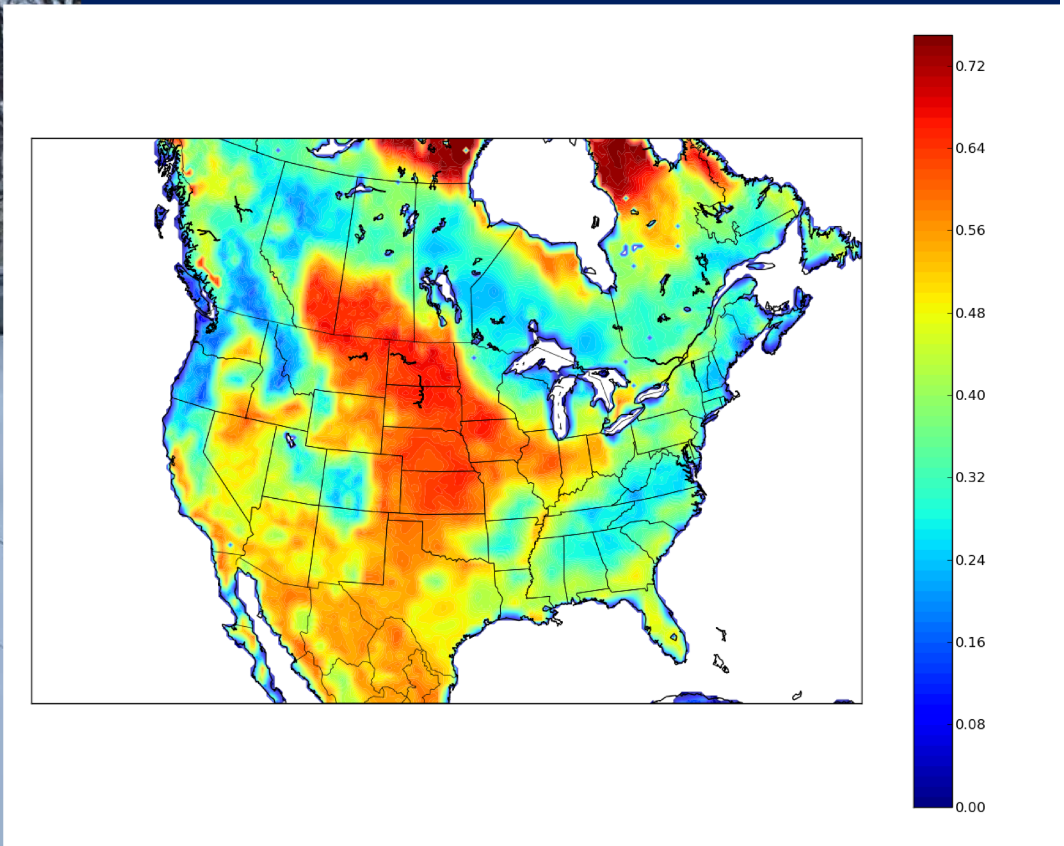
Potential Impact of Land Cover Change on Crop Yield

S. America Soybeans

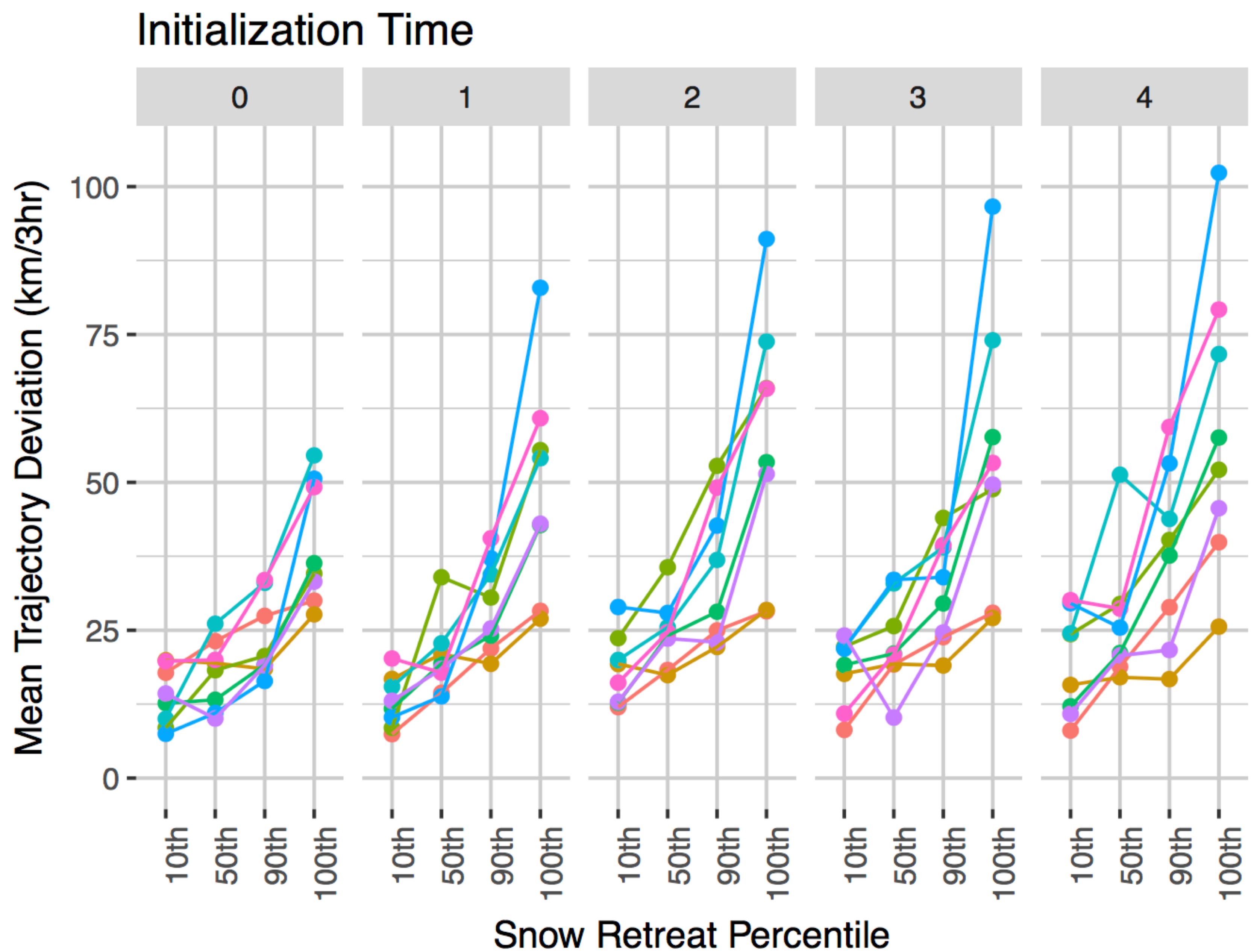


Bagley et al., 2012, ERL



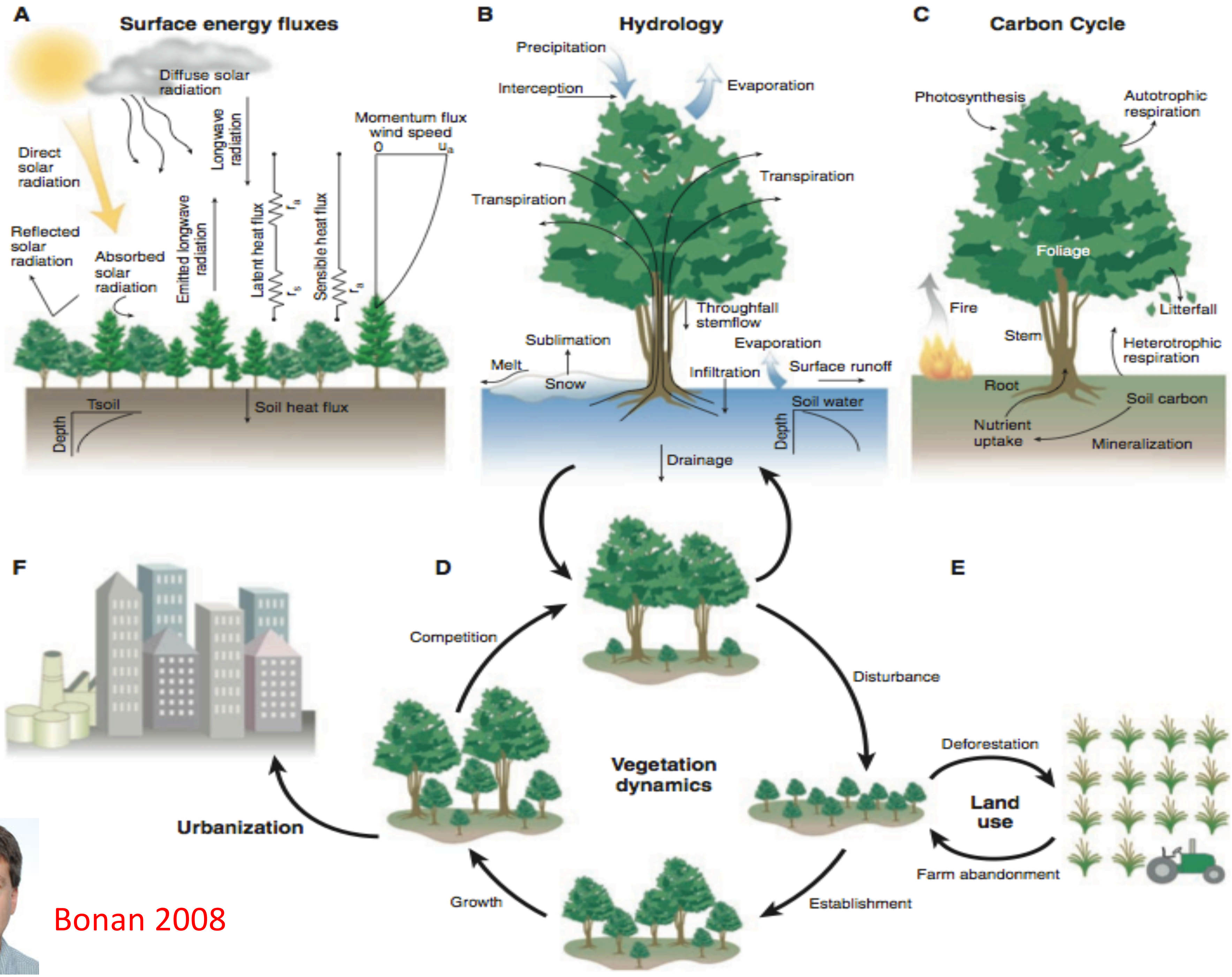


Clare et al., in prep, J Climate



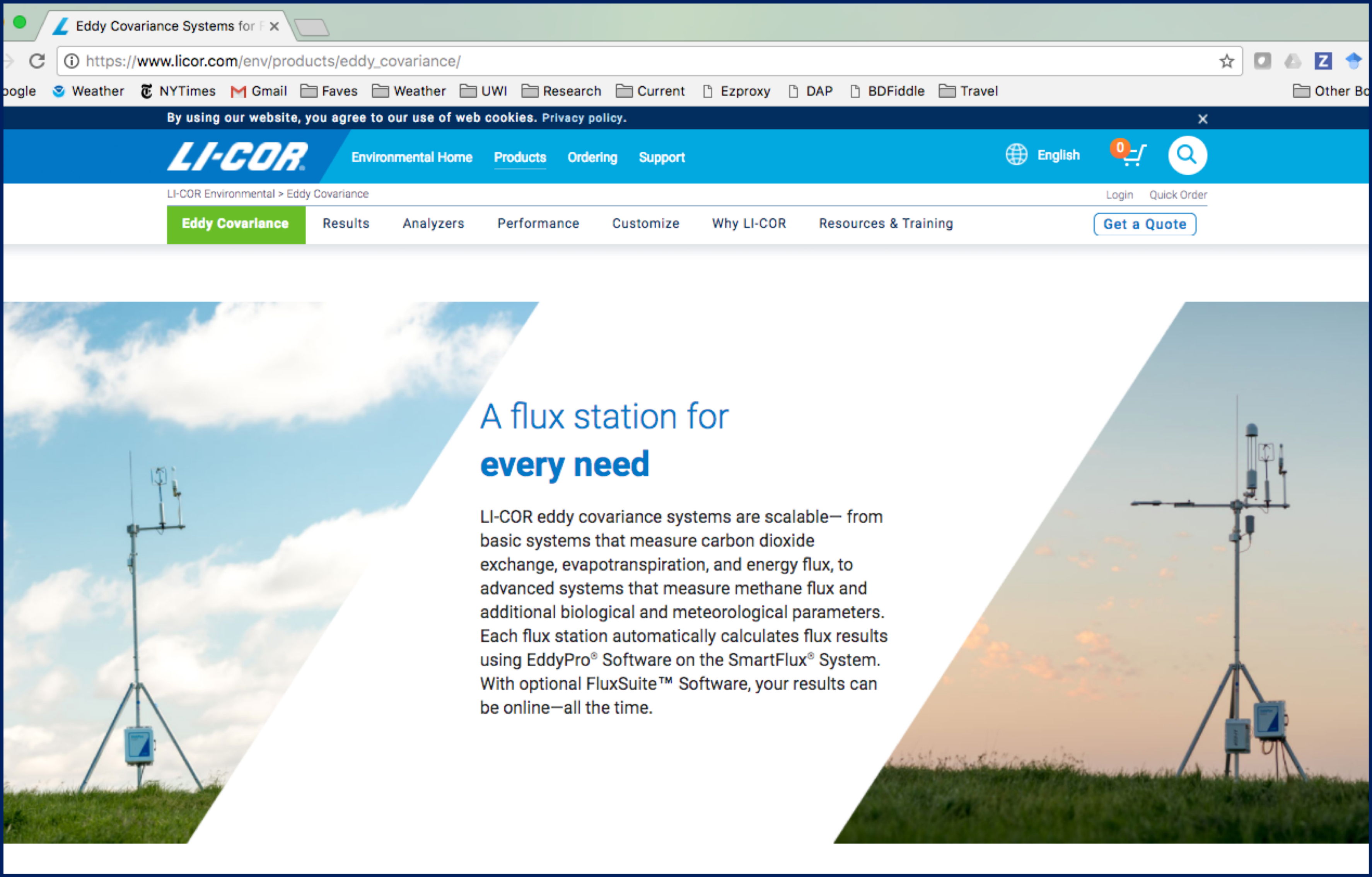
Rydzik and Desai, 2012; Clare et al ., in prep; figure by Michael Johnson

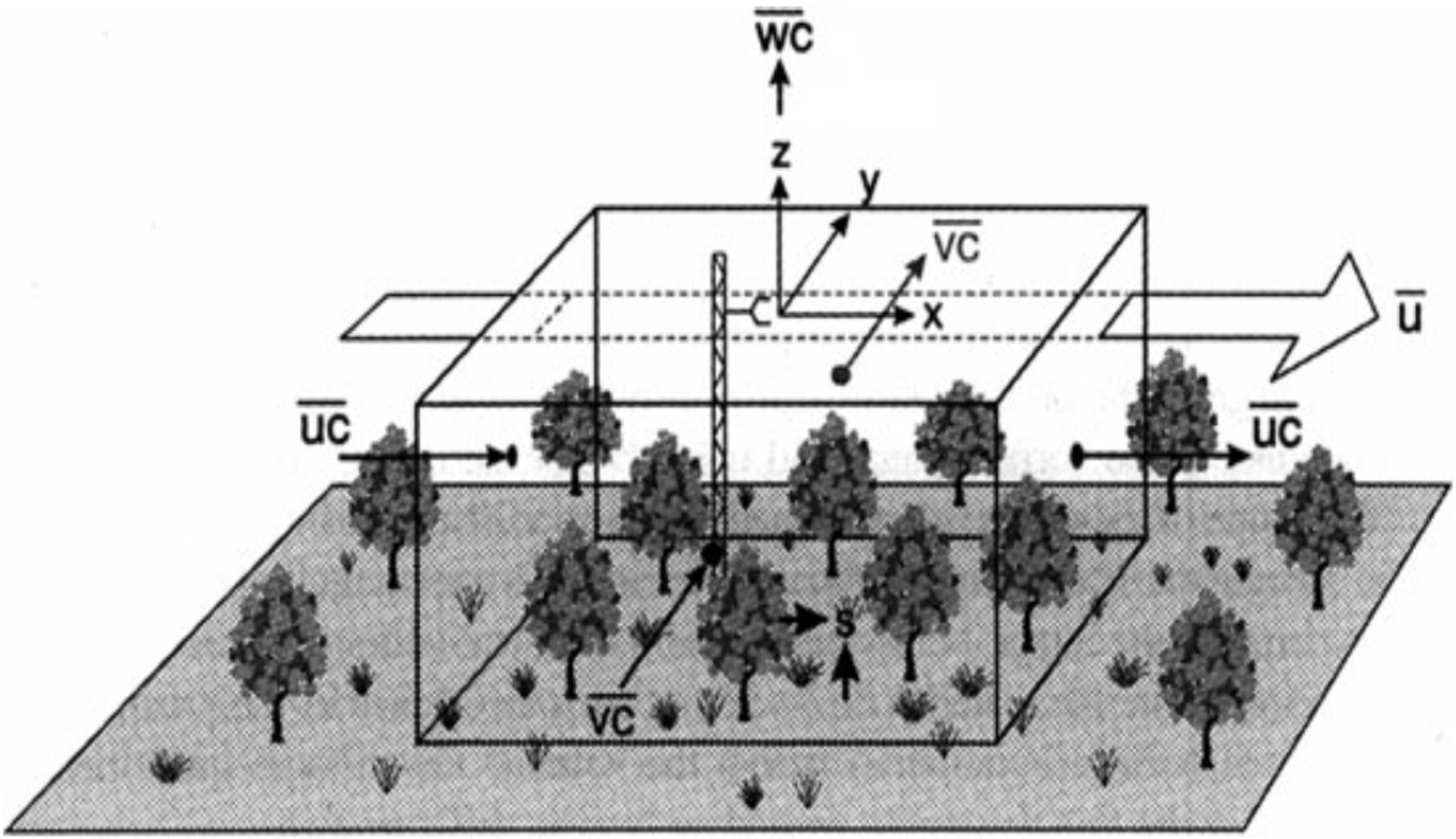
Forests in Flux



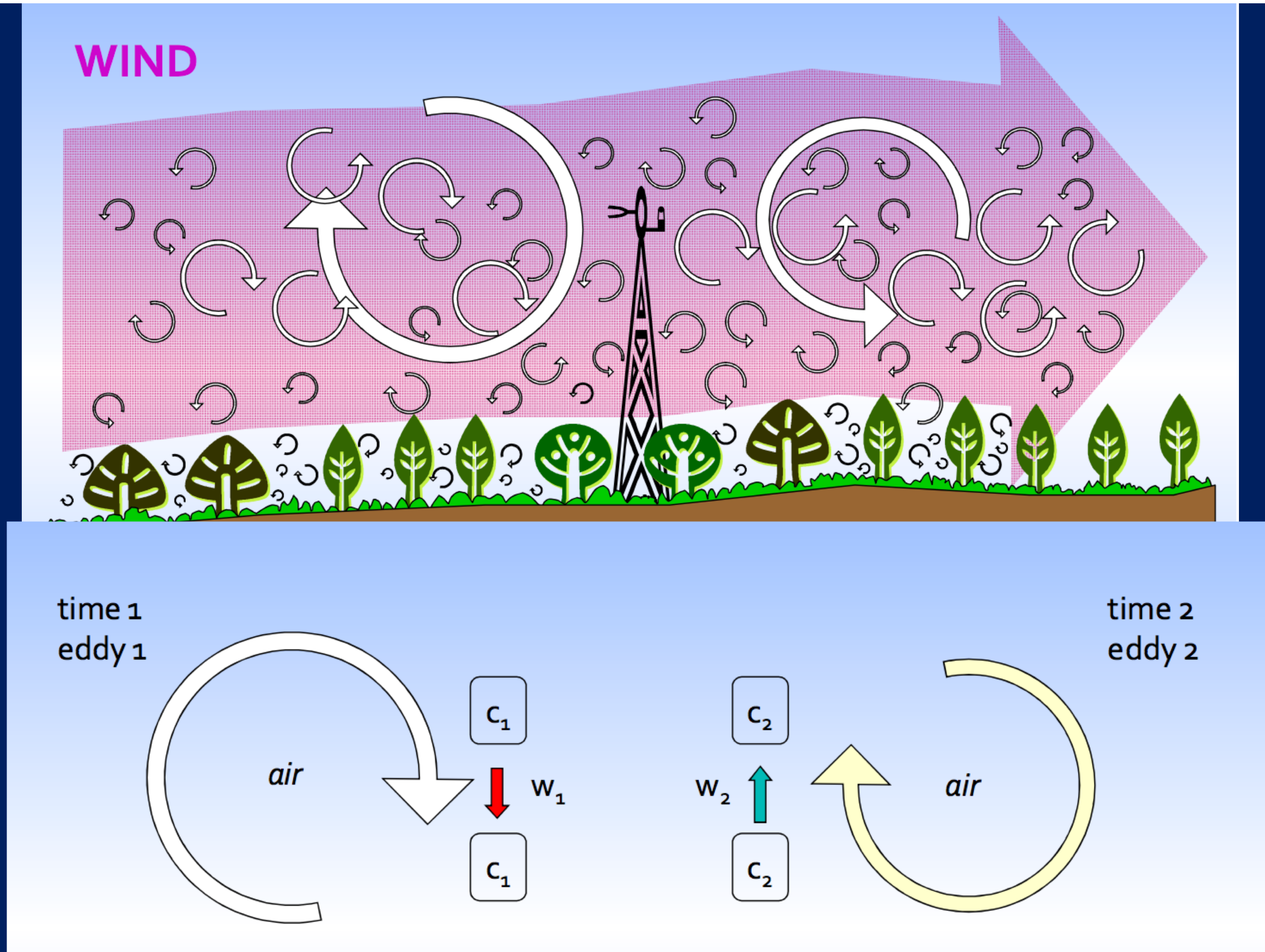
Bonan 2008

Enter eddy covariance flux towers

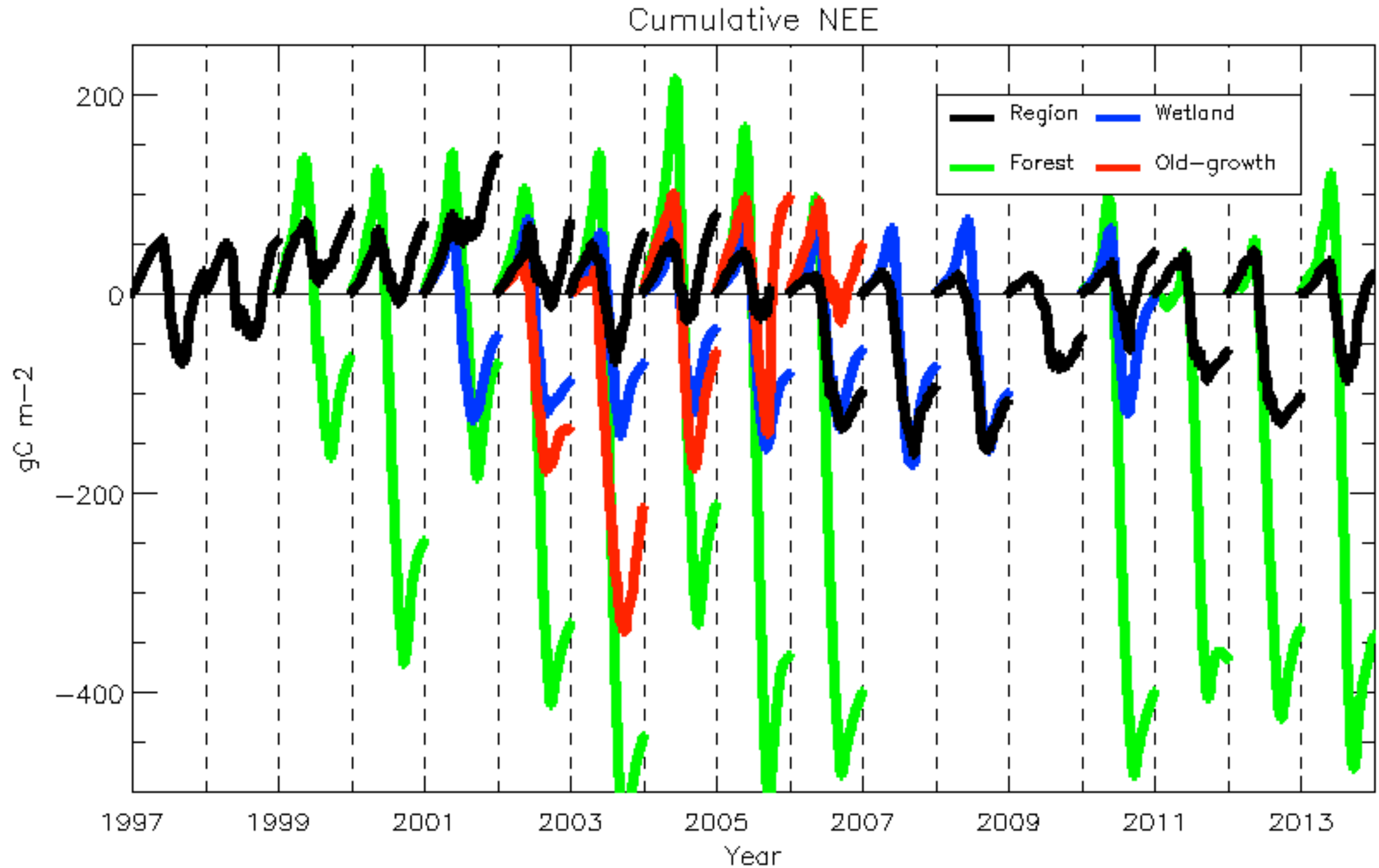


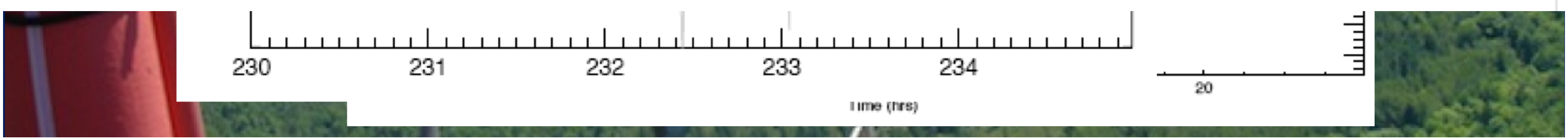


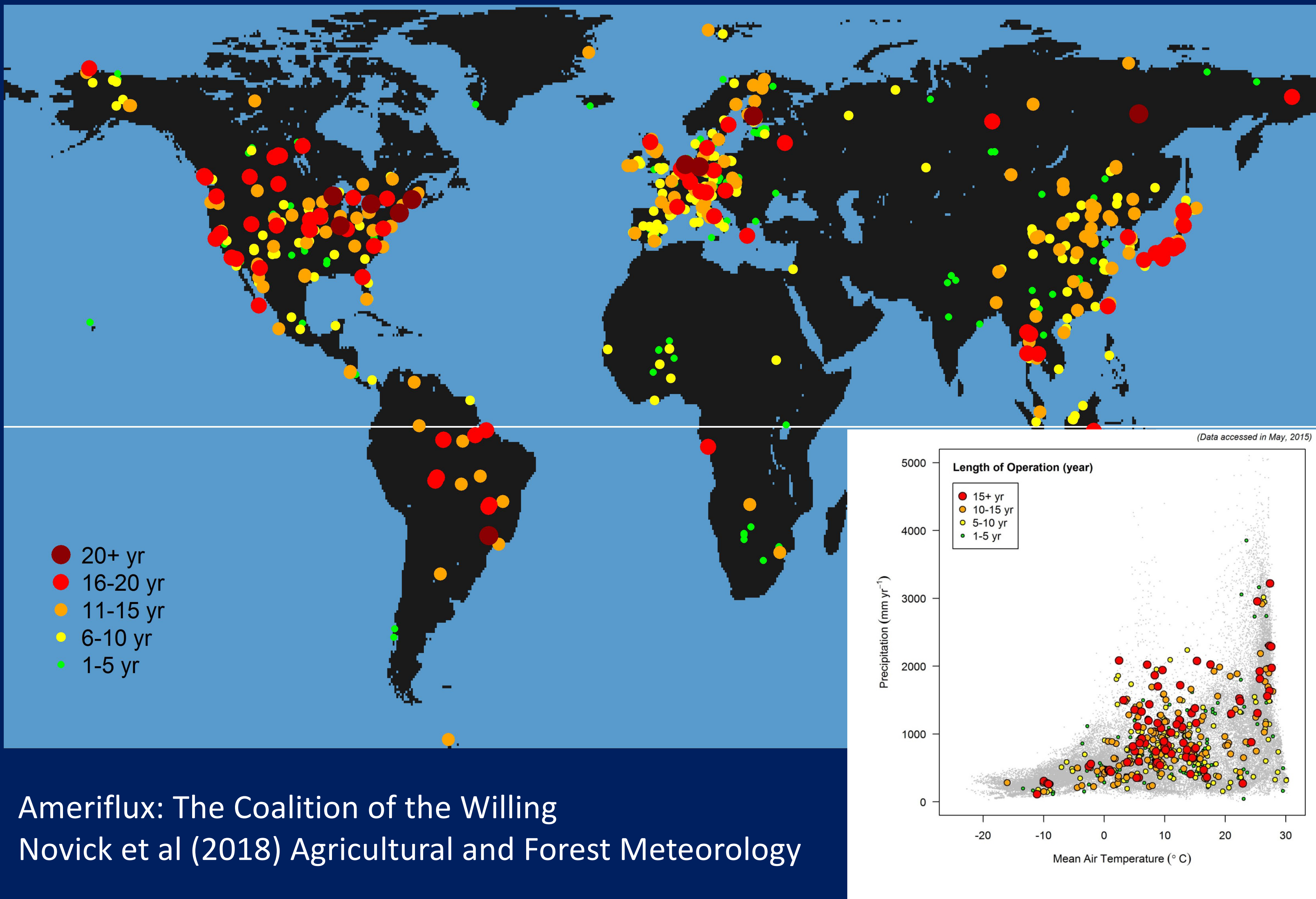
Finnigan et al (2003)



Burba and Anderson (2010)


Cumulative NEE
Region
Wetland
Forest
Old−growth
gC m−2
200
0
−200
−400
1997
1999
2001
2003
2005
2007
2009
2011
2013
Year

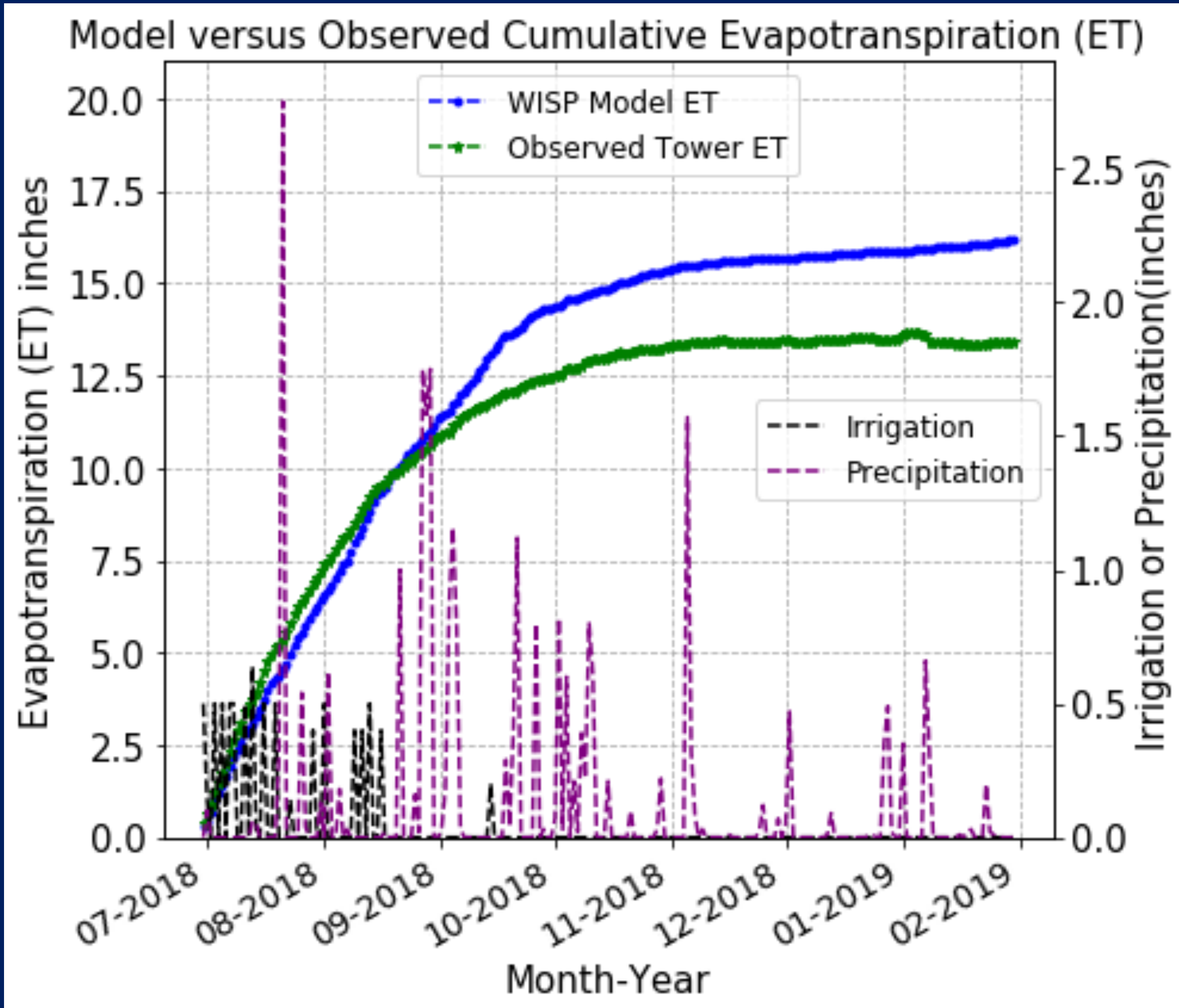

230
231
232
233
234
20



Ameriflux: The Coalition of the Willing

Novick et al (2018) Agricultural and Forest Meteorology


US-CS1
Heartland Farm
Operating from Jun 30, 2018
DELTA



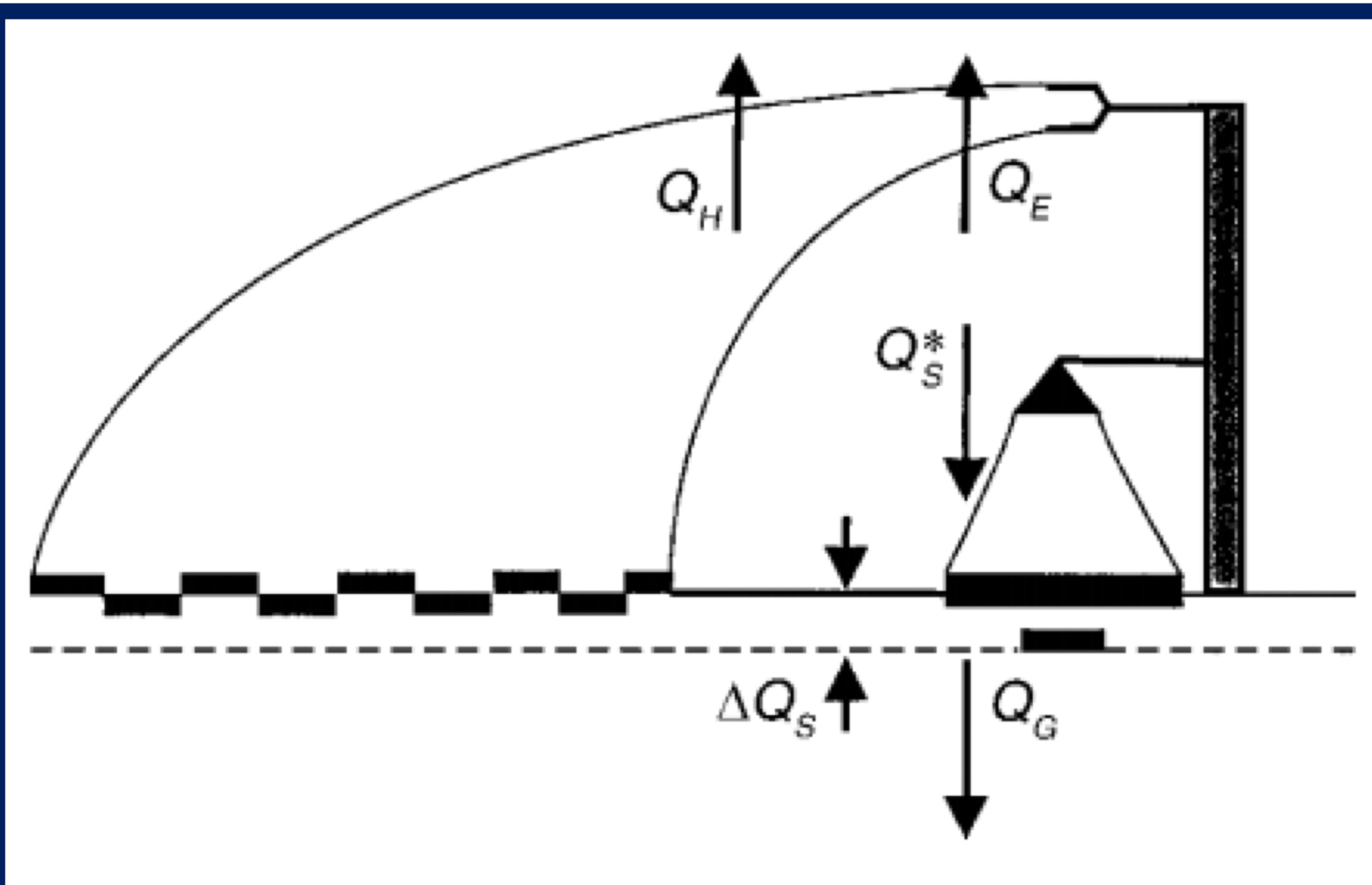
Model versus Observed Cumulative Evapotranspiration (ET)
WISP Model ET
Observed Tower ET
Irrigation
Precipitation
Evapotranspiration (ET) inches
Irrigation or Precipitation(inches)
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
2.5
2.0
1.5
1.0
0.5
0.0
07-2018
08-2018
09-2018
10-2018
11-2018
12-2018
01-2019
02-2019
Month-Year

But…

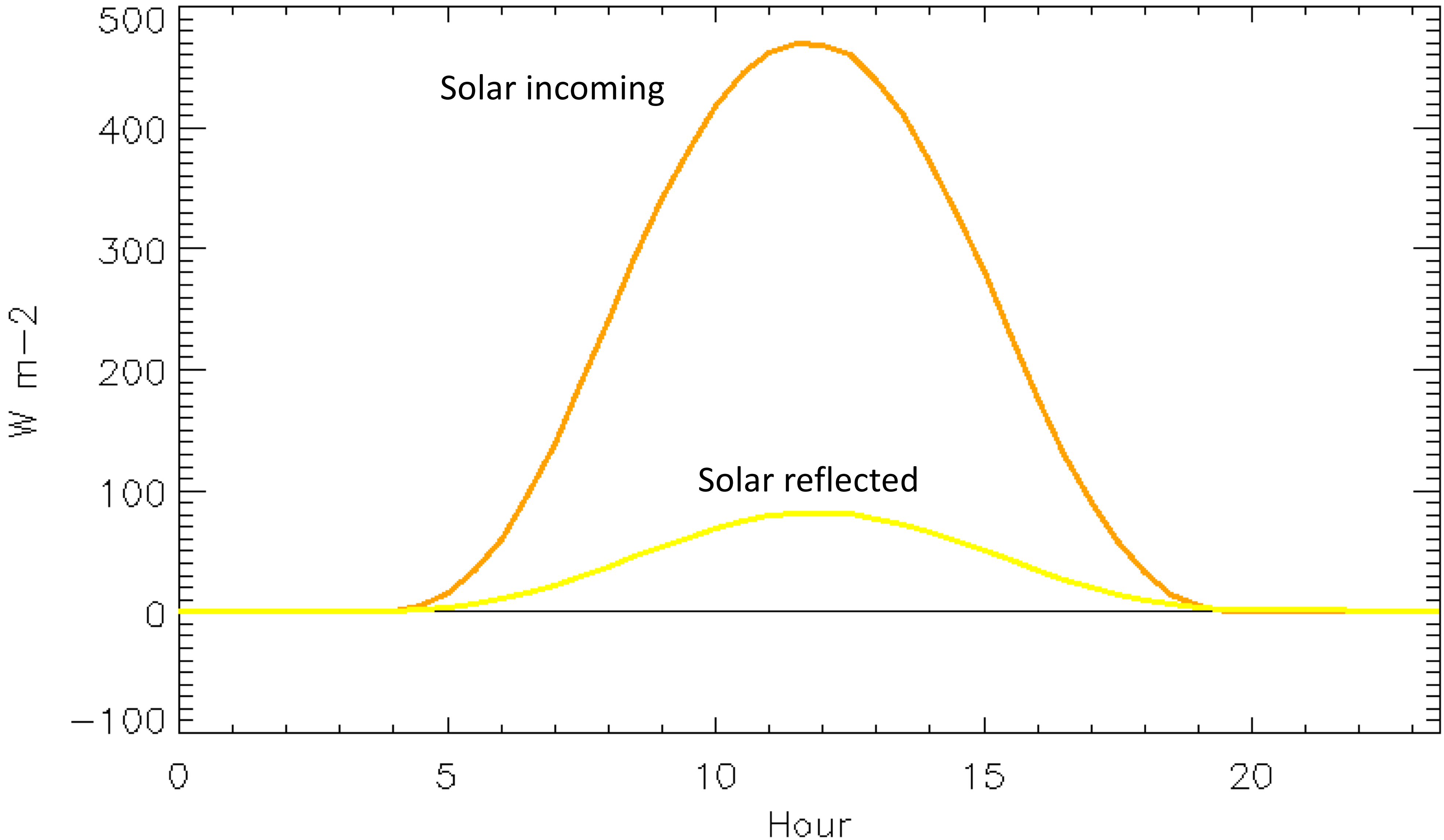
Ecological Applications, 18(6), 2008, pp. 1351–1367

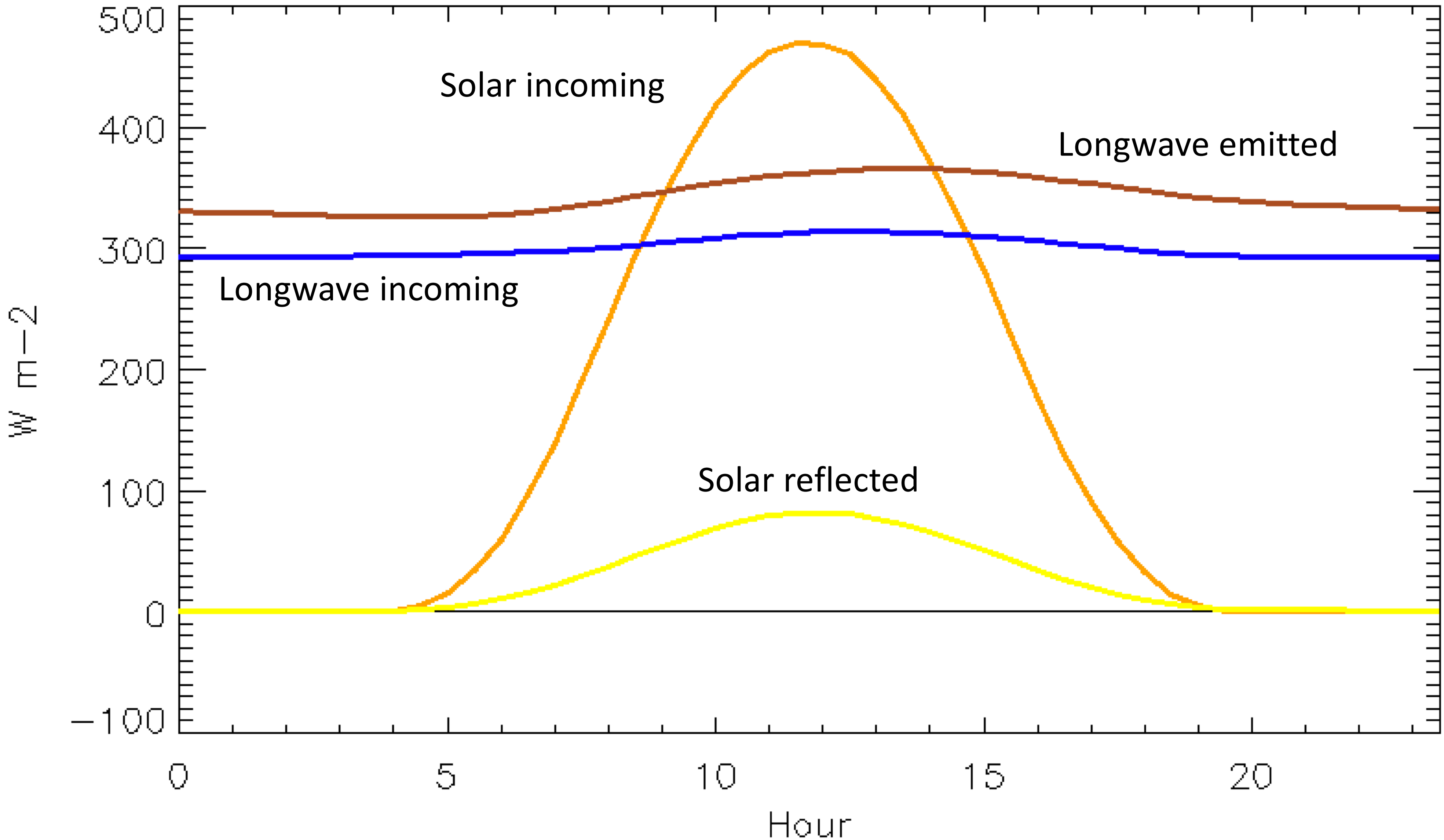
THE ENERGY BALANCE CLOSURE PROBLEM: AN OVERVIEW

THOMAS FOKEN[1]

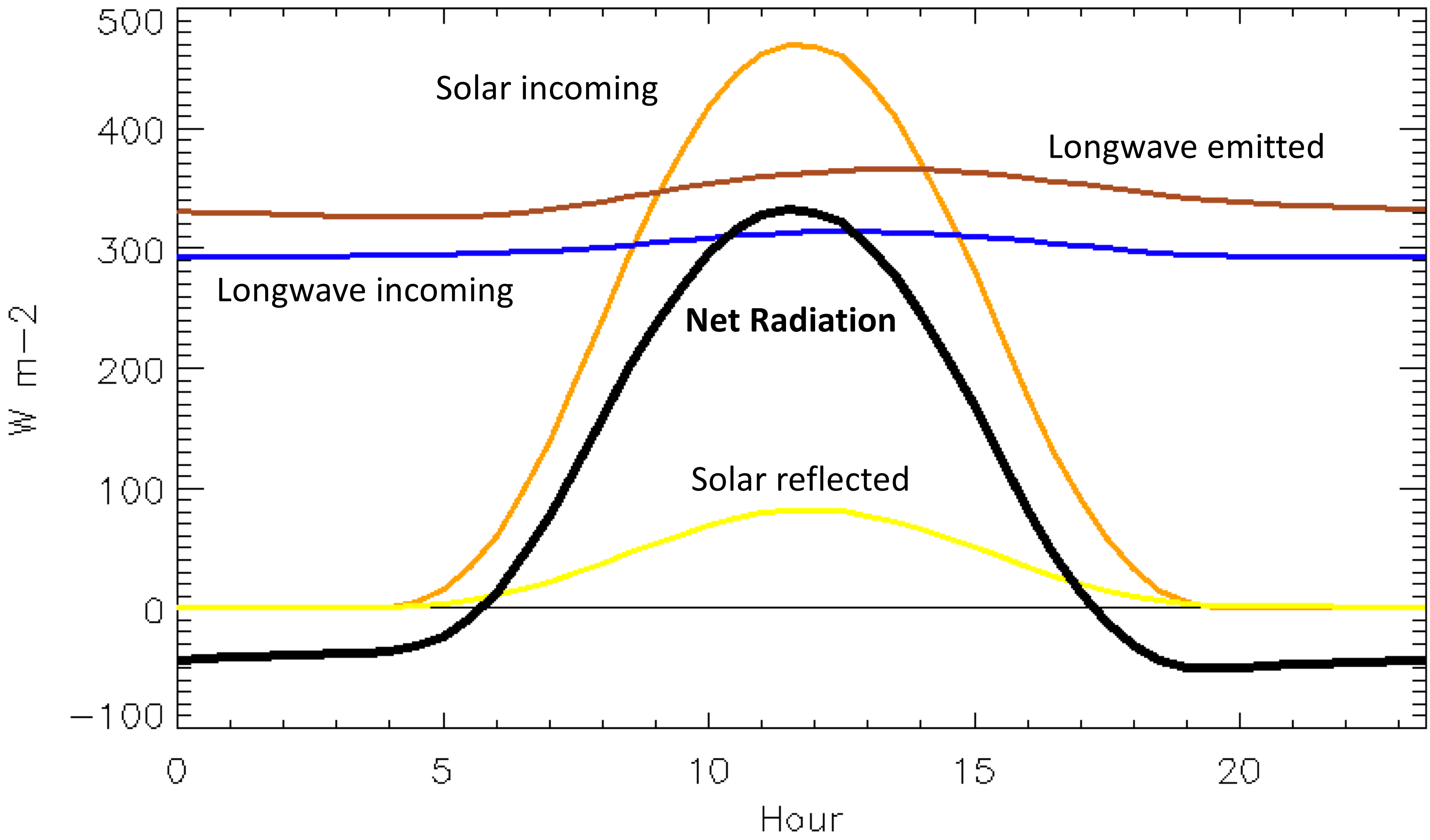



US-Syv (Sylvania)
Desai et al., 2005, Ag For Met

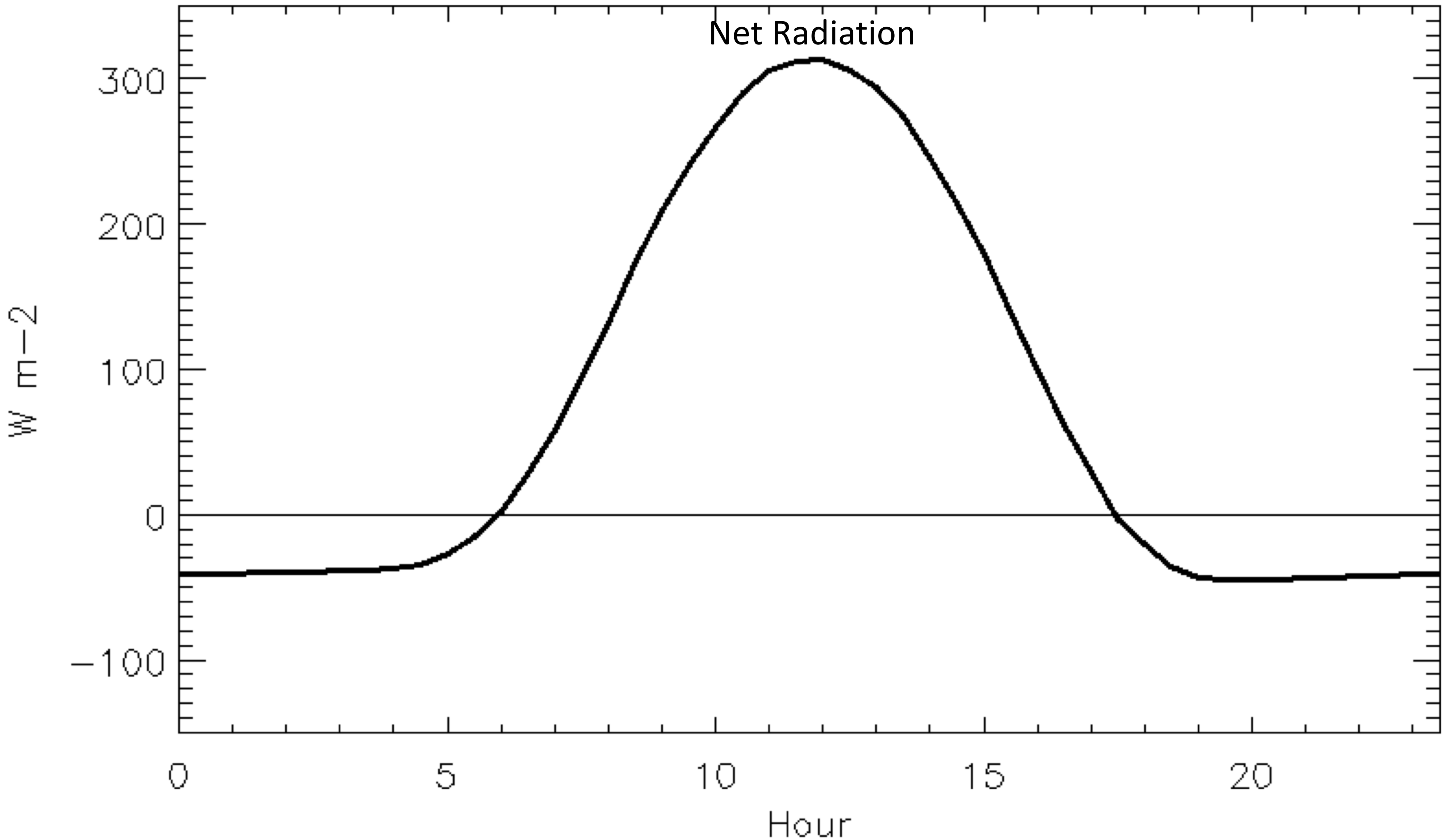

Solar incoming
Solar reflected
500
400
300
200
100
0
−100
W m−2
0
5
10
15
20
Hour



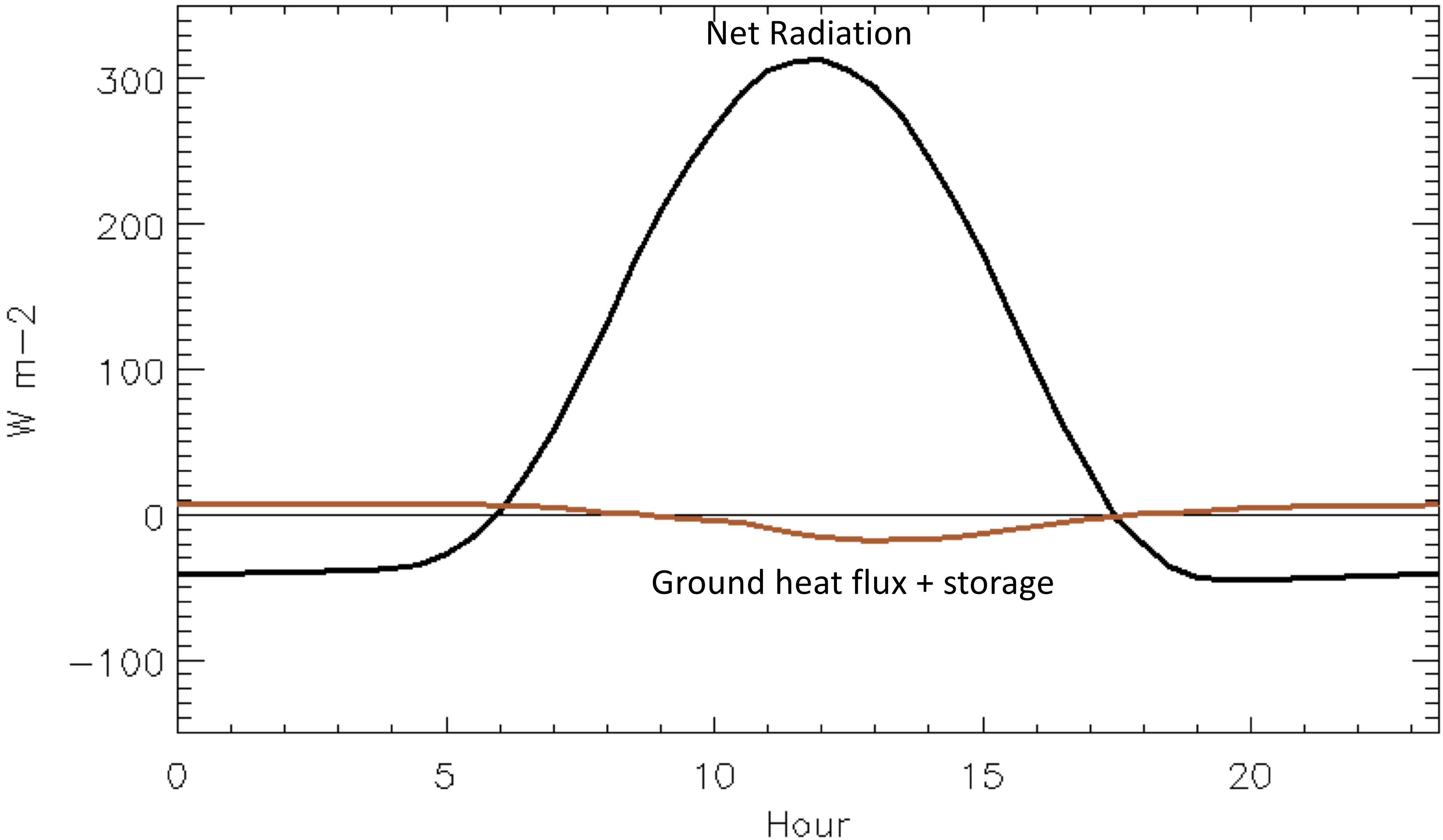
Solar incoming
Longwave emitted
Longwave incoming
Solar reflected
500
400
300
200
100
0
−100
W m−2
0
5
10
15
20
Hour

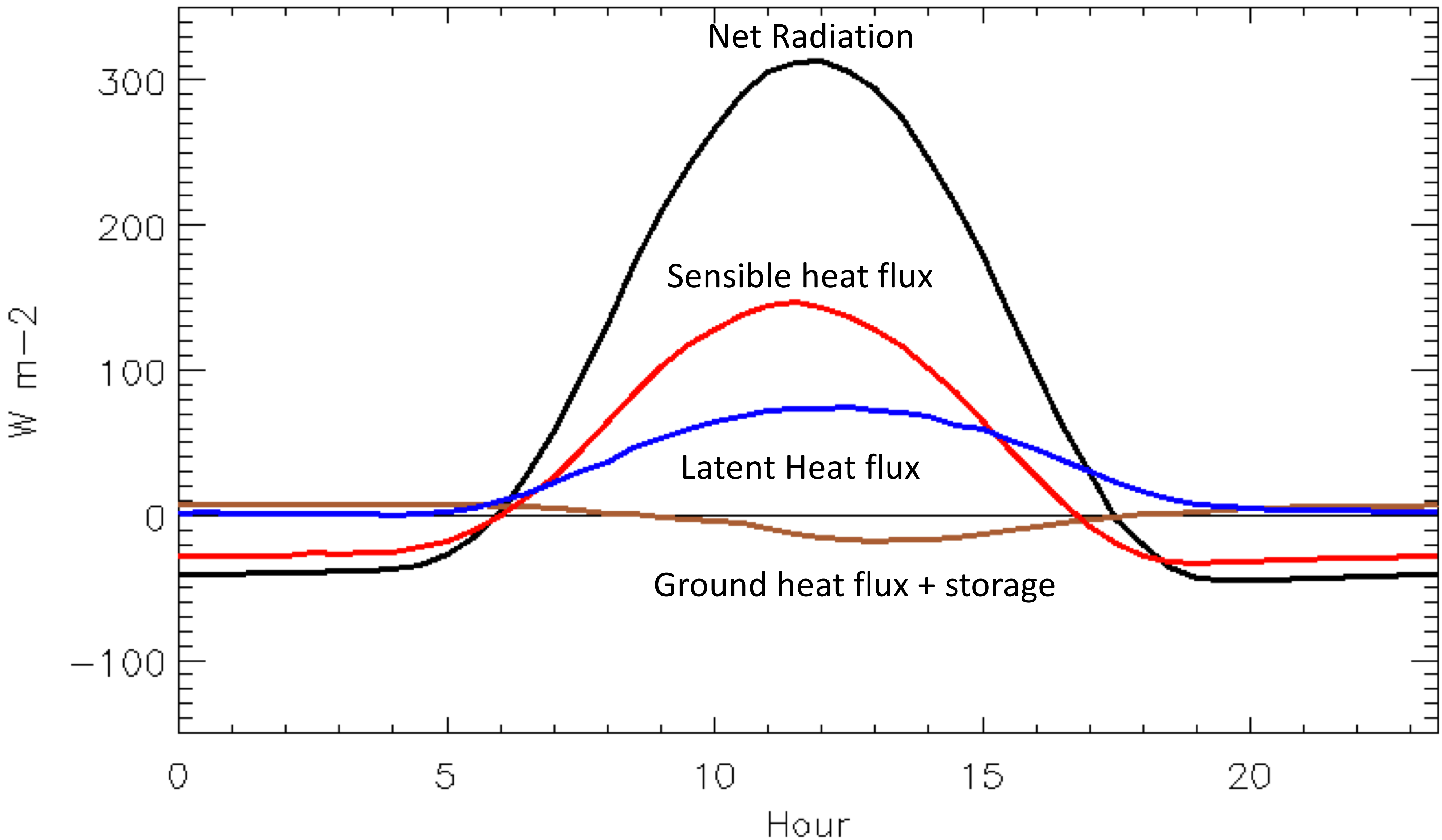


500
400
300
200
100
0
−100
W m−2
0
5
10
15
20
Hour
Solar incoming
Longwave emitted
Longwave incoming
Net Radiation
Solar reflected

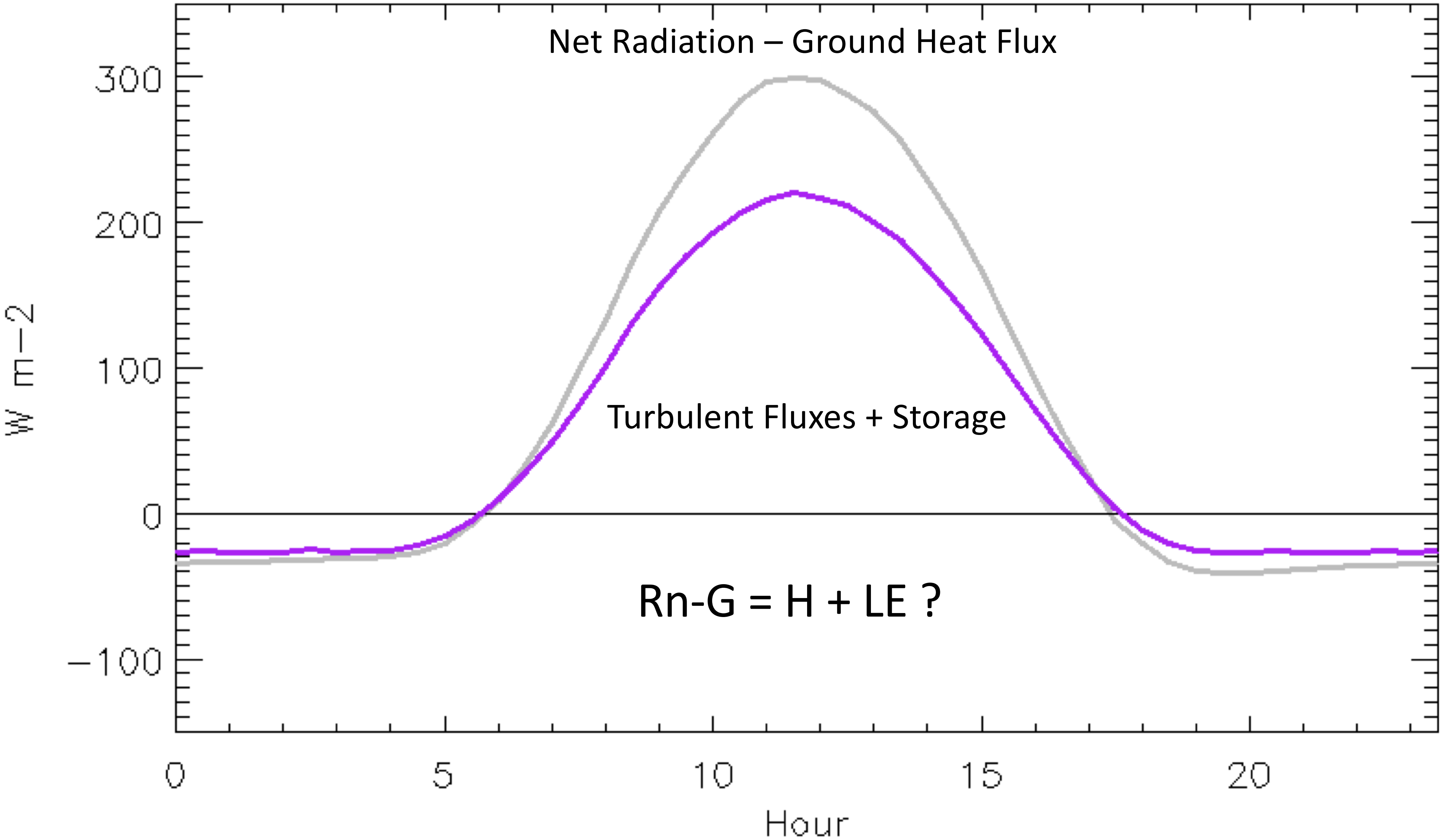


Net Radiation
300
200
100
0
−100
W m−2
0
5
10
15
20
Hour

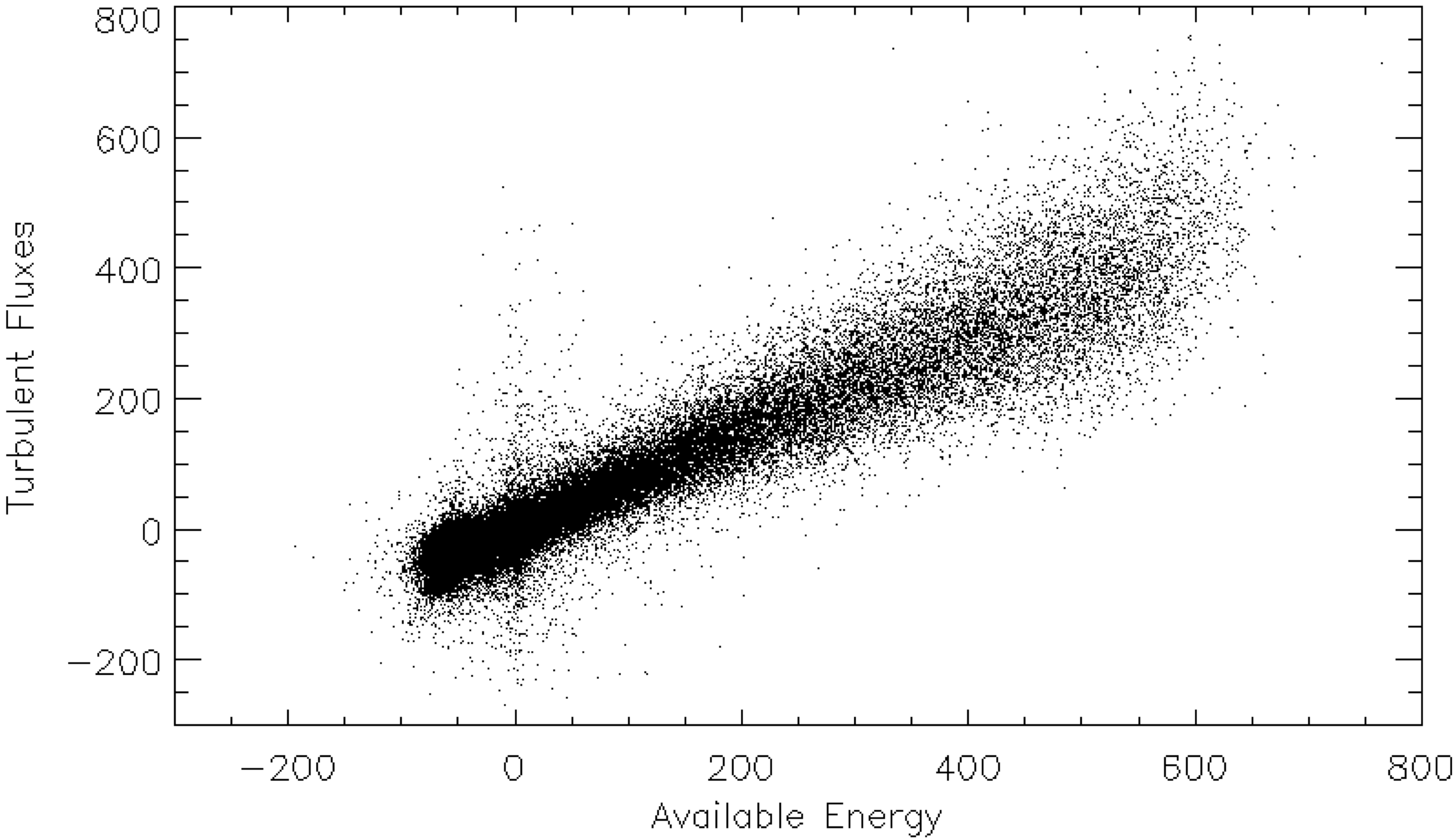

Net Radiation
Ground heat flux + storage
W m−2
300
200
100
0
−100
0
5
10
15
20
Hour



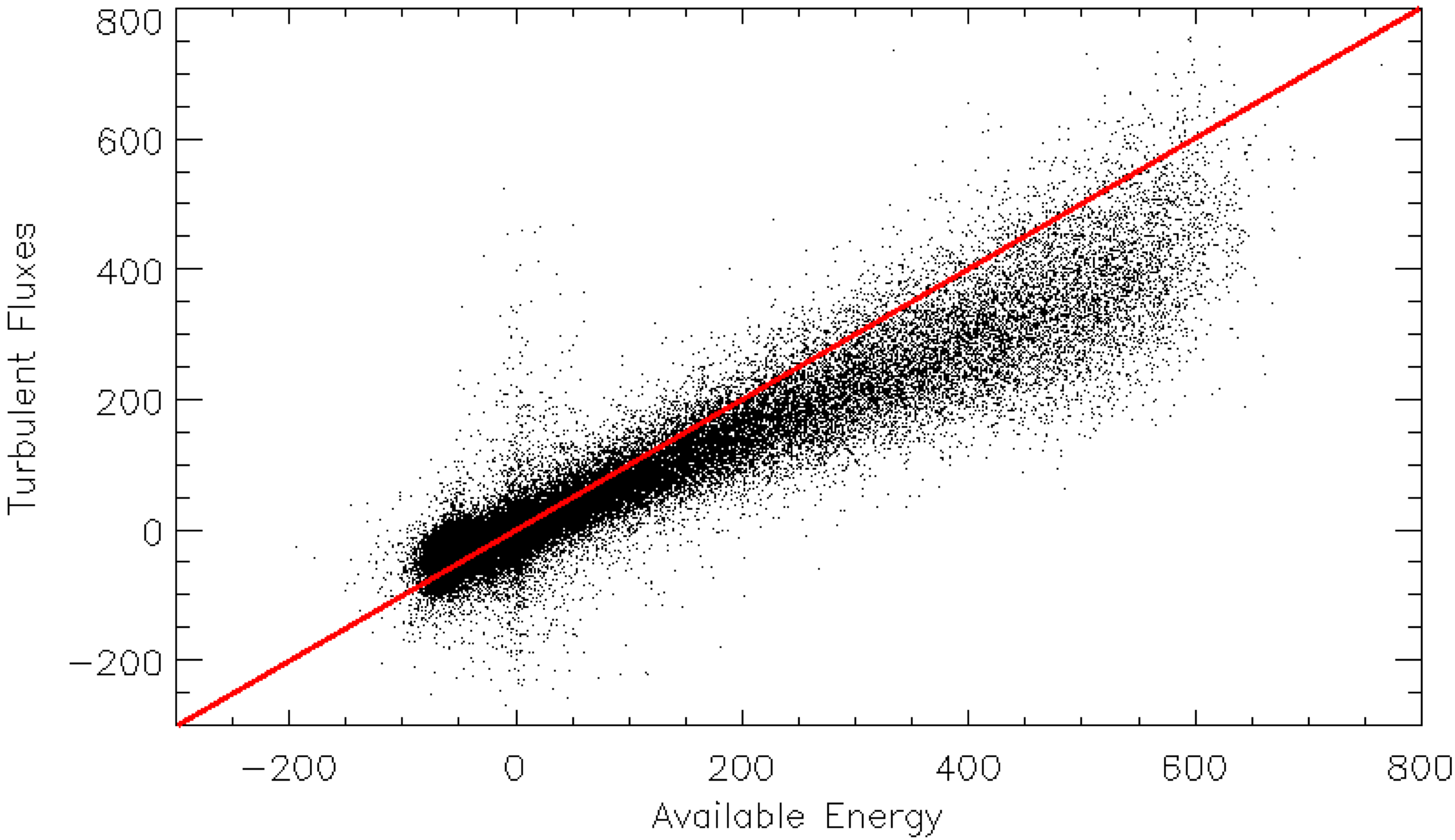
Net Radiation
Sensible heat flux
Latent Heat flux
Ground heat flux + storage
300
200
100
0
−100
W m−2
0
5
10
15
20
Hour

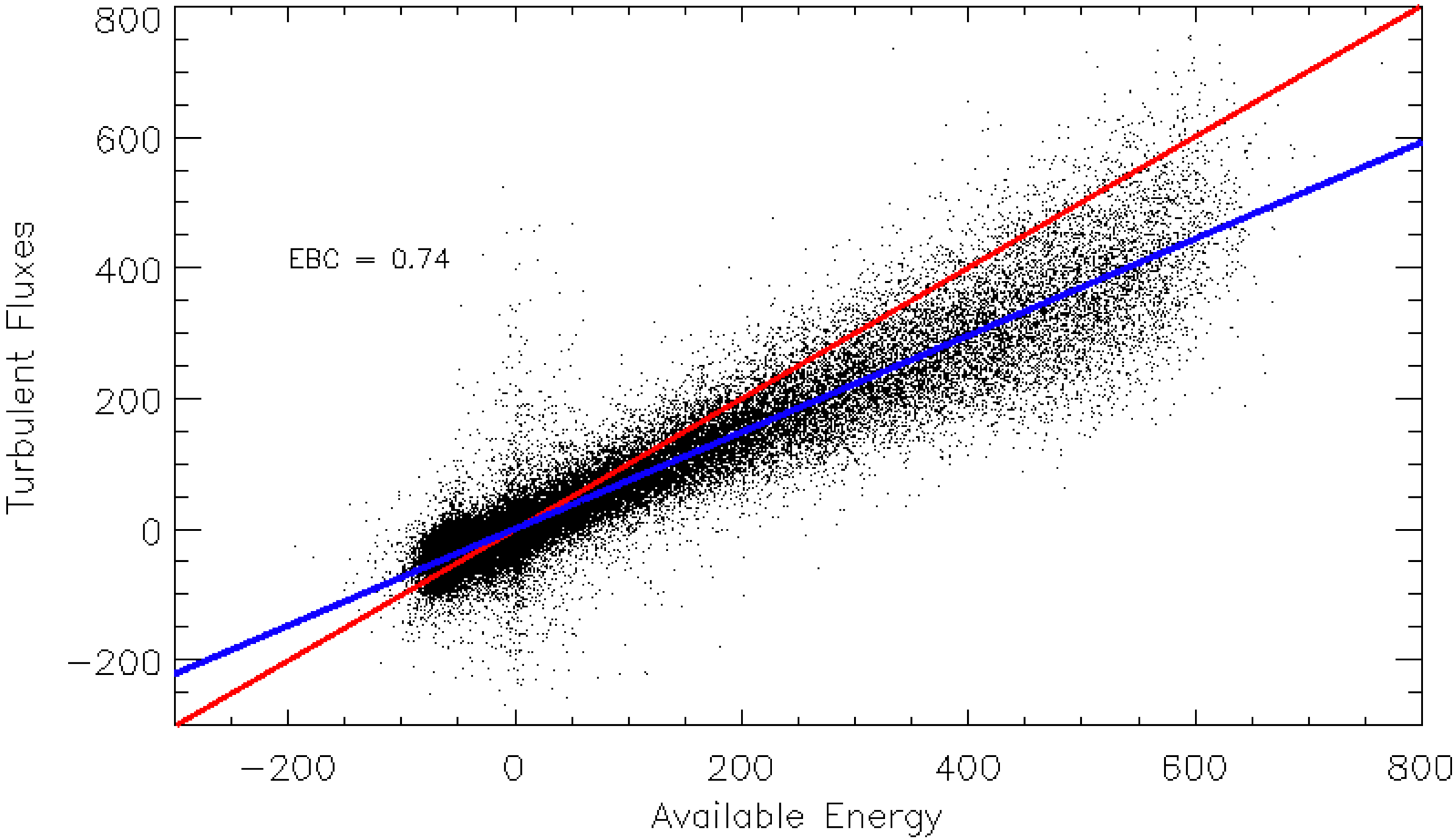


Net Radiation – Ground Heat Flux
Turbulent Fluxes + Storage
Rn-G = H + LE ?
300
200
100
0
−100
W m−2
0
5
10
15
20
Hour



800
600
400
200
0
−200
Turbulent Fluxes
−200
0
200
400
600
800
Available Energy


Turbulent Fluxes
Available Energy
800
600
400
200
0
−200
−200
0
200
400
600
800



EBC = 0.74
Turbulent Fluxes
Available Energy
800
600
400
200
0
−200
−200
0
200
400
600
800

Energy Imbalance is Common But Variable in Space and Time

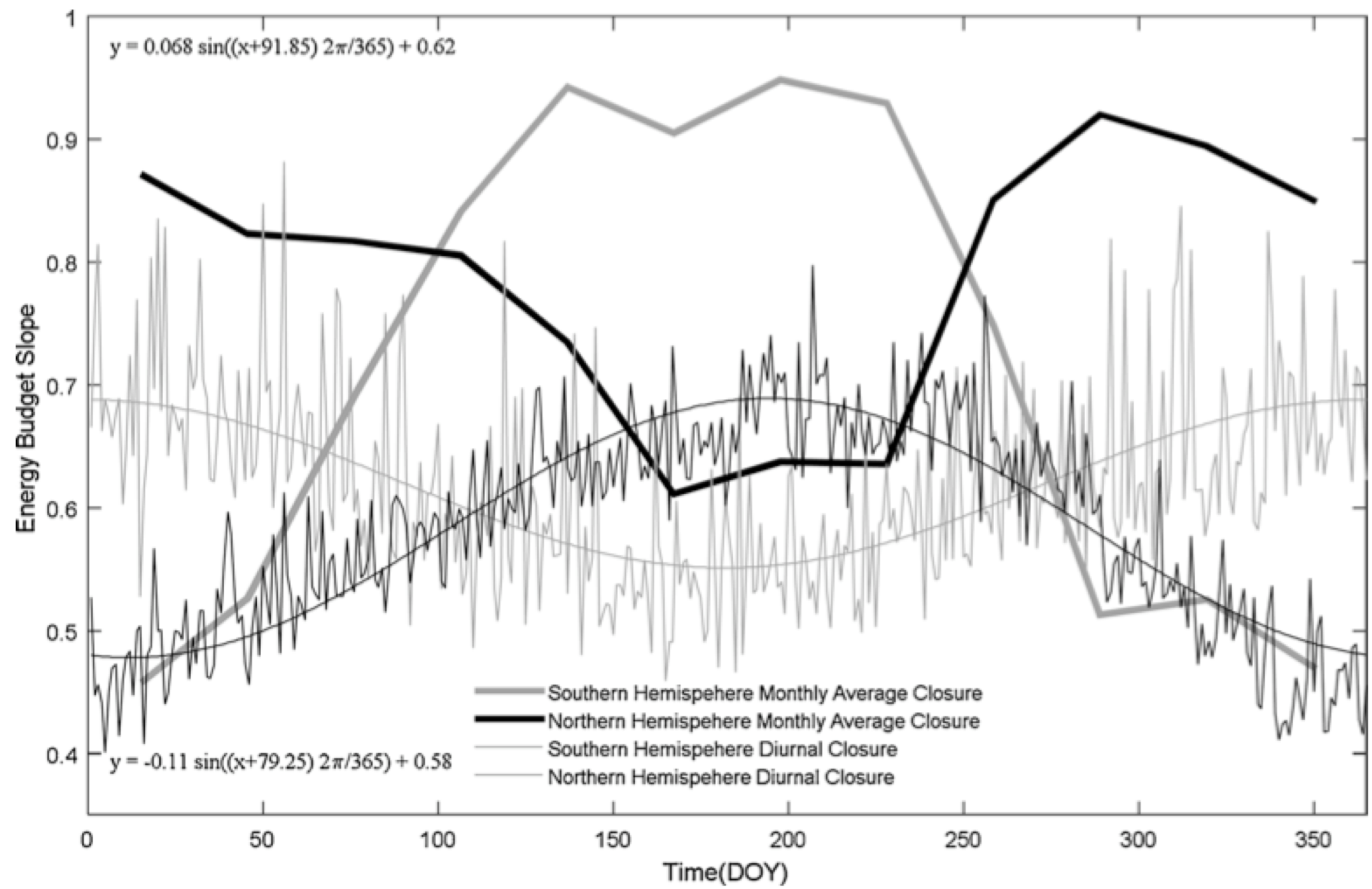


Fig. 7. Variation over an average year in FLUXNET2015 site energy closure, based on regression slope. Site separated by northern hemisphere (black, n = 132) and southern hemisphere (grey, n = 27). Bold lines shows monthly average regression energy closure at northern (bold black) and southern (bold grey) hemisphere sites.

Reed et al., 2018, Ag For Met

WHY!?!?

Bad Instruments?

ELSEVIER

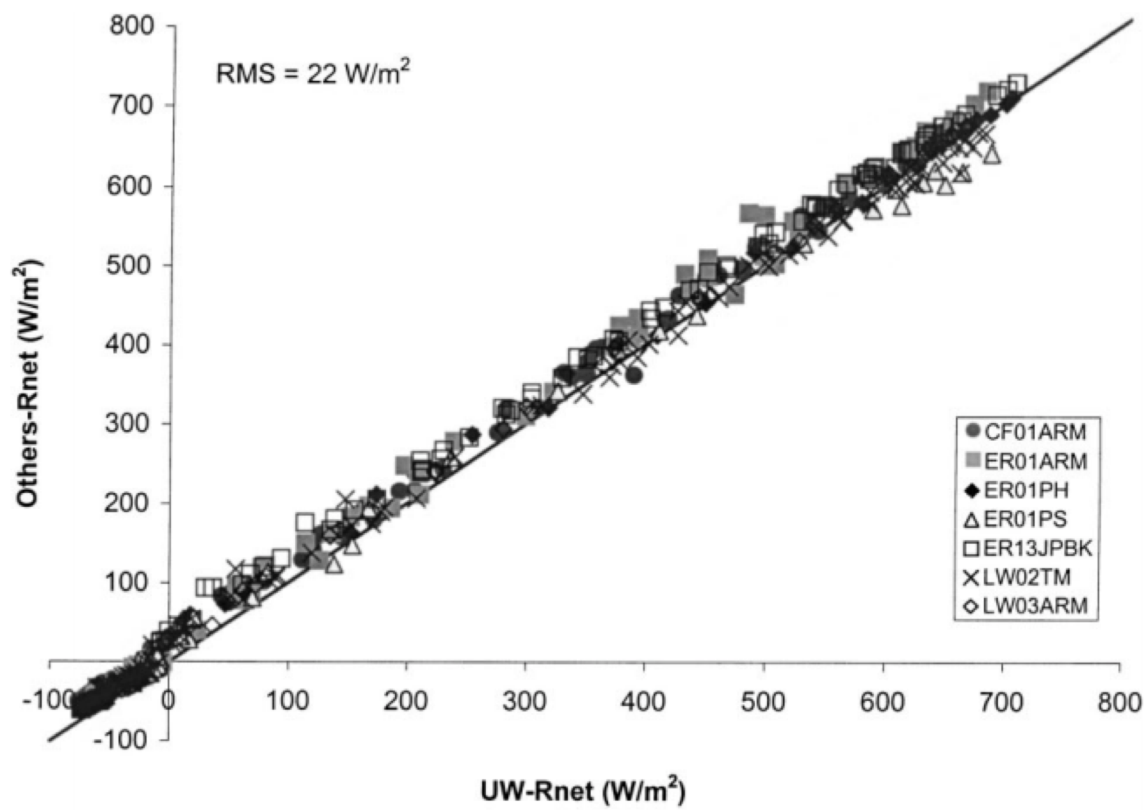
Agricultural and Forest Meteorology 103 (2000) 279–300

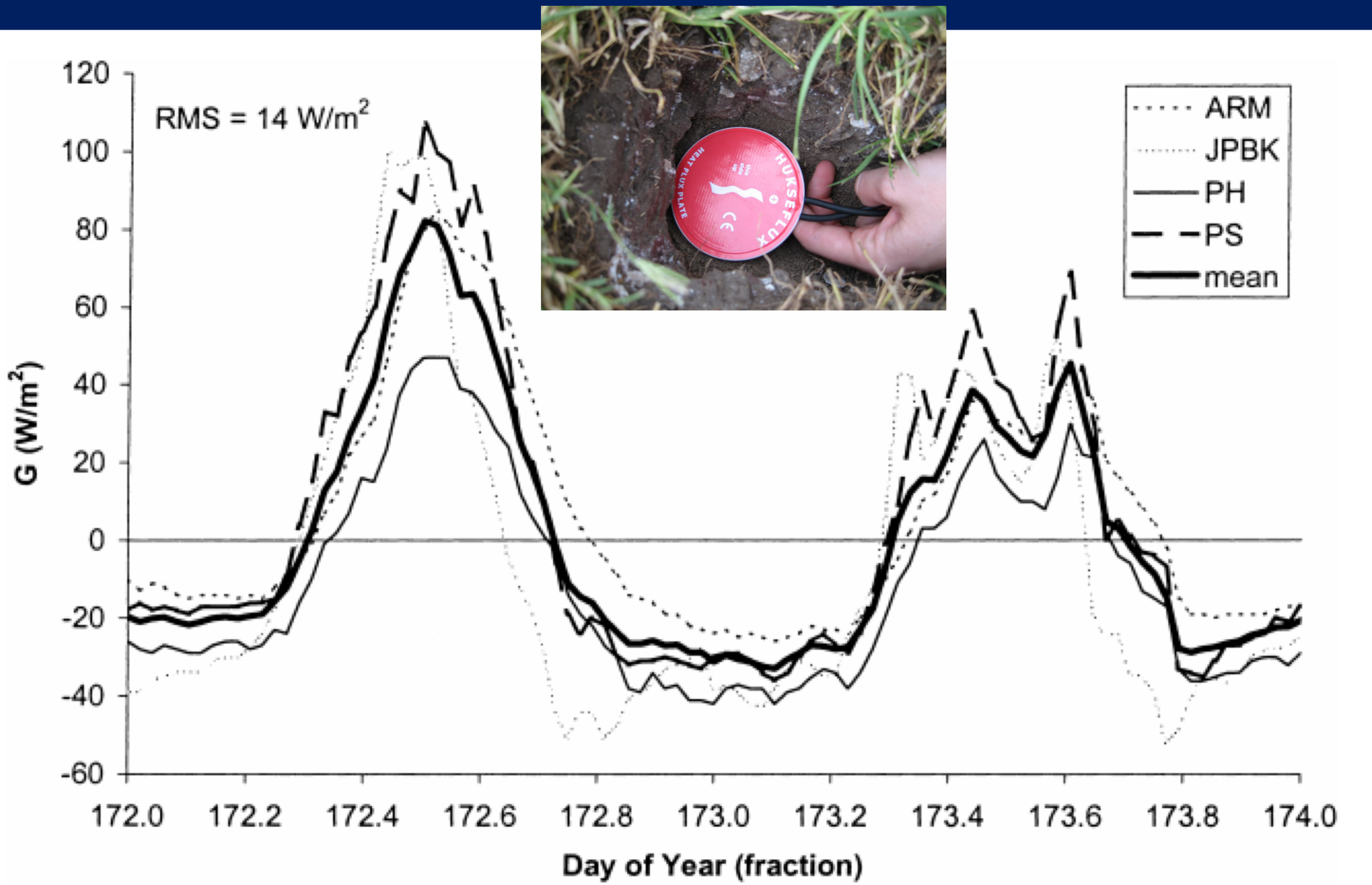
METEOROLOGY

www.elsevier.com/locate/agrform

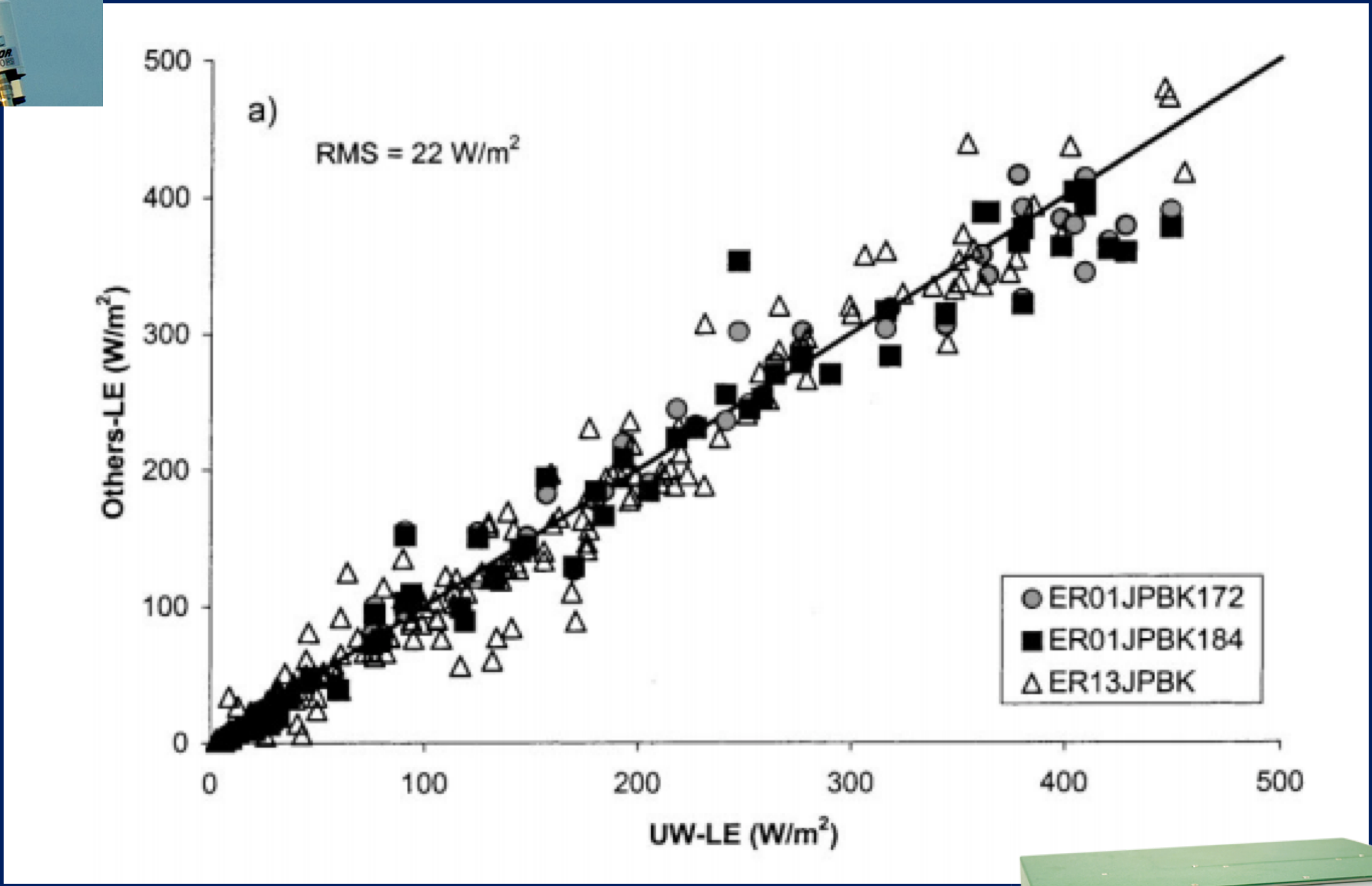
Correcting eddy-covariance flux underestimates over a grassland

T.E. Twine[a,*], W.P. Kustas[b], J.M. Norman[c], D.R. Cook[d], P.R. Houser[e], T.P. Meyers[f], J.H. Prueger[g], P.J. Starks[h], M.L. Wesely[d]





RMS = 14 W/m2
ARM
JPBK
PH
PS
mean
HUKSEFLUX
HEAT FLUX PLATE
G (W/m2)
Day of Year (fraction)
120
100
80
60
40
20
0
-20
-40
-60
172.0
172.2
172.4
172.6
172.8
173.0
173.2
173.4
173.6
173.8
174.0



a)
RMS = 22 W/m2
Others-LE (W/m2)
UW-LE (W/m2)
0
100
200
300
400
500
ER01JPBK172
ER01JPBK184
ER13JPBK

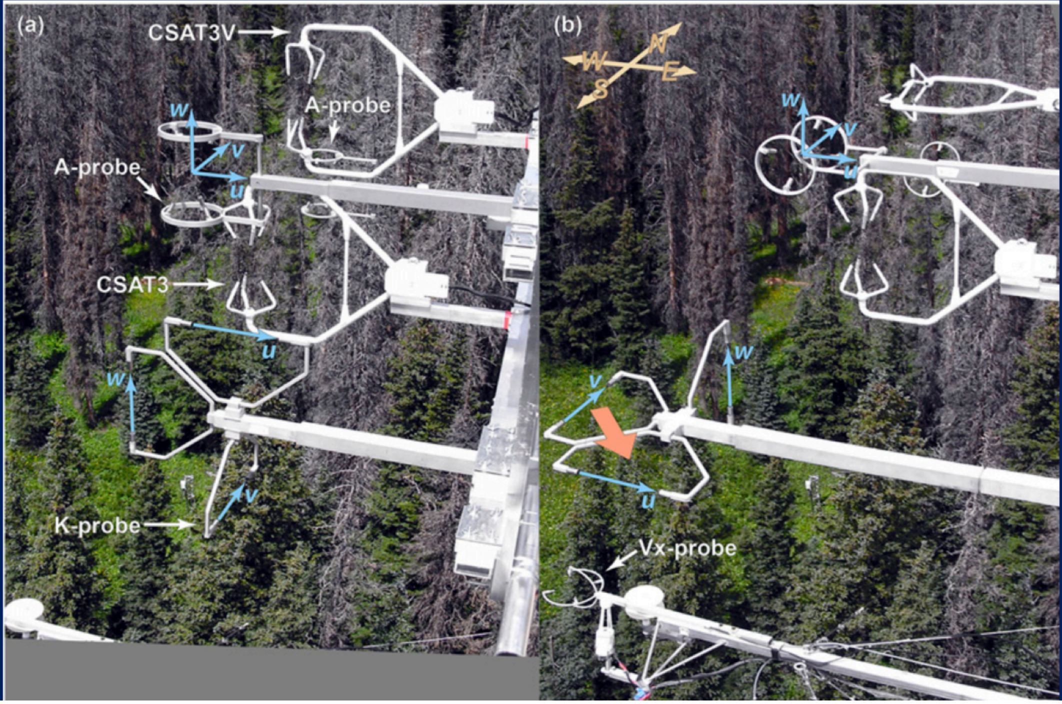
LI-COR
LI-7000 CO2/H2O Analyzer

All Sonic Anemometers Need to Correct for Transducer and Structural Shadowing in Their Velocity Measurements*

JOHN M. FRANK

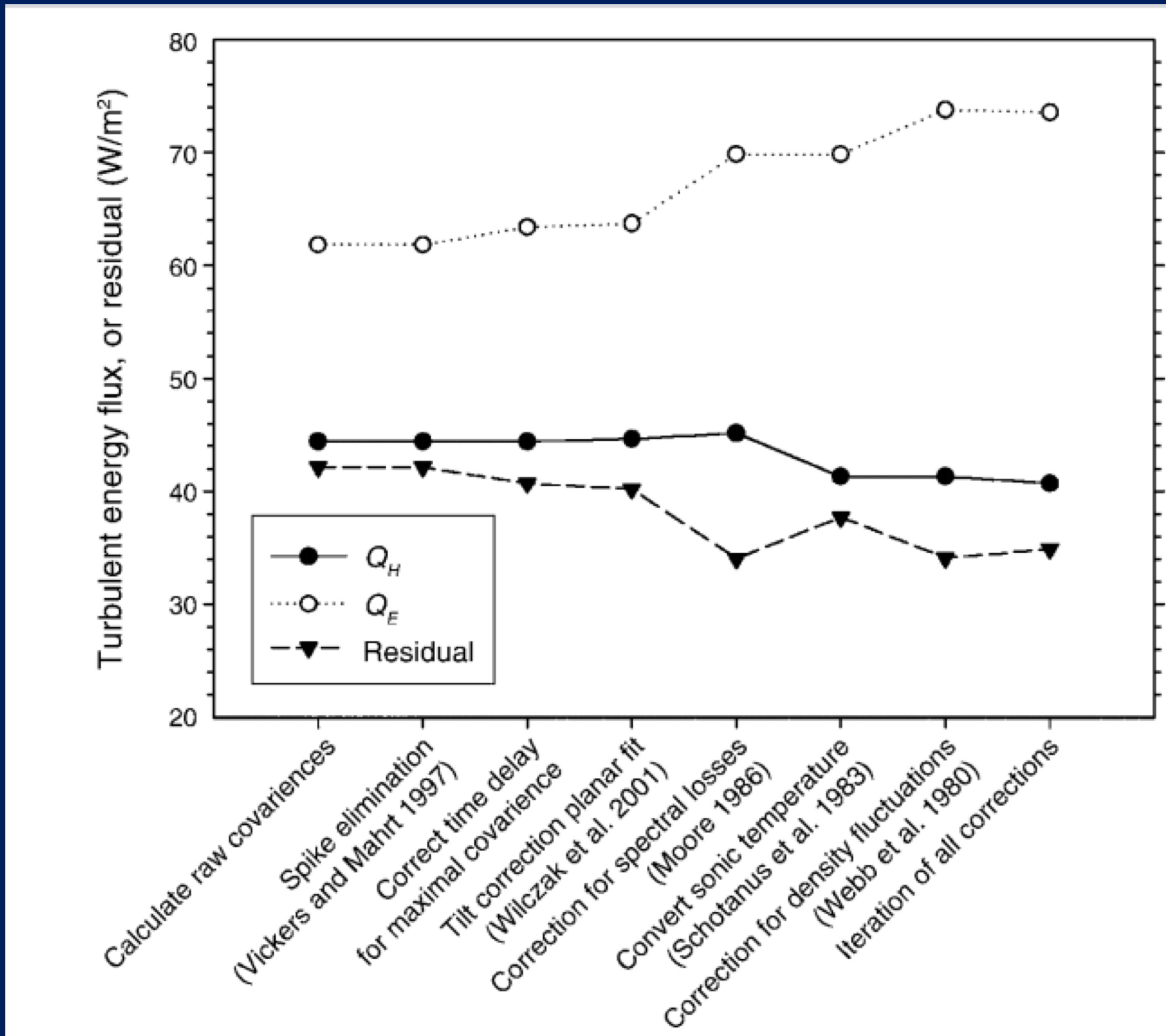
J. Atmos Ocean Tech, 2016

H	K-probe	**+1% ± 7.2%**
	A-probe	**−4% ± 7.9%**
	CSAT3	**+1% ± 6.2%**
	CSAT3V	**−0% ± 4.4%**
	Vx-probe*	**+5% ± 0.1%**



NO!

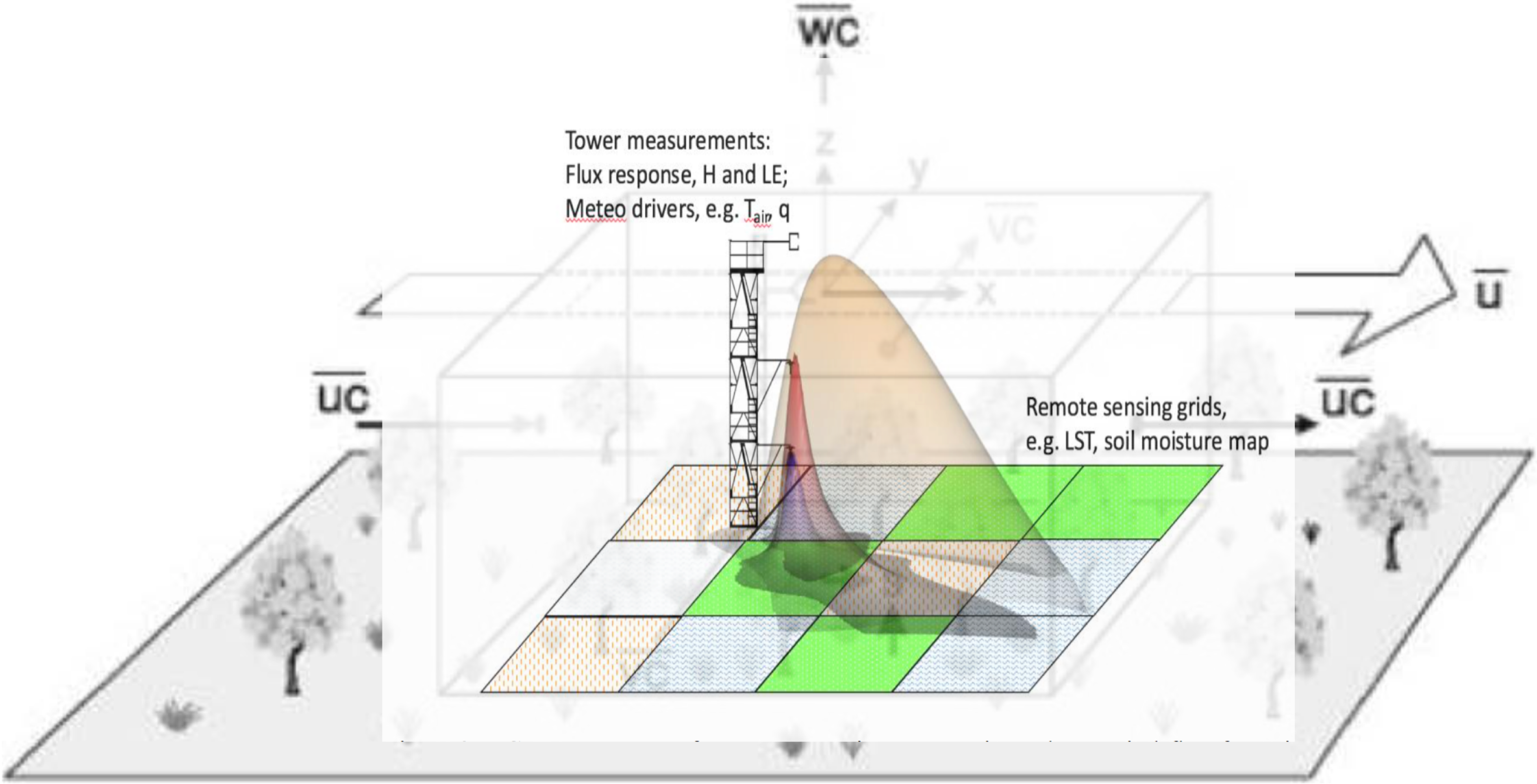
Bad Flux Processing?



Turbulent energy flux, or residual (W/m²)
80
70
60
50
40
30
20
Q_H
Q_E
Residual
Calculate raw covariences
Spike elimination (Vickers and Mahrt 1997)
Correct time delay for maximal covarience
Tilt correction planar fit (Wilczak et al. 2001)
Correction for spectral losses (Moore 1986)
Convert sonic temperature (Schotanus et al. 1983)
Correction for density fluctuations (Webb et al. 1980)
Iteration of all corrections

Foken 2003

a

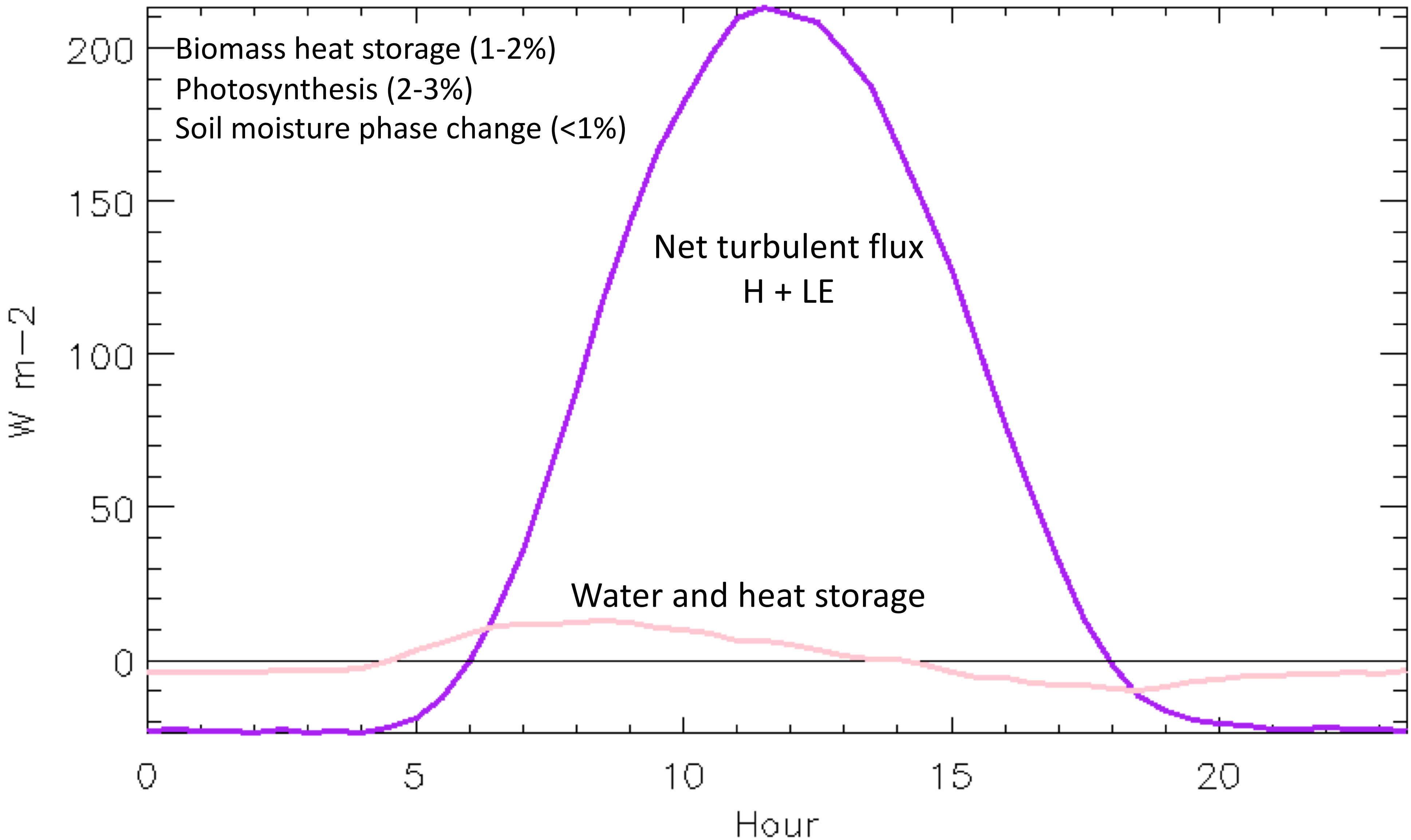


wc
z
y
vc
x
u
uc
uc
Tower measurements:
Flux response, H and LE;
Meteo drivers, e.g. T_{air}, q
Remote sensing grids,
e.g. LST, soil moisture map

NO!

Towers too tall?

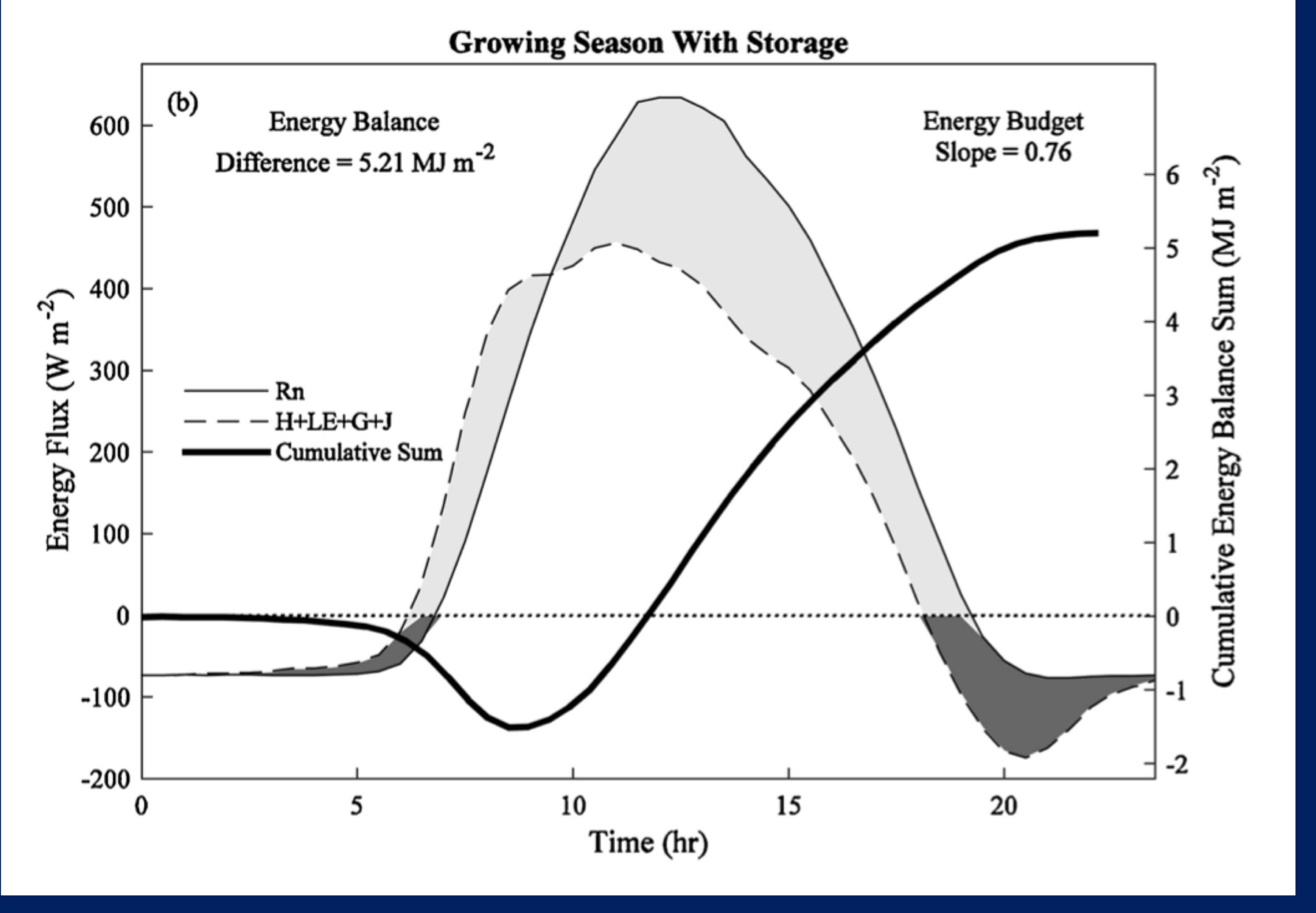
$$\int_0^h \overline{\frac{\partial c}{\partial t}} \mathrm{d}z + \overline{w'c'}(h) = \bar{S}$$


Biomass heat storage (1-2%)
Photosynthesis (2-3%)
Soil moisture phase change (<1%)
Net turbulent flux
H + LE
Water and heat storage
W m−2
200
150
100
50
0
0
5
10
15
20
Hour

Time dependency of eddy covariance site energy balance

David E. Reed[a,b,*], John M. Frank[b,c], Brent E. Ewers[b], Ankur R. Desai[a]

Agricultural and Forest Meteorology 249 (2018) 467–478



NO!

Lateral Fluxes?

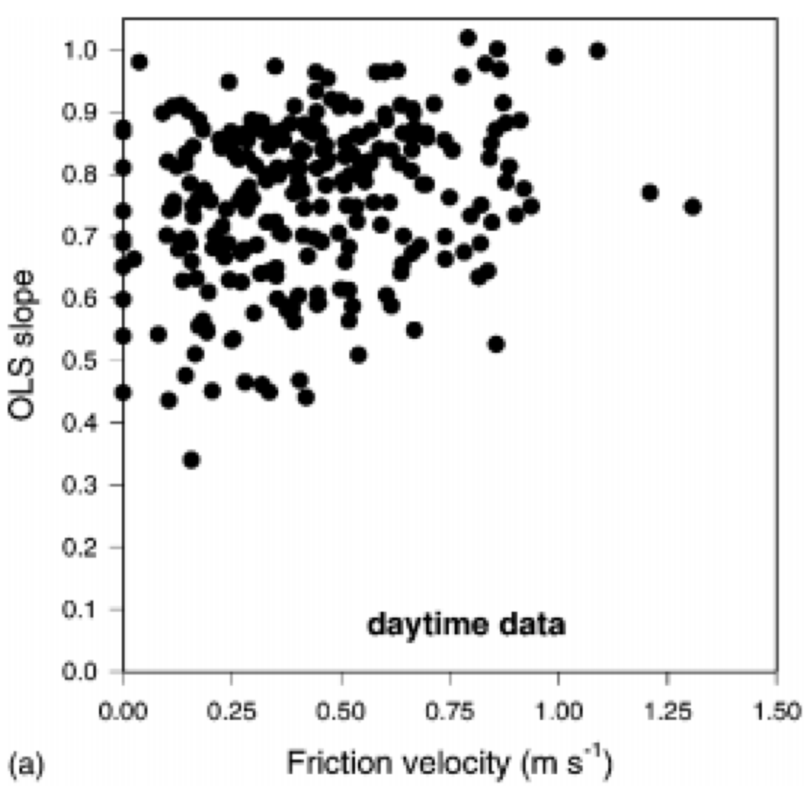
ELSEVIER

Agricultural and Forest Meteorology 113 (2002) 223–243

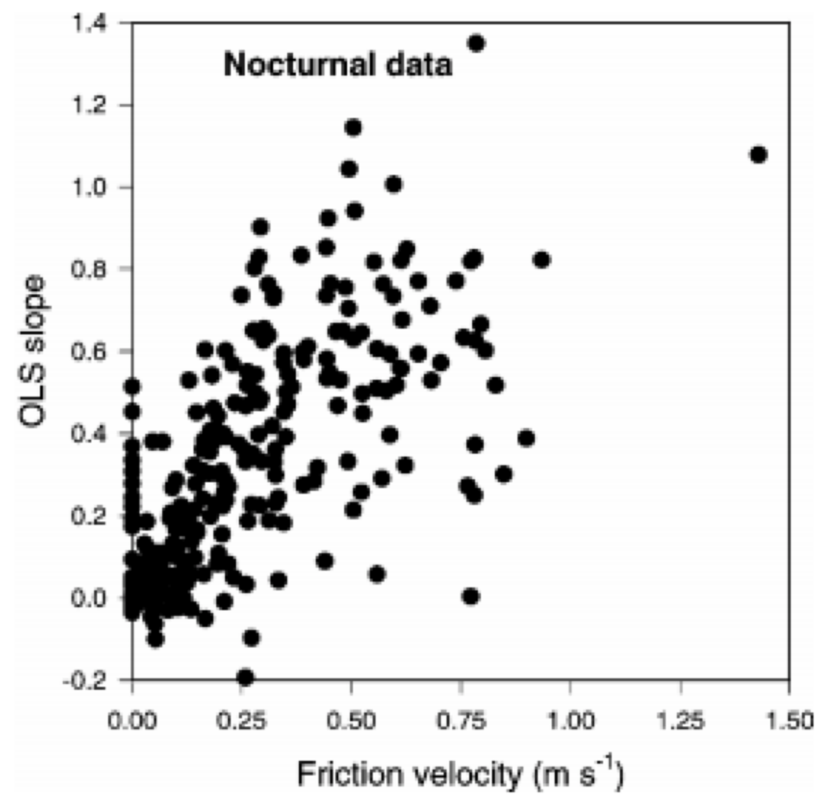
www.elsevier.com/locate/agrformet

Energy balance closure at FLUXNET sites

Kell Wilson [a], Allen Goldstein [b], Eva Falge [c], Marc Aubinet [d], Dennis Baldocchi [b,*], Paul Berbigier [e], Christian Bernhofer [f], Reinhart Ceulemans [g], Han Dolman [h], Chris Field [i], Achim Grelle [j], Andreas Ibrom [k], B.E. Law [l], Andy Kowalski [g], Tilden Meyers [a], John Moncrieff [m], Russ Monson [n], Walter Oechel [o], John Tenhunen [c], Riccardo Valentini [p], Shashi Verma [q]



(a)

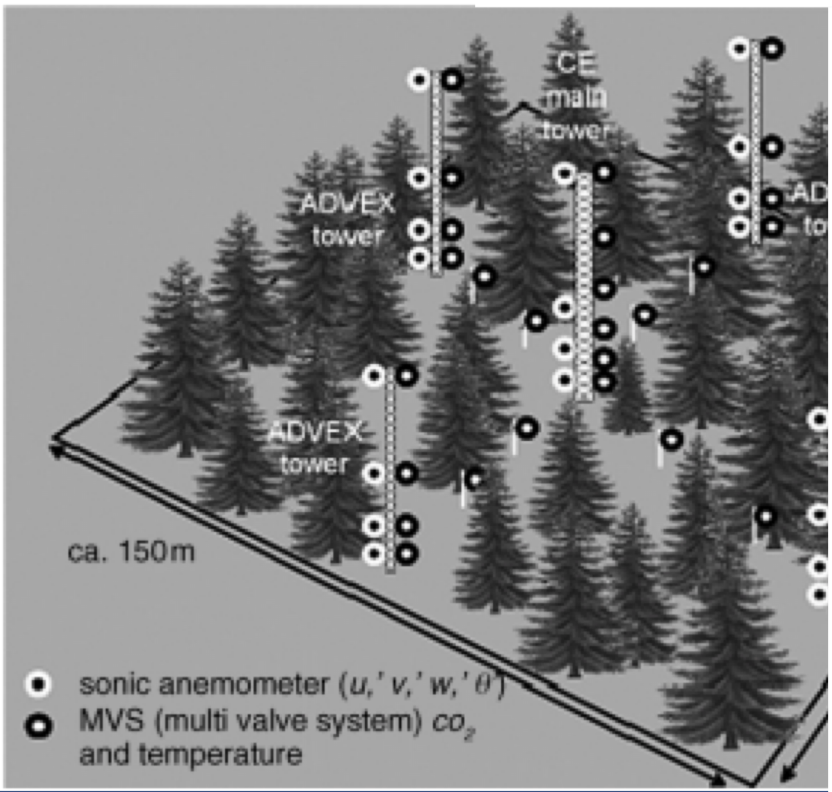


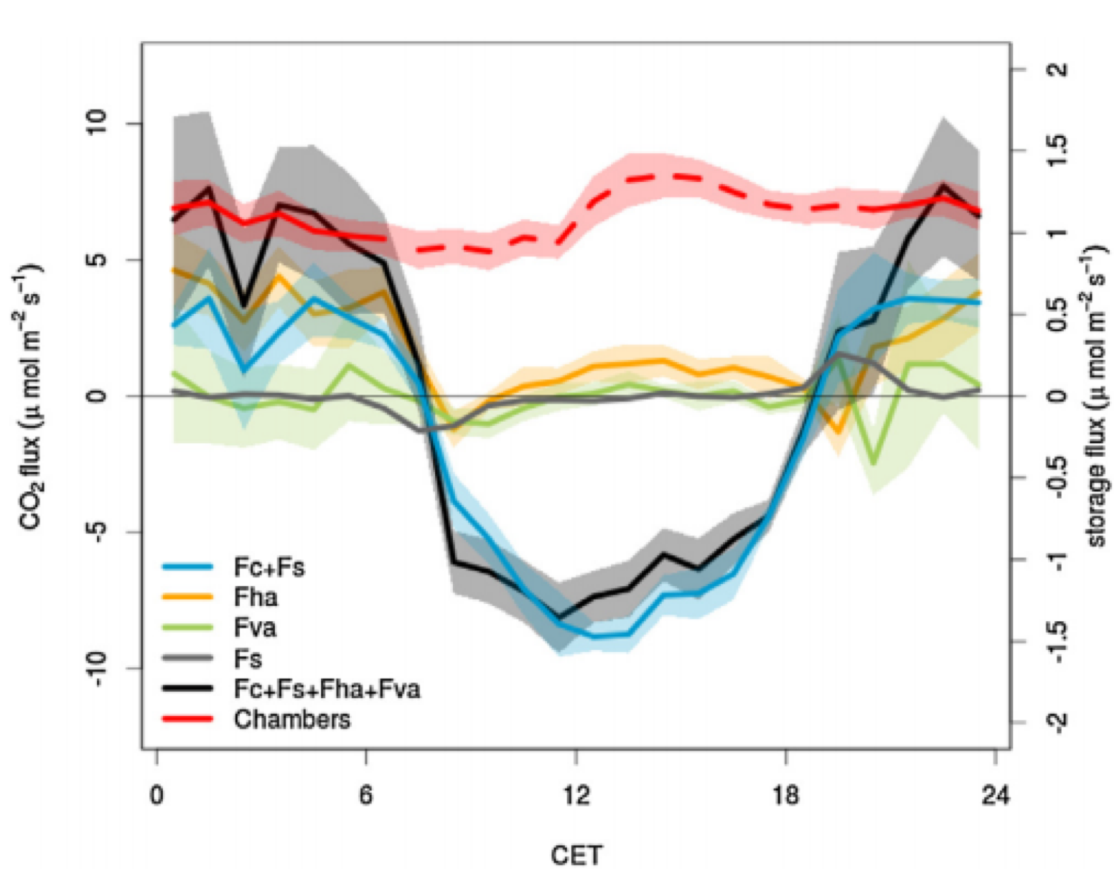
Comparison of horizontal and vertical advective CO_2 fluxes at three forest sites

Christian Feigenwinter[a,g,*], *Christian Bernhofer*[b], *Uwe Eichelmann*[b],
[redacted]

Contribution of advection to nighttime ecosystem respiration at a mountain grassland in complex terrain

Marta Galvagno[a,*], Georg Wohlfahrt[b], Edoardo Cremonese[a], Gianluca Filippa[a], Mirco Migliavacca[c], Umberto Mora di Cella[a], Eva van Gorsel[d]

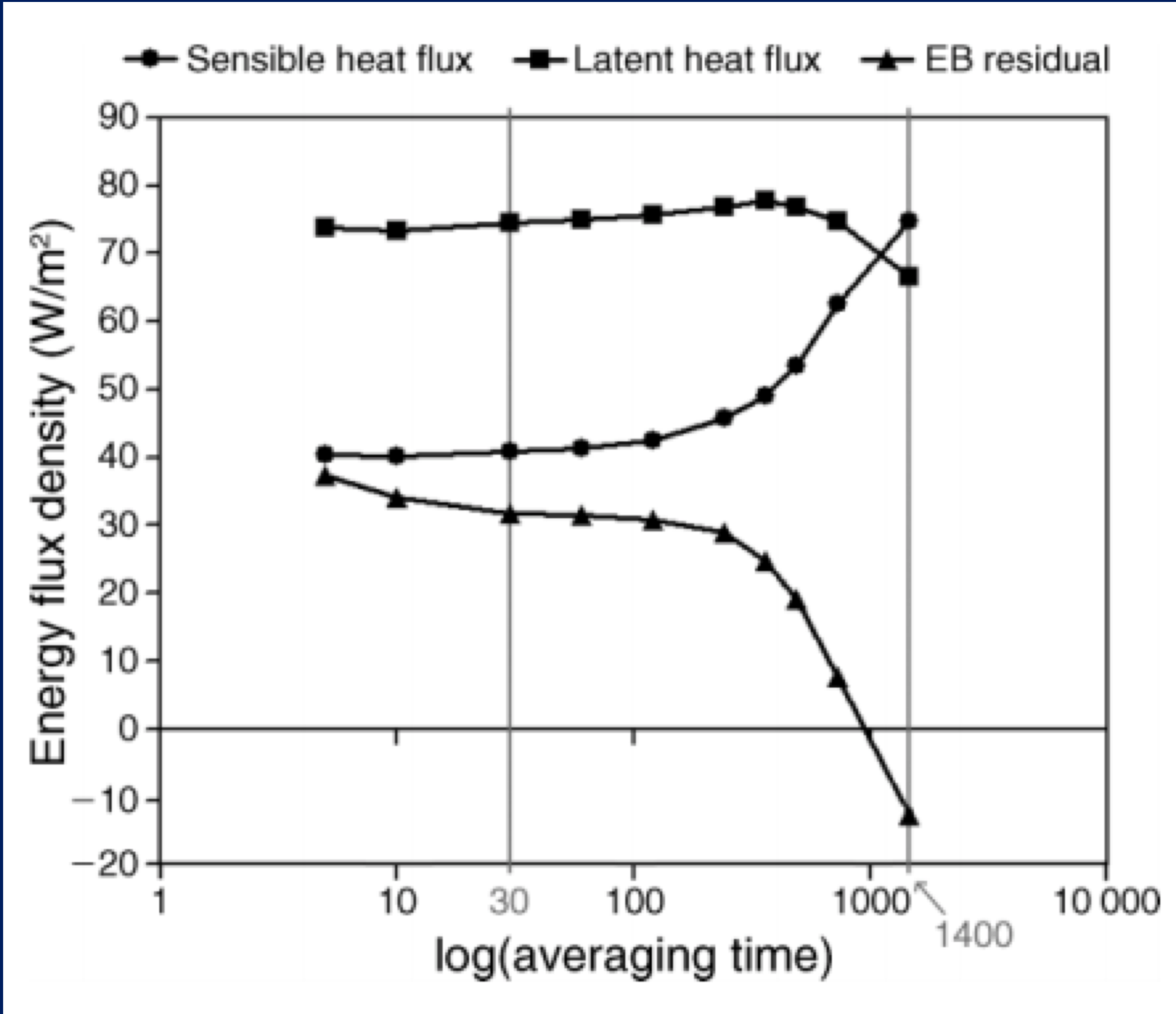




NO!

Mesoscale fluxes?

- Violation of assumptions:
  - Ergodicity
  - Homogeneity
  - Stationarity



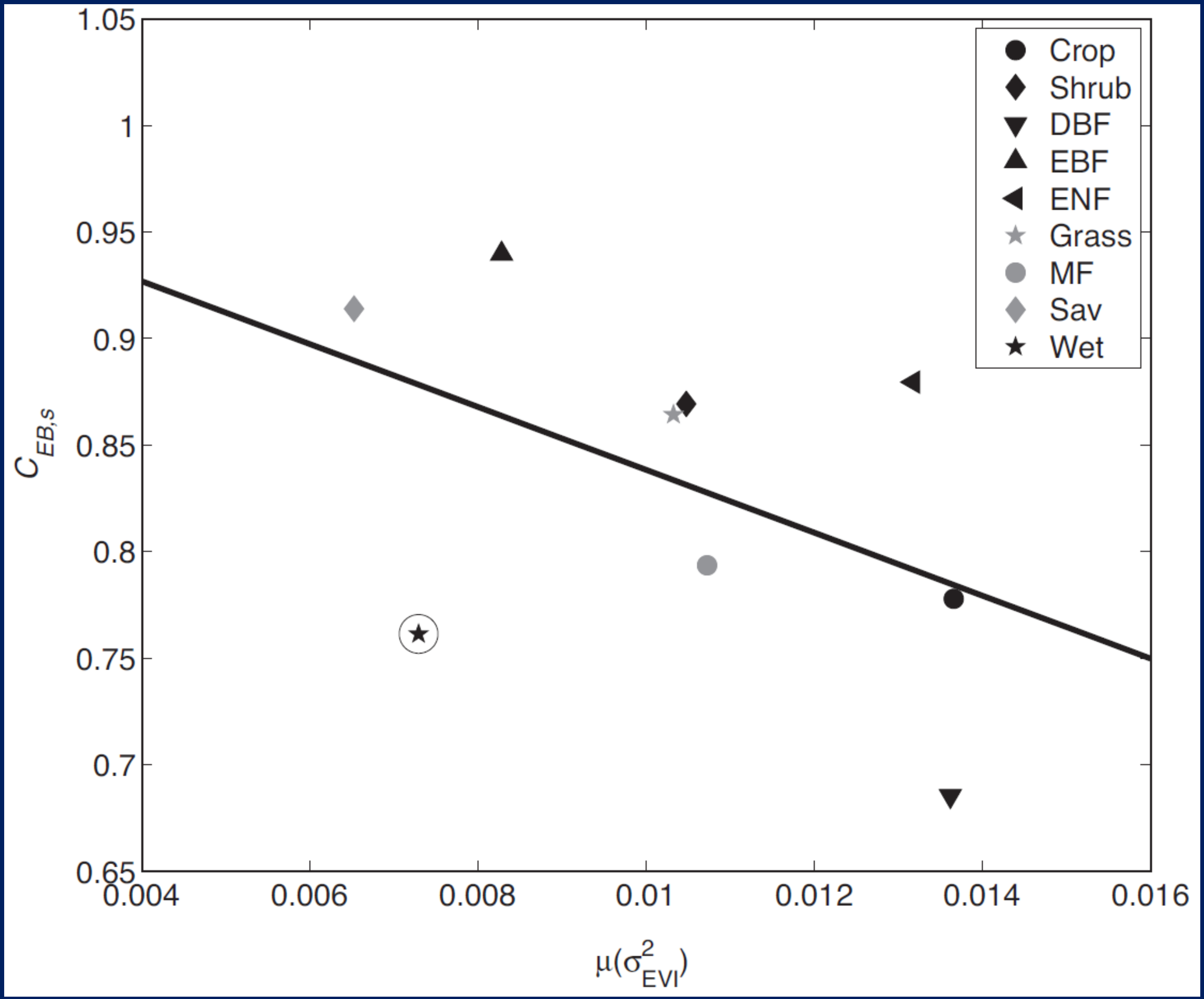
Sensible heat flux
Latent heat flux
EB residual
Energy flux density (W/m²)
90
80
70
60
50
40
30
20
10
0
−10
−20
1
10
30
100
1000
10 000
1400
log(averaging time)

Foken 2003

Energy imbalance worsens with increased regional spatial heterogeneity

EBC=
H+Le

Rnet-G



Greenness spatial variance

Stoy et al., 2013, AFM

Landscape variance potentially drives stationary eddies

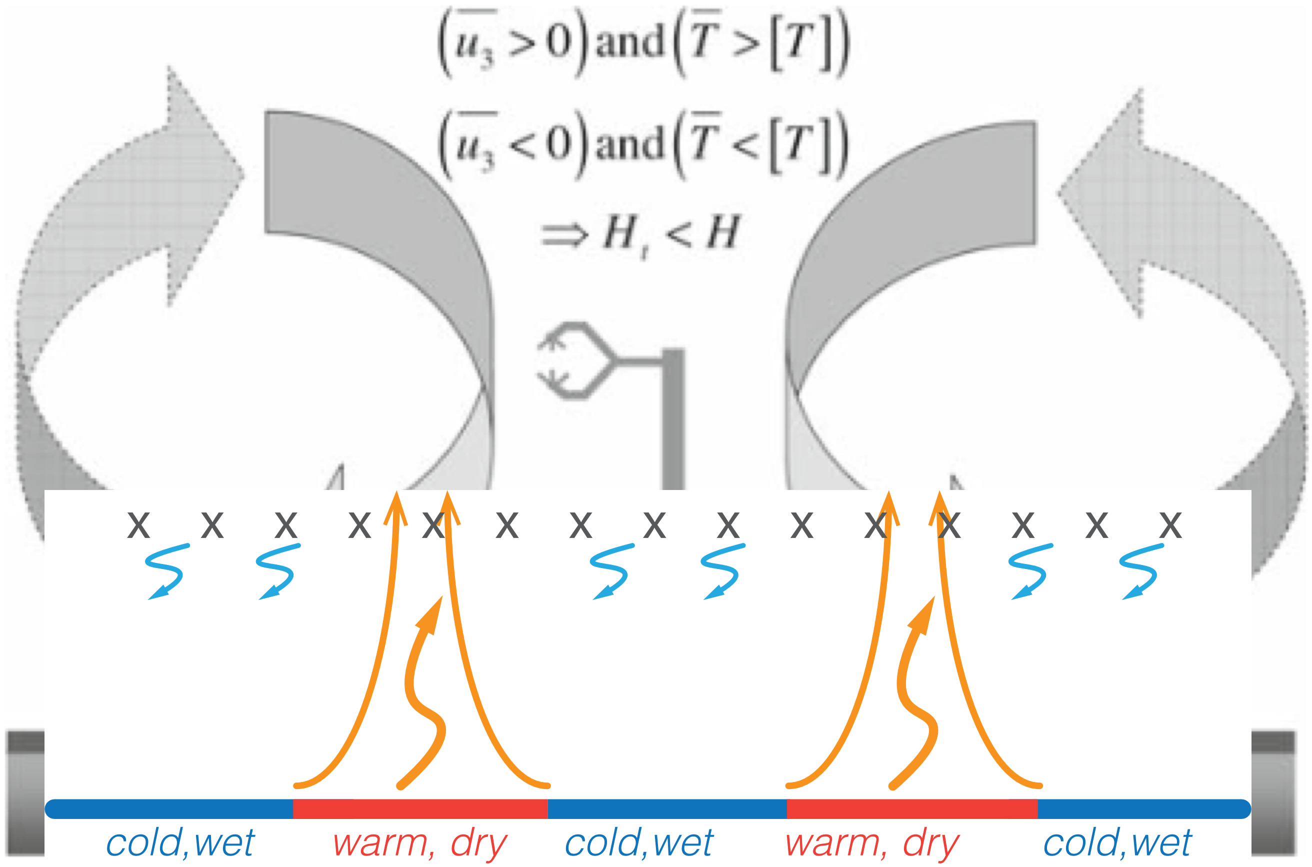


Fig. 1 Schematic showing how quasi-stationary eddies cause an underestimation of the total sensible heat flux H when using the temporal EC method to calculate H_t. The single-point sonic measurement in the centre is not able to resolve quasi-stationary eddies

Mauder et al., 2008, BLM; Kröniger et al., 2018, BLM

Can we get out of this mess?

Can data mining help eddy-covariance see the landscape? A large-eddy simulation study

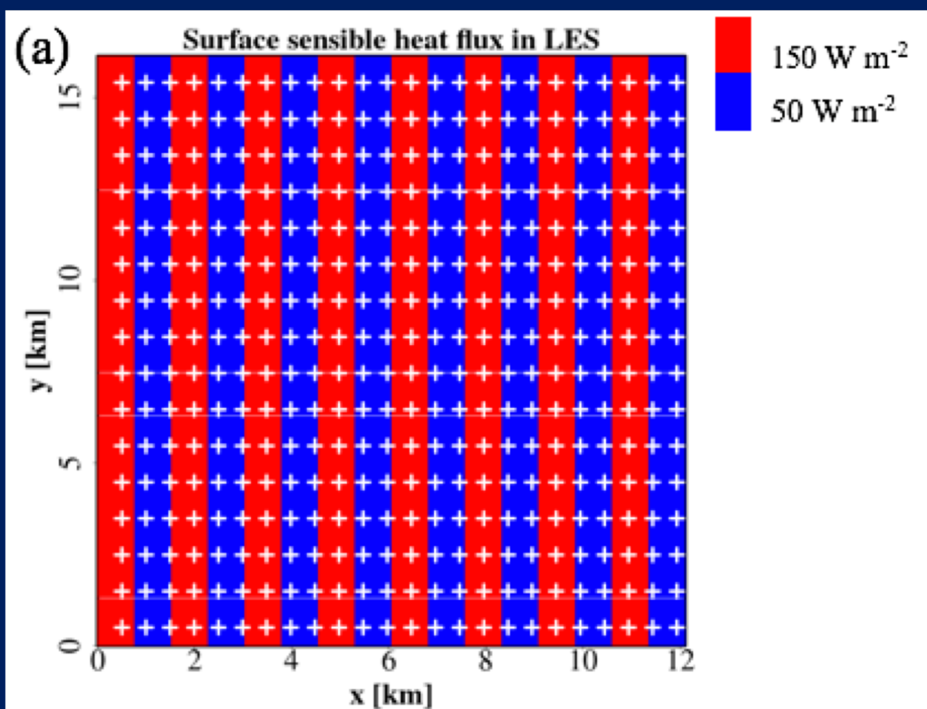
Authors: Ke Xu[1,2,*], Matthias Sühring[2], Stefan Metzger[3,1], David Durden[3], Ankur R Desai[1]

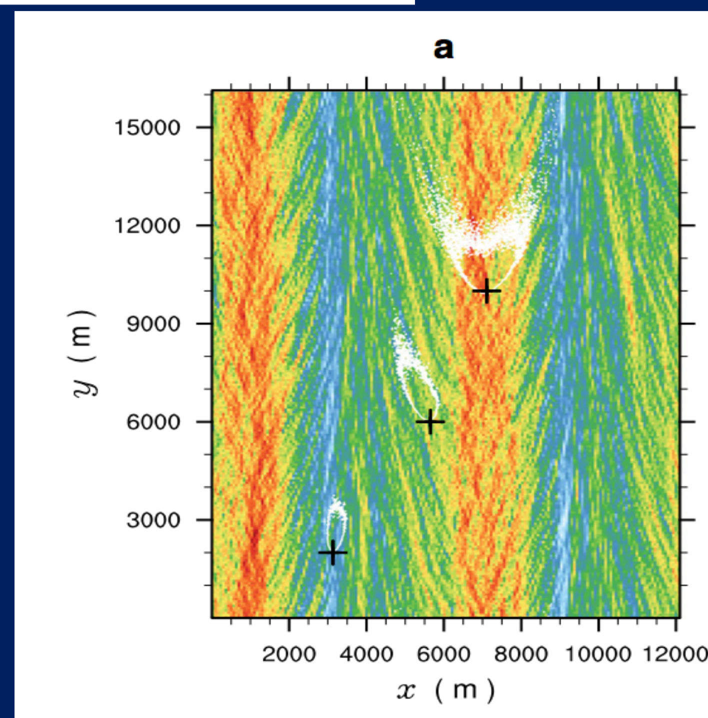
Boundary-Layer Meteorology
https://doi.org/10.1007/s10546-018-0387-x

RESEARCH ARTICLE

Trade-Offs in Flux Disaggregation: A Large-Eddy Simulation Study

Matthias Sühring[1] · Stefan Metzger[2,3] · Ke Xu[3] · Dave Durden[2] · Ankur Desai[3]





Boundary-Layer Meteorol (2007) 123:77–98
DOI 10.1007/s10546-006-9133-x

ORIGINAL PAPER

Spatial representativeness of single tower measurements and the imbalance problem with eddy-covariance fluxes: results of a large-eddy simulation study

Gerald Steinfeld · Marcus Oliver Letzel · Siegfried Raasch · Manabu Kanda · Atsushi Inagaki

We can test 3 spatial eddy covariance methods that account for meso-scale eddies

$$[\overline{F}] = \overline{[w \langle \Theta \rangle]} + \overline{[w\Theta'_{\text{filter}}]} + [\overline{w\Theta_b}]$$

Boundary-Layer Meteorol
DOI 10.1007/s10546-016-0161-x

RESEARCH ARTICLE

Exploring Eddy-Covariance Measurements Using a Spatial Approach: The Eddy Matrix

Christian Engelmann[1,2] · Christian Bernhofer[1]

$$B_{\text{comb}} = \overline{\langle w''\theta'' \rangle} + \overline{\langle w \rangle' \langle \theta \rangle'} \quad (3a)$$

$$= \overline{B_a} + \left(\frac{1}{M-1}\right) \sum_{i=1}^{M} \left(\left(\langle w \rangle_i - \overline{\langle w \rangle}\right)\left(\langle \theta \rangle_i - \overline{\langle \theta \rangle}\right)\right), \quad (3b)$$

Boundary-Layer Meteorol (2008) 128:151–172
DOI 10.1007/s10546-008-9279-9

ORIGINAL PAPER

Measurement of the Sensible Eddy Heat Flux Based on Spatial Averaging of Continuous Ground-Based Observations

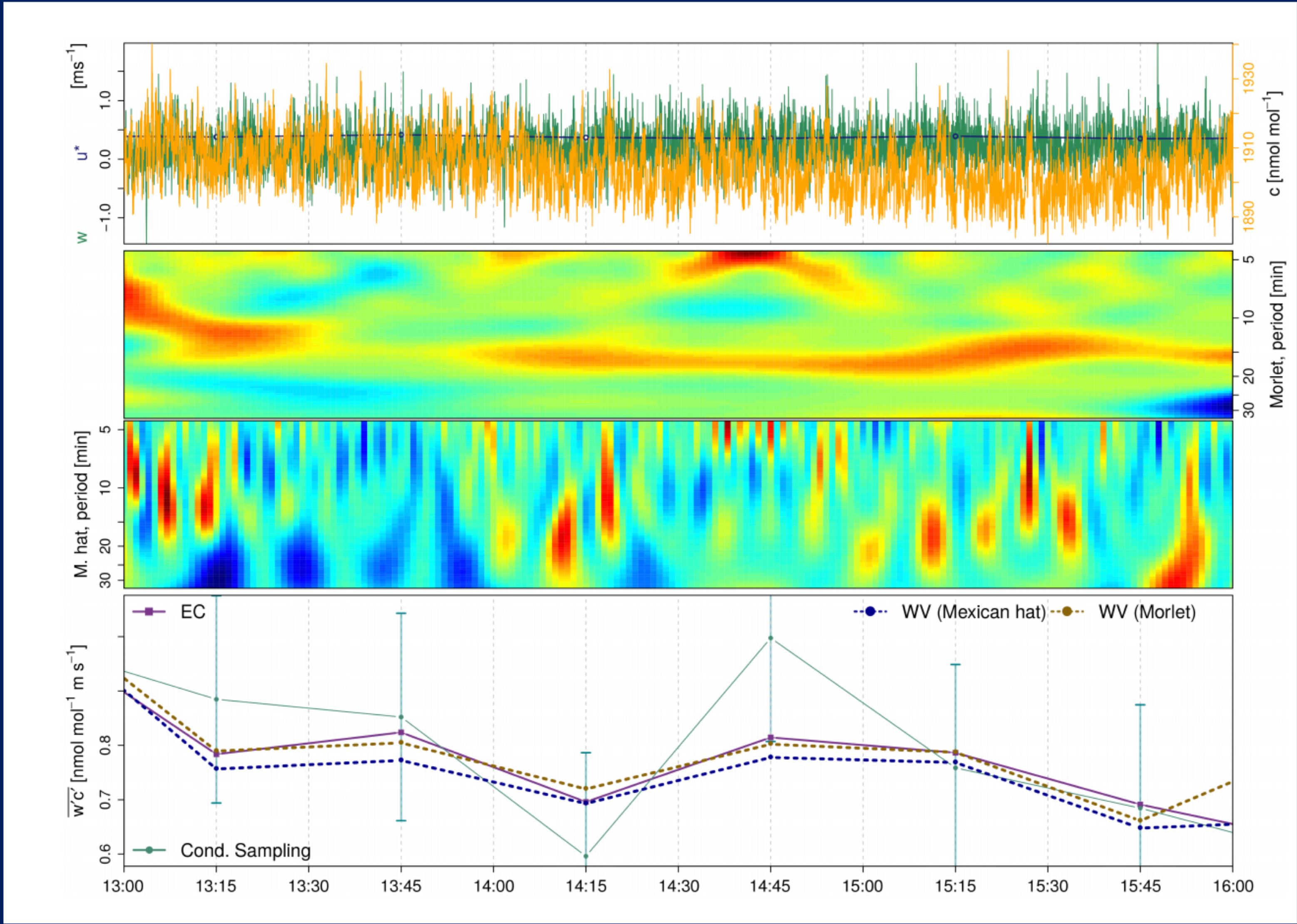
M. Mauder · R. L. Desjardins · E. Pattey · Z. Gao · R. van Haarlem

$$H = \overline{u_3}\left(\overline{T} - T_0\right) + \overline{u_3' T'} \approx \overline{u_3}\left(\overline{T} - [T]\right) + \overline{u_3' T'} = \overline{u_3}\left(\overline{T} - [T]\right) + H_t$$

Flux calculation of short turbulent events – comparison of three methods

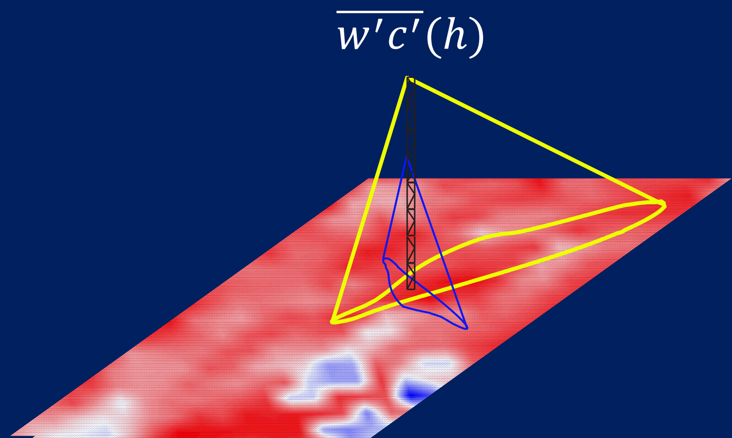
Carsten Schaller[1,2,a], Mathias Göckede[2], and Thomas Foken[1,3]

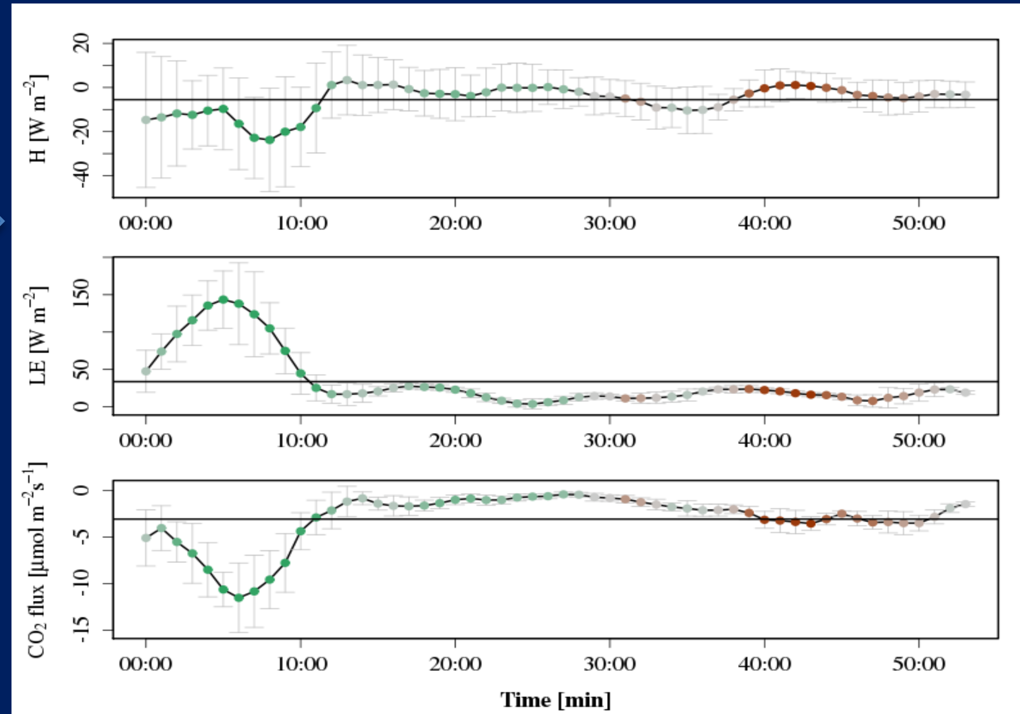
Atmos Meas Tech 2017



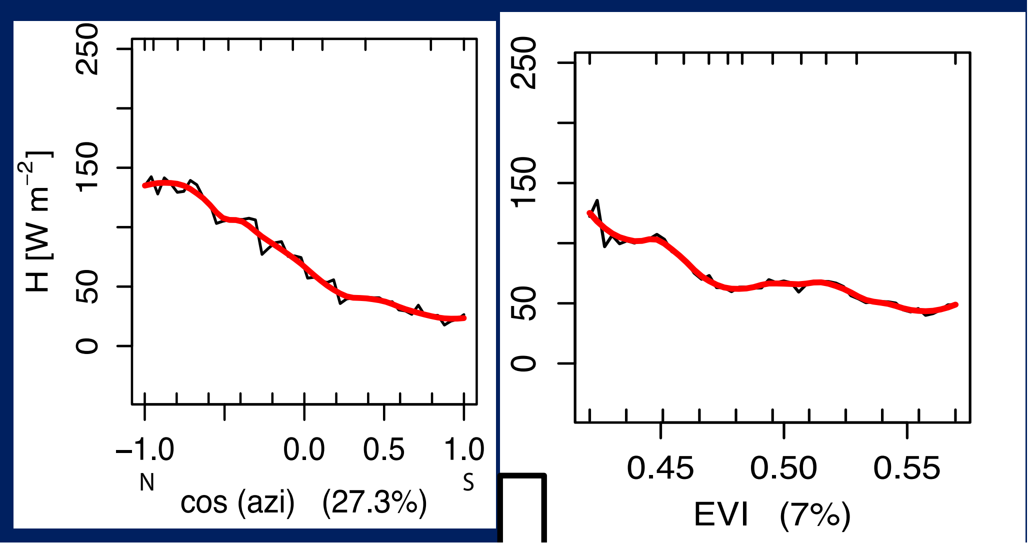
Environmental Response Function (ERF) scaling method

Metzger et al., 2013, Biogeosci , Xu et al., 2017, AFM, Metzger, 2018, AFM, Xu et al., 2018, AFM

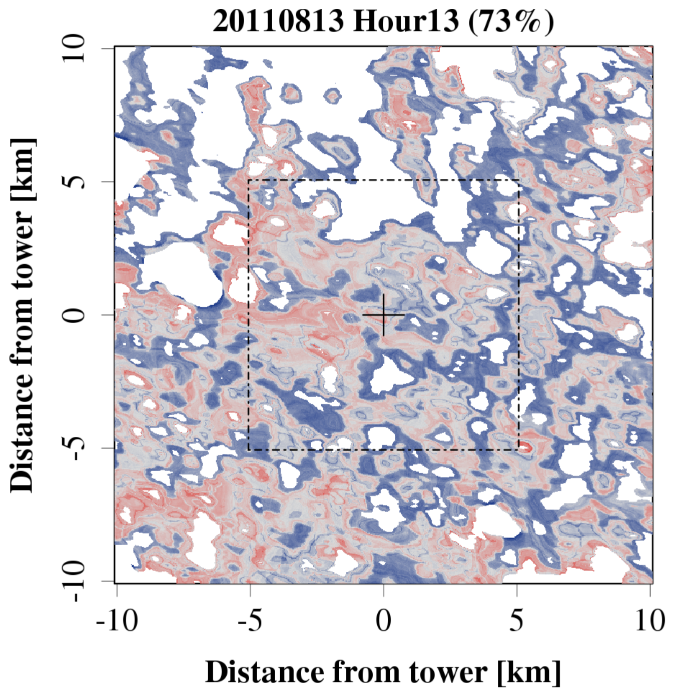




Extracted relationships



Domain-projected turbulent flux at measurement level



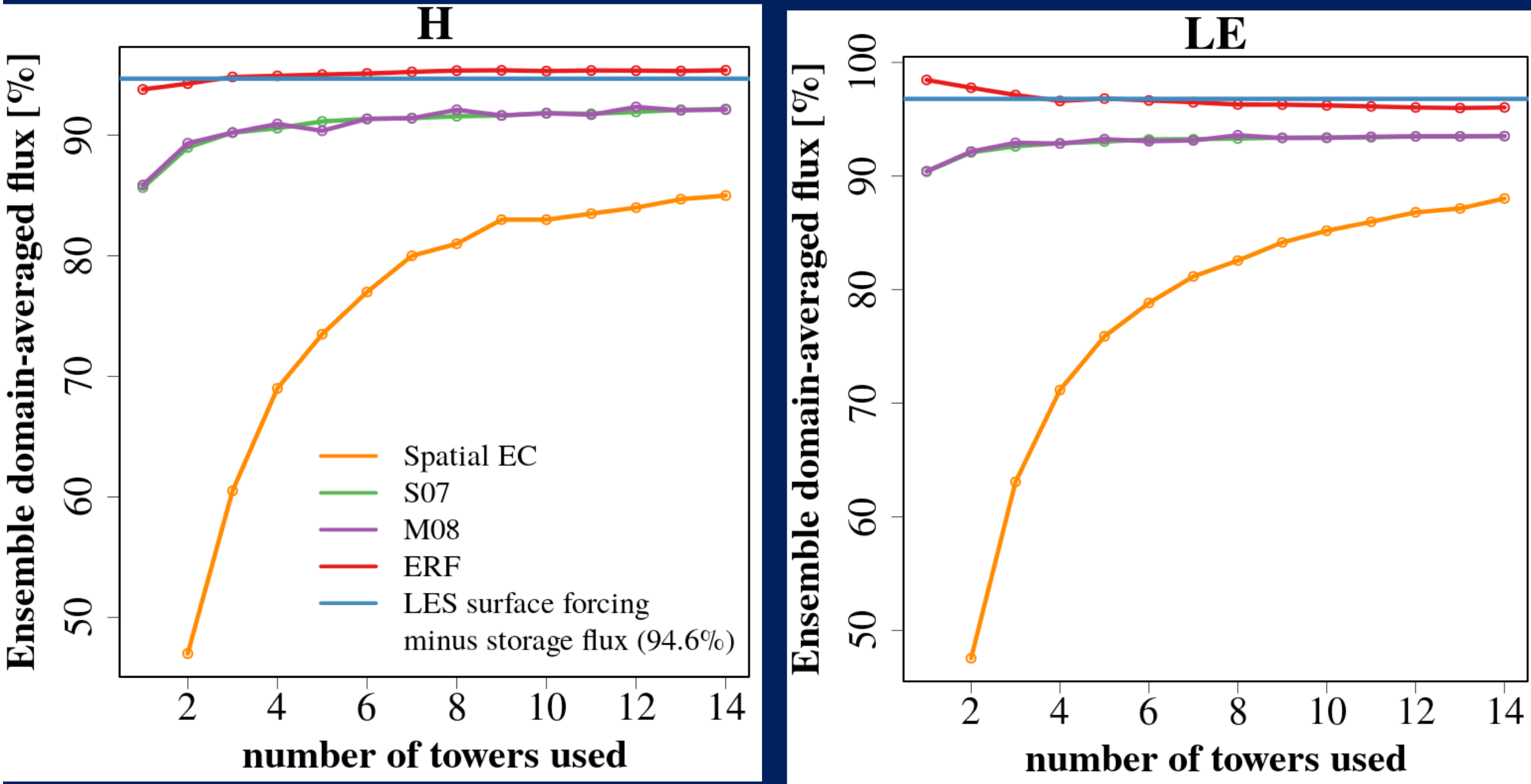


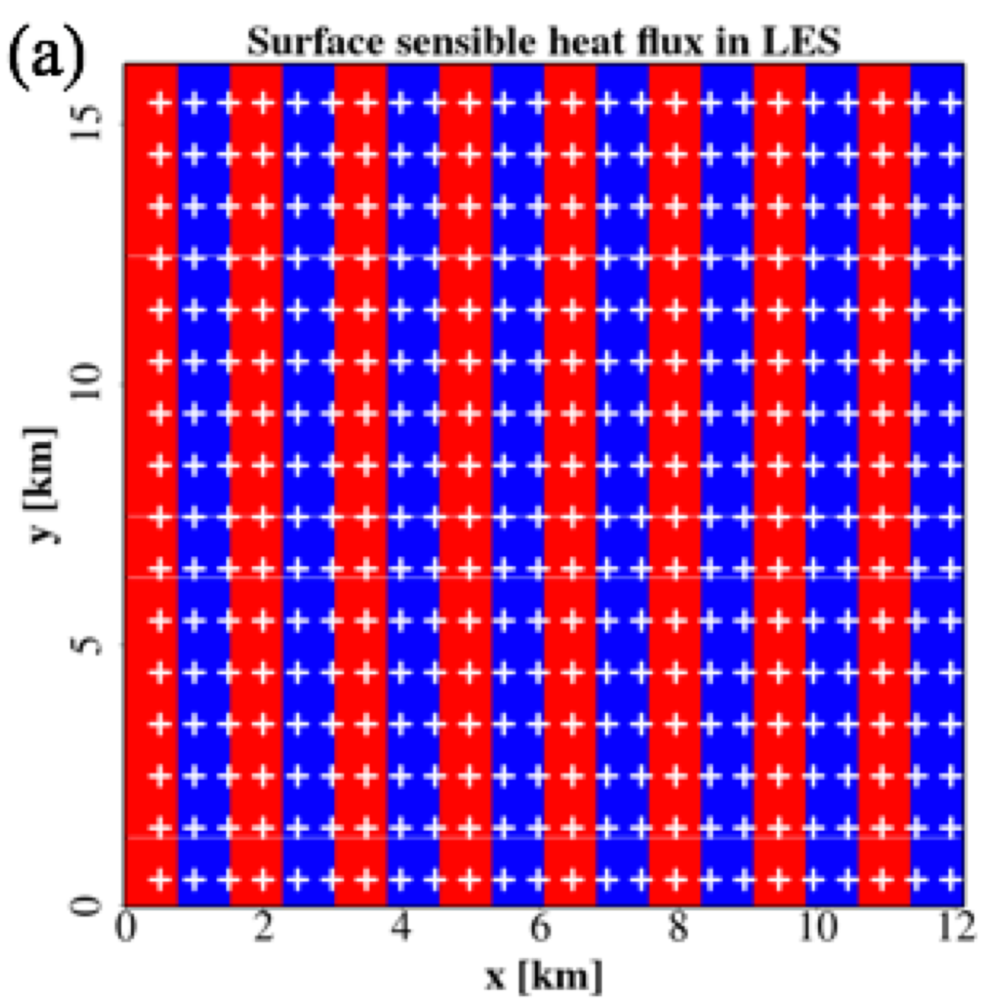
Fig. 3. Ensemble-averaged heat fluxes at 49 m using 1 to 14 virtual towers, randomly chosen from the 320 locations depicted in Figure 1, using different upscaling approaches: spatial eddy-covariance (spatial EC), spatio-temporal eddy-covariance approach (S07 and M08), and Environmental Response Function (ERF) for a) H, b) LE. Reference (blue line) is the 100% minus storage flux. From Xu et al., in review, BLM

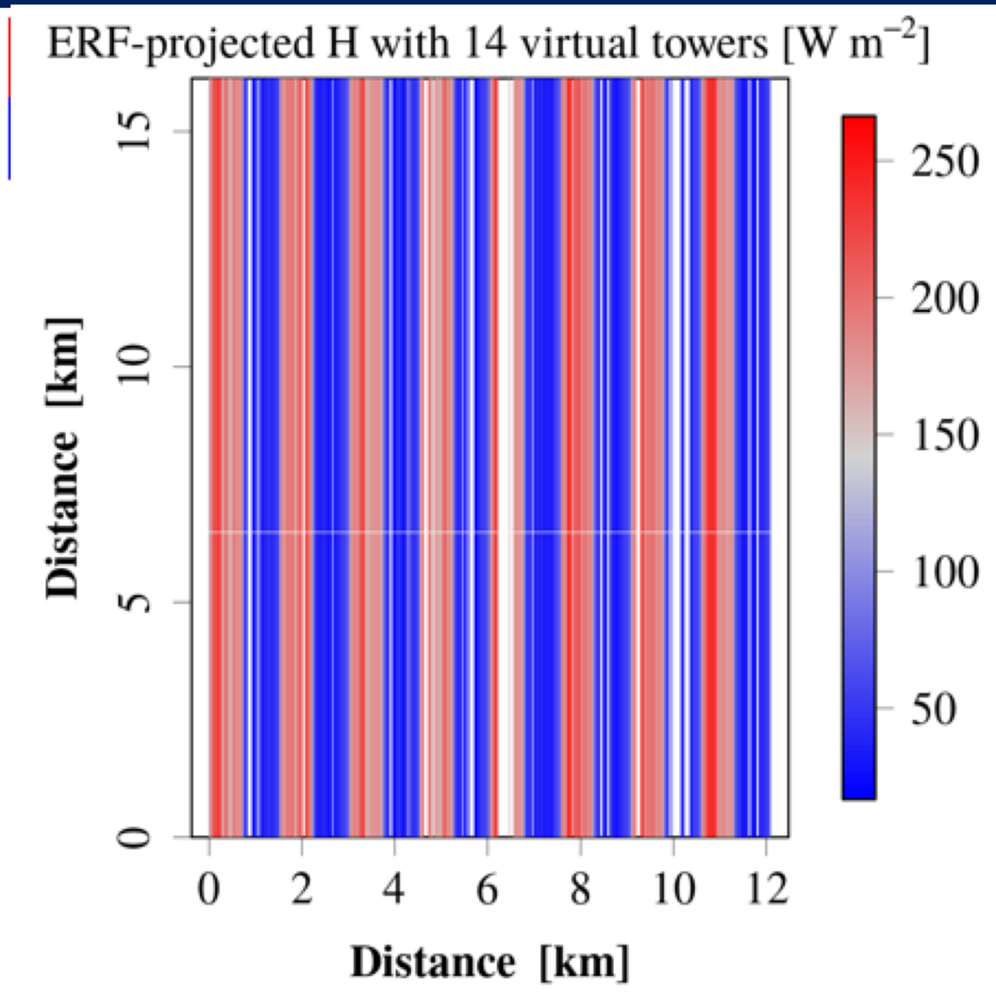
“Secondary circulation” = Mesoscale flux!

	Turbulent flux	Secondary circulations	Storage flux	Atmospheric skewness	Sum
H	85.6%	8.2%	5.4%	1.5%	100.8%
LE	90.4%	8.05%	3.4%	-2.4%	99.45%
H + LE	88.8%	8.1%	4.1%	-1.1%	100.1%

Table 1 Energy budget for traditional eddy-covariance turbulent flux, the secondary circulations (calculated as the difference between S07 domain-mean flux derived with one tower and with 14 towers), storage flux, atmospheric skewness (calculated as the difference between ERF domain mean derived with one tower and with 14 towers) and unmeasured components of sensible heat flux (H), latent heat flux (LE), and H + LE.

With 14 towers, we can recover highly heterogeneous fluxes in LES with ERF





Original

Xu et al, in review, BLM

Retrieved

Agricultural and Forest Meteorology 255 (2018)

Surface-atmosphere exchange in a box: Making the control volume a suitable representation for in-situ observations

Stefan Metzger[a,b,*]

Surface-atmosphere exchange in a box: Space-time resolved storage and net vertical fluxes from tower-based eddy covariance

Ke Xu[a,*], Stefan Metzger[a,b], Ankur R. Desai[a]

Geosci. Model Dev., 10, 3189–3206, 2017
https://doi.org/10.5194/gmd-10-3189-2017

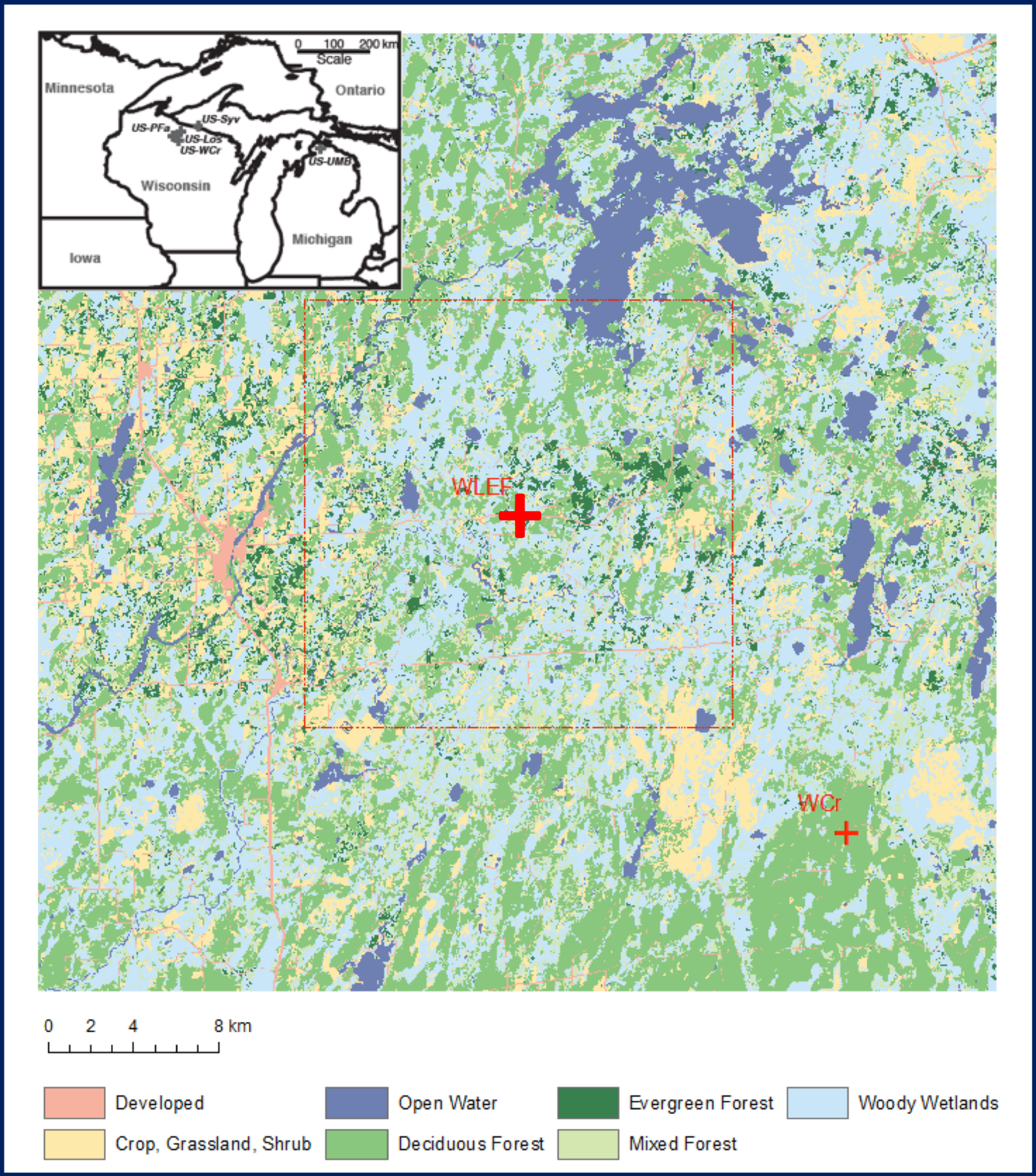
Geoscientific
Model Development
Open Access

eddy4R 0.2.0: a DevOps model for community-extensible processing and analysis of eddy-covariance data based on R, Git, Docker, and HDF5

Stefan Metzger[1,2], David Durden[1], Cove Sturtevant[1], Hongyan Luo[1], Natchaya Pingintha-Durden[1], Torsten Sachs[3], Andrei Serafimovich[3], Jörg Hartmann[4], Jiahong Li[5], Ke Xu[2], and Ankur R. Desai[2]

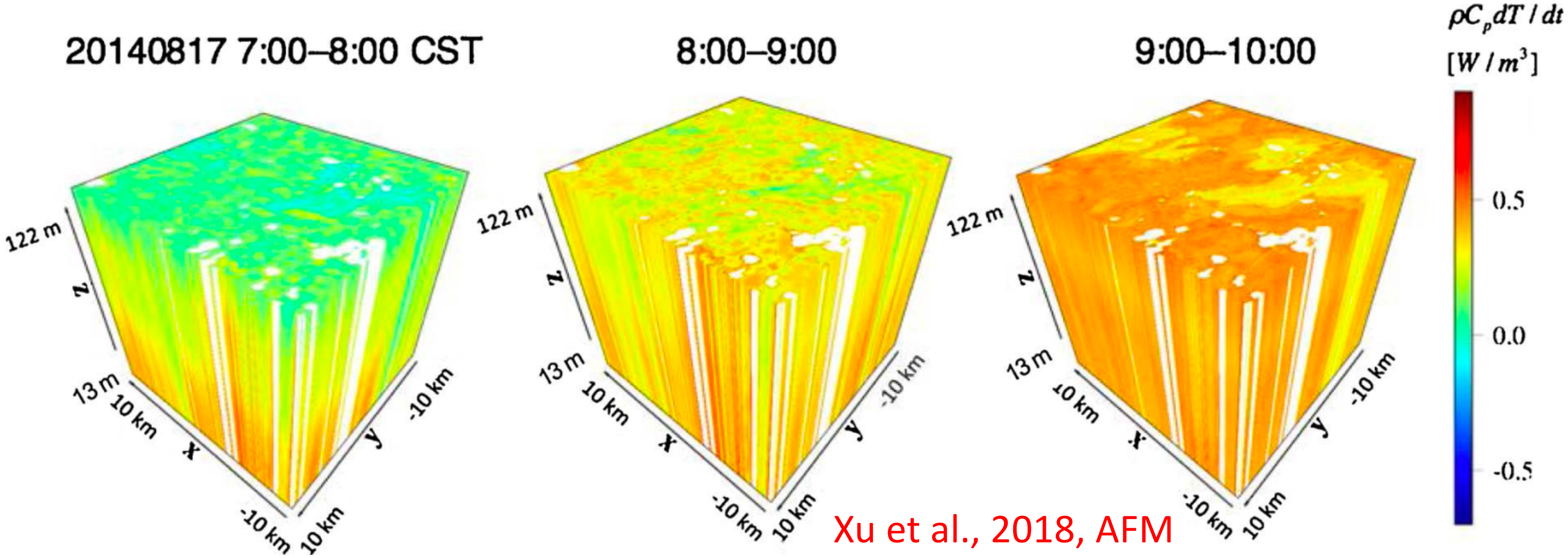
[1]National Ecological Observatory Network, Battelle, 1685 38th Street, Boulder, CO 80301, USA

Park Falls/Chequamegon National Forest region, WI

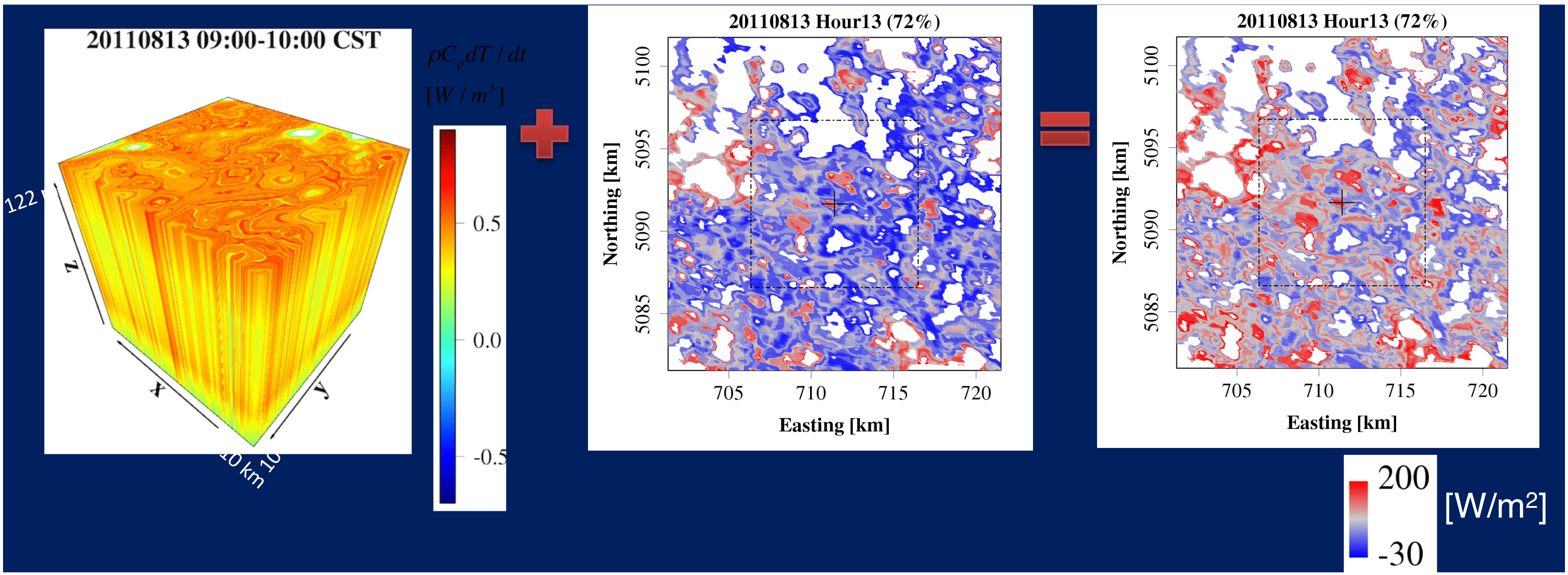


Tall Ameriflux Park Falls WLEF tower; Measurement in 2011 Aug at 30, 122 m.

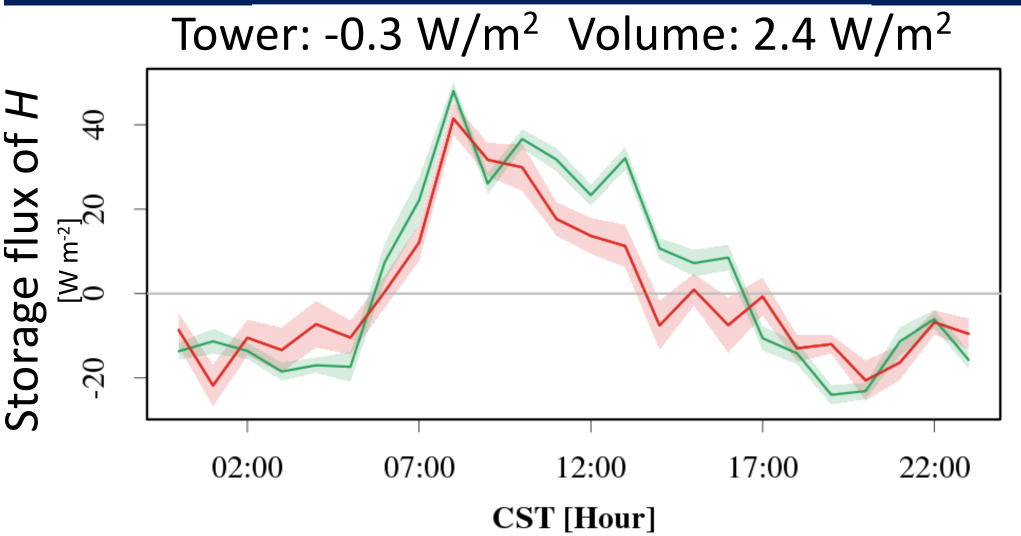
Credit: Matt Rydzik (U Wisconsin)

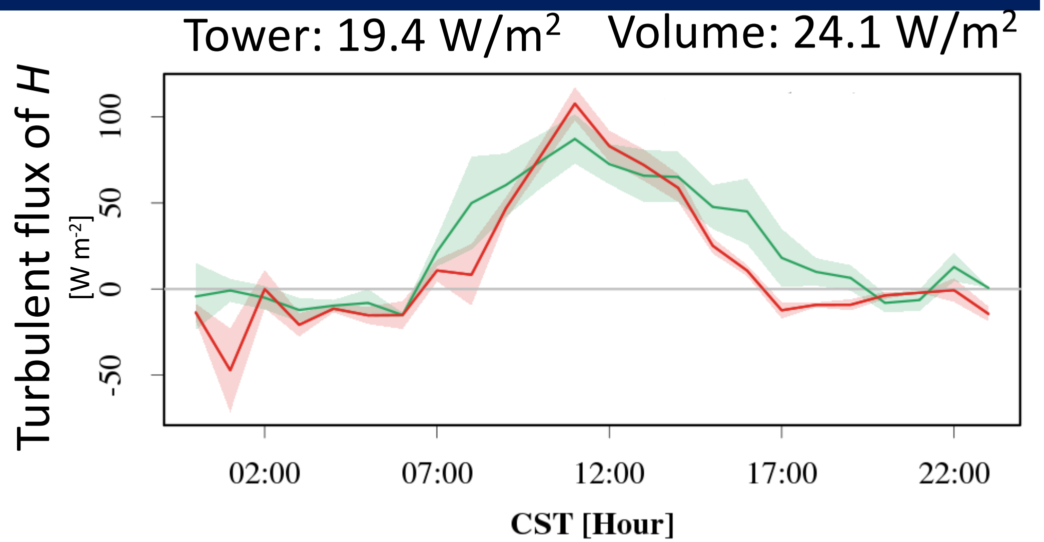


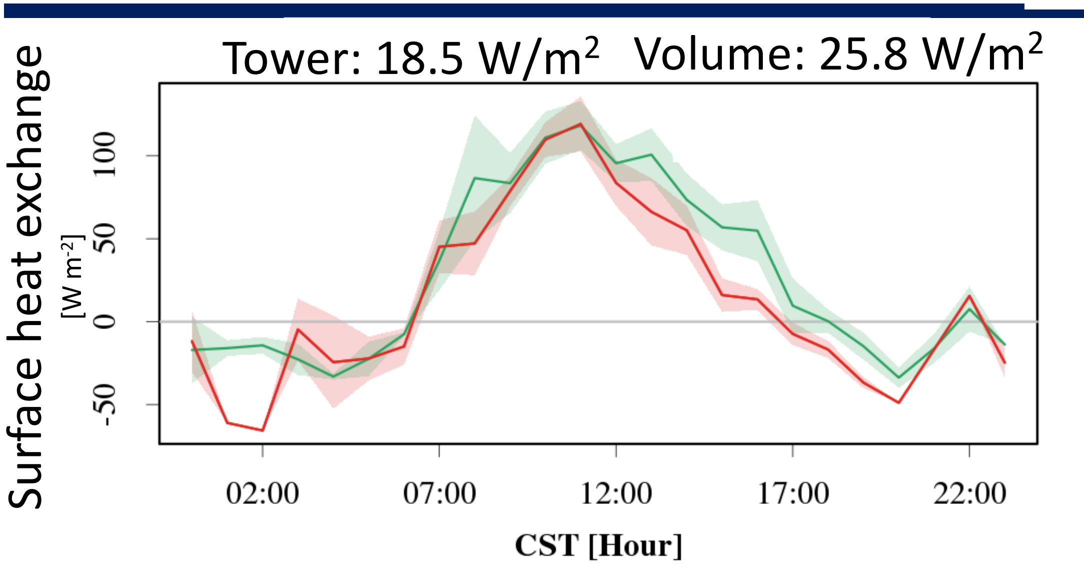
Xu et al., 2018, AFM



Does rectified surface atmosphere exchange help ?







tower-observed

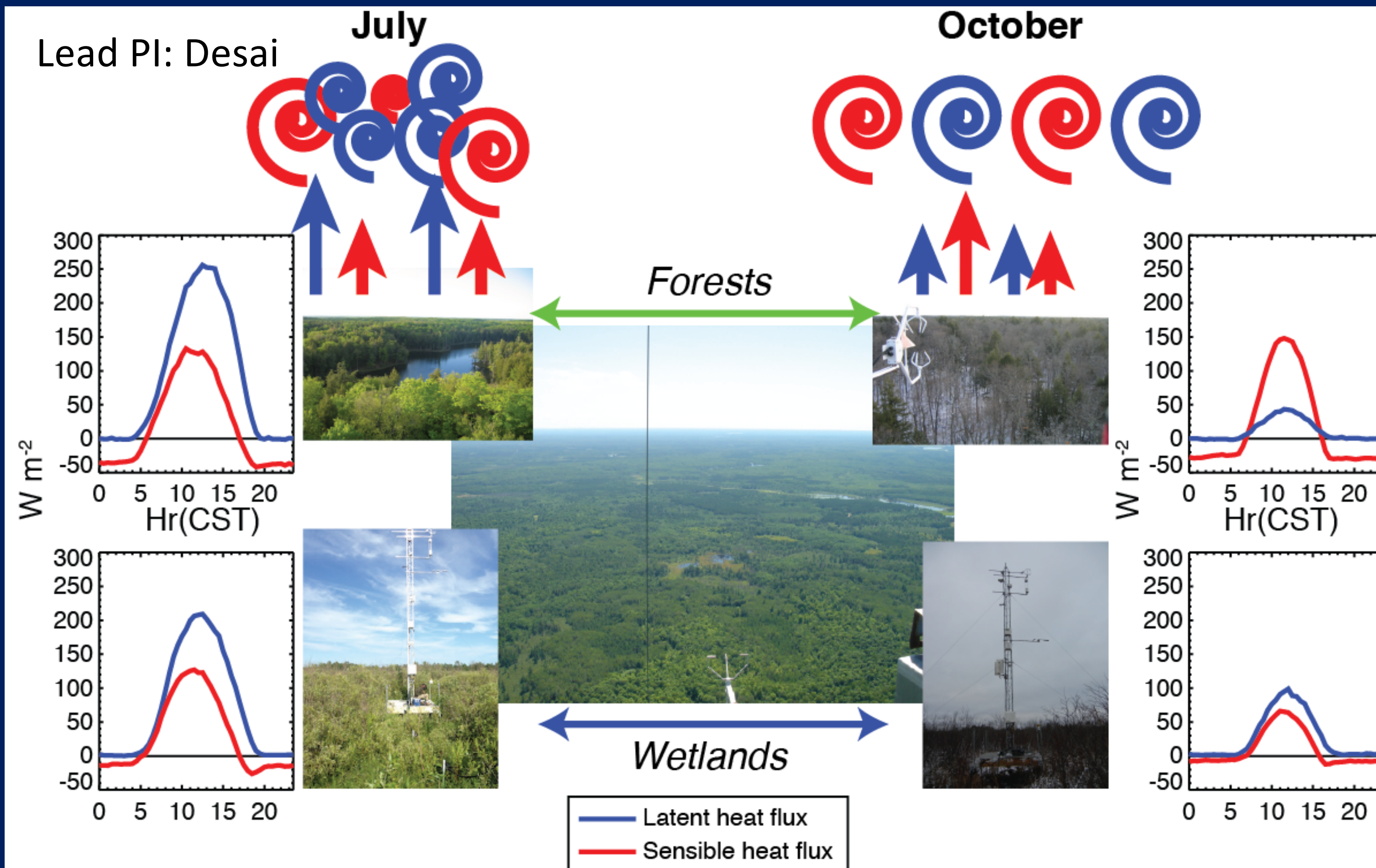
volume-rectified

volume-rectified energy flux is + 7.3 W/m²

So how does that lead to this?

Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors (CHEESEHEAD)

NSF: U Wisc Madison-U Wisc Milwaukee-NASA GSFC-NCAR-U Wyoming-KIT IFU-Montana State



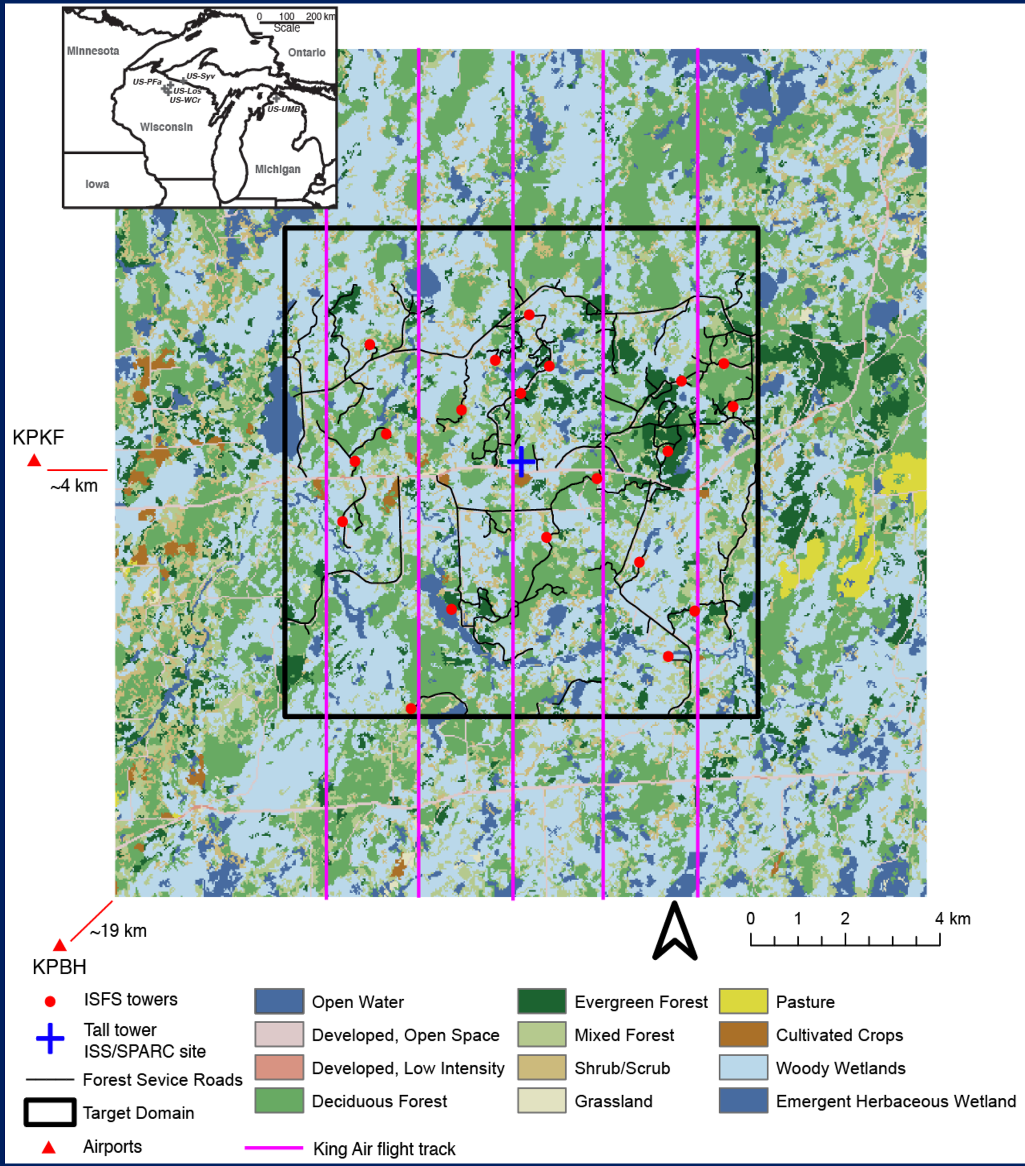
Experimental Design

- Distribute 19 rapid-deployment eddy covariance flux towers (red dots) within 10x10 km box (black box, right) around US-PFa WLEF tall tower (blue cross).
- Run July-Oct 2019
- Ecophys, NPP, and phenology bi-weekly sampling

- Place in-situ and remote profiling instruments in 100 m clearing.

- 3 IOPs in late Jul, late Aug, late Sep with airborne legs in 2 km spacing at 500 and 1000 ft AGL (purple lines).
    - Upward pointing LiDAR to map PBL dept. Raman LiDAR for profiles of temperature and water vapor, if possible
    - Hyperspectral visible-IR and canopy LiDAR mapping mission from UW SpecEx

- LES simulations for each IOP and select cases across study period



Surface (mostly distributed in 10x10 km area)

University of Wisconsin-Madison, Atmospheric and Oceanic Sciences (DESAI)

Ameriflux/NOAA very tall tower (US-PFa / WLEF)	Continuous, funded by DOE Ameriflux
ChEAS Ameriflux tower network (US-WCr/US-Los)	Continuous, funded by DOE Ameriflux

University of Wisconsin-Milwaukee, Geography (SCHWARTZ)

Ground-based vegetation/phenology sampling	July-Oct, weekly, campaign/student-based

NCAR EOL Integrated Surface Flux System (ISFS)

15-20 10-20 m EC flux towers	July-Oct, above canopy fluxes and met

In-Situ Profiling (mostly at US-PFa Very tall tower)

NCAR EOL Integrated Sounding System (ISS)

449 MHz modular wind profiler + RASS	July-Oct, Winds, T/RH profile
Radiosonde	Every morning (12 UTC) July-Oct

UW Space Science and Engineering Center Portable Atmospheric Research Center (SPARC)

Atmospheric Emitted Radiance Interferometer (AERI)	July-Oct, T and RH profile
HALO Photonics Streamline scanning Doppler LiDAR	July-Oct, Winds and turbulence
High-Spectral Resolution Lidar (HSRL)	July-Oct, aerosol backscatter
Vaisala Ceilometer	July-Oct, PBL depth

University of Wisconsin-Madison, Atmospheric and Oceanic Sciences (DESAI)

3-hourly high-resolution PBL sondes during IOPs	Daily during IOPs

Karlsruhe Institute for Technology (VOGELMANN)

DIAL/Raman Lidar	July-Oct, T and H2O profile
2x HALO Photonics Streamline scanning Doppler LiDAR	July-Oct, Winds and turbulence

Airborne

University of Wyoming King Air

Eddy covariance, Raman LiDAR, cloud LiDAR (70 hours)	2 IOPs w/ 8 hour ferry + 26 hours sampling

University of Wisconsin Spectral Explorer (UWSpex) (TOWNSEND)

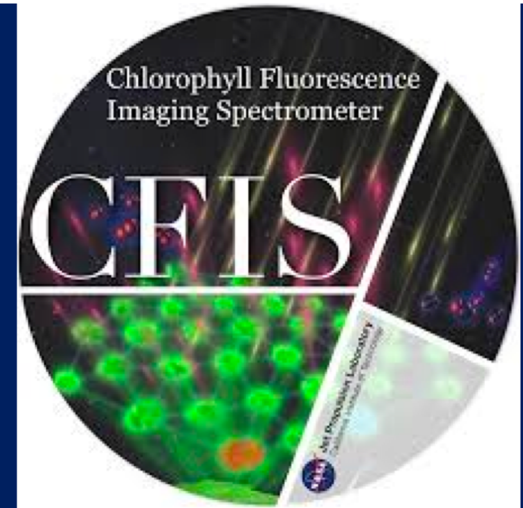
Surface mapping of 400-2500 nm spectra	2 IOPs

University of Wisconsin Ultralight (PETTY)

Boundary-layer heat and water budget of domain; low level characterization of BL inhomogeneities	2 IOPs




courtesy of Vanda Grubisic, Desert


Chlorophyll Fluorescence
Imaging Spectrometer
CFIS


N59DW

What did we learn?

- Surface fluxes of energy and carbon are an important boundary condition on the climate system
- Eddy covariance flux towers have been used extensively to measure them, but with a known bias in energy fluxes that may affect carbon too
- The bias is partly a result of larger scale motions that can be corrected using novel computation approaches with wavelets and machine learning
- A bunch of CHEESEHEADs will soon find out how reliable it is!

THANKS!!!

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Photo: J Thom