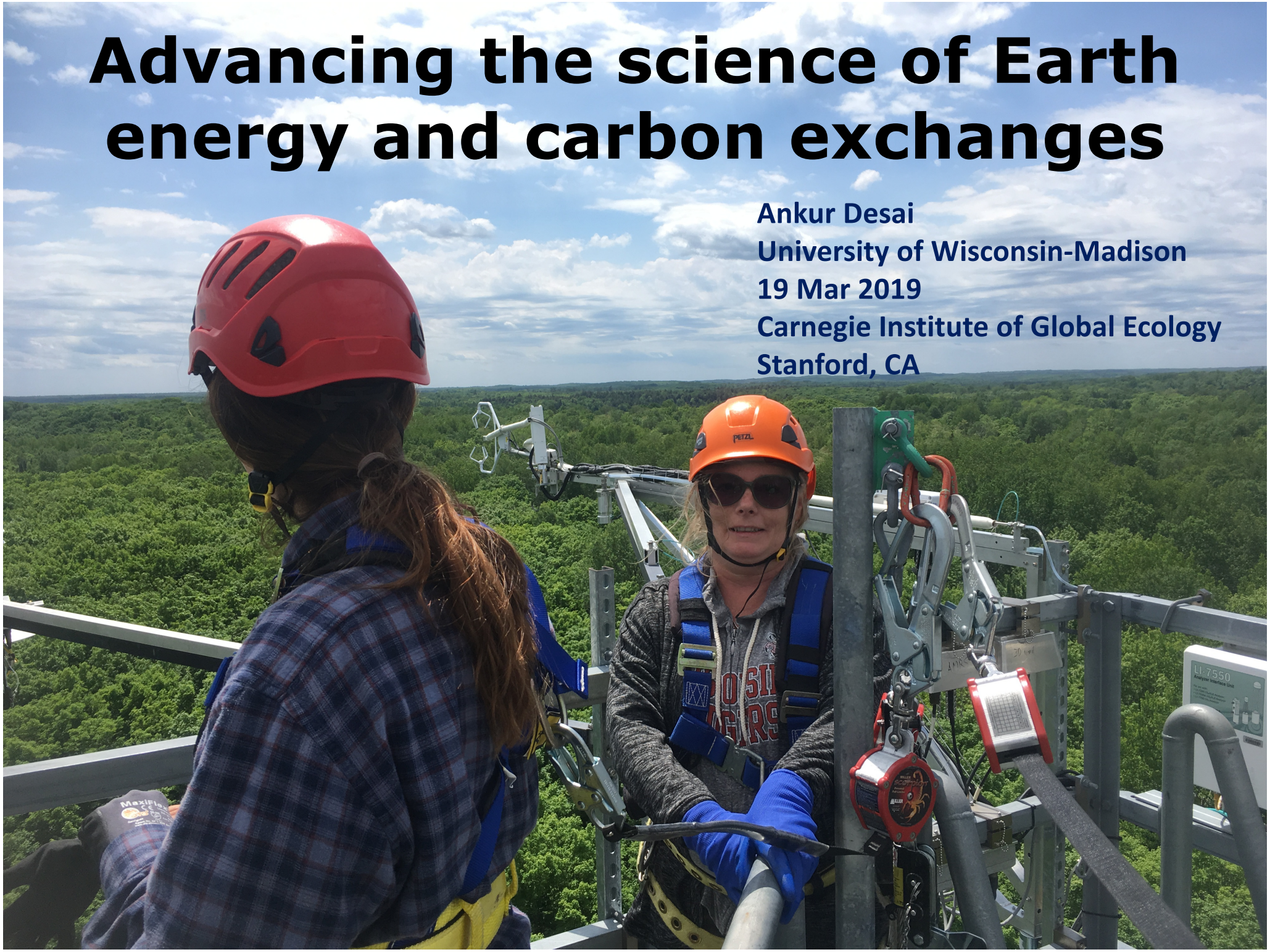
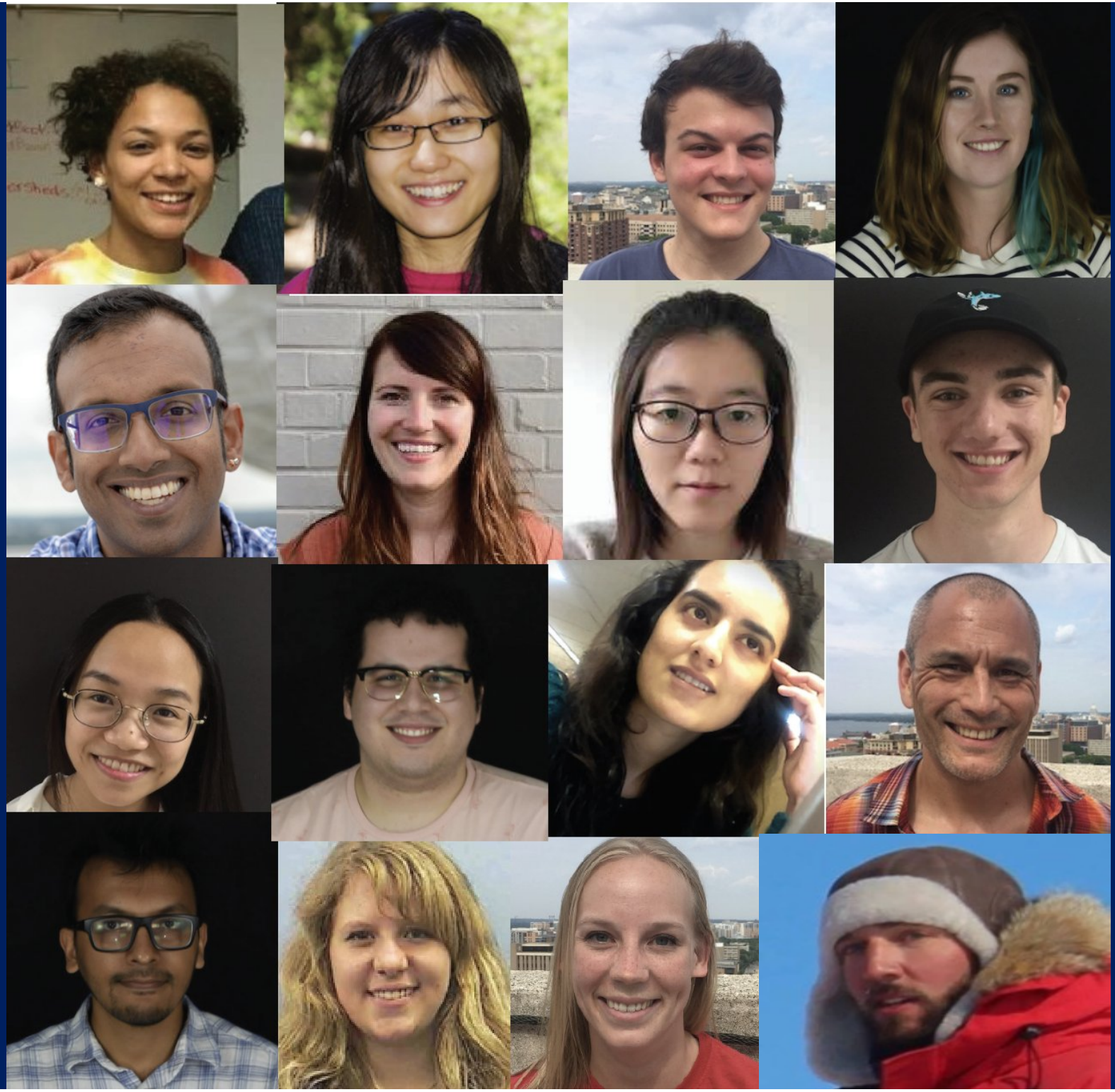
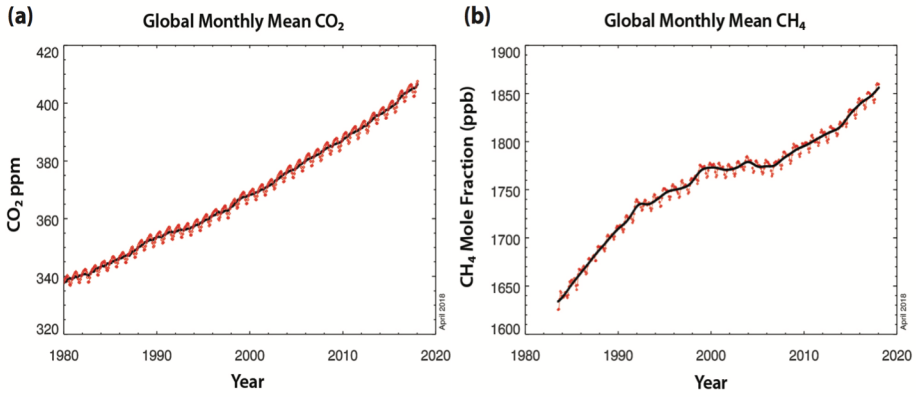
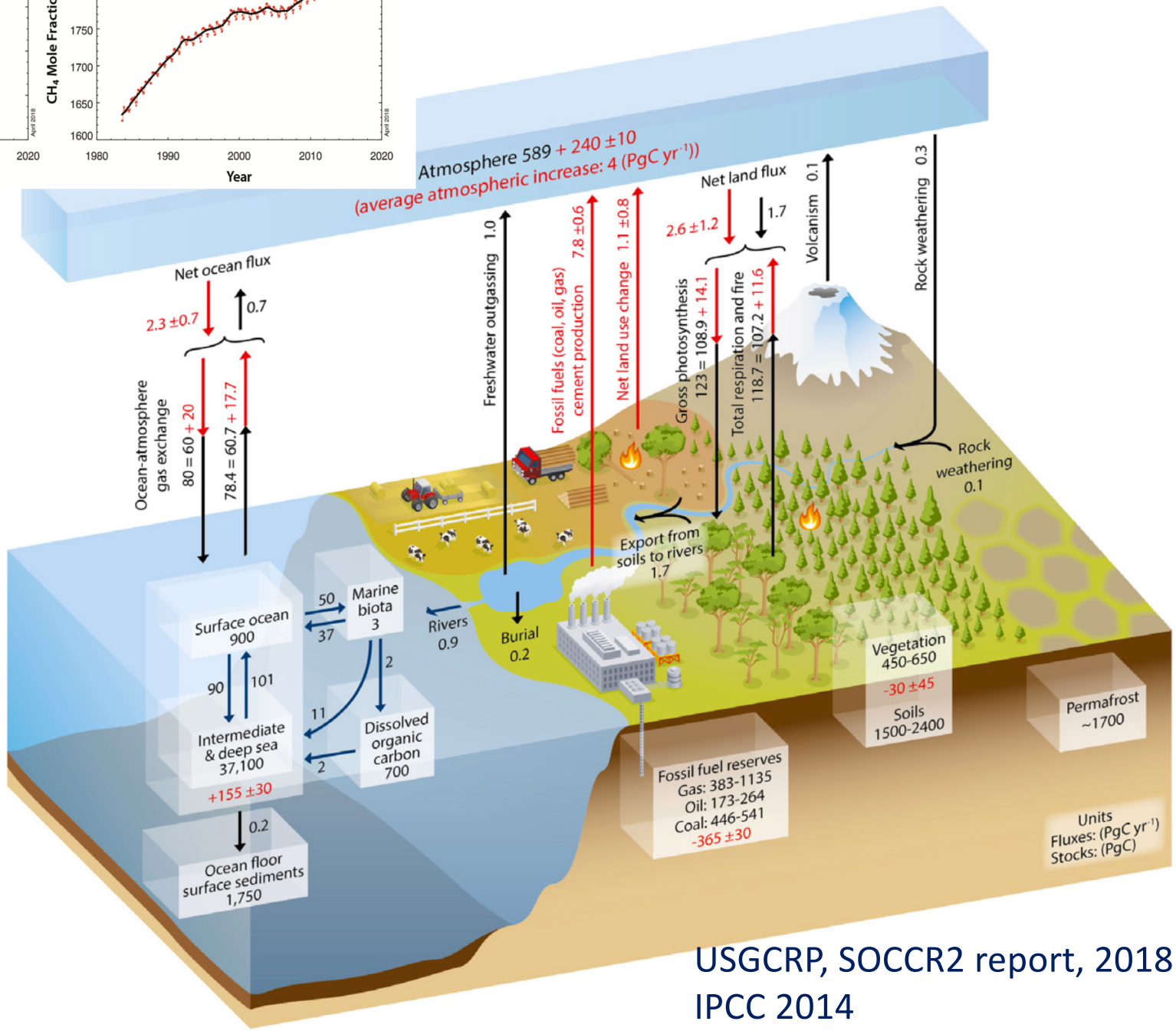
Advancing the science of Earth energy and carbon exchanges



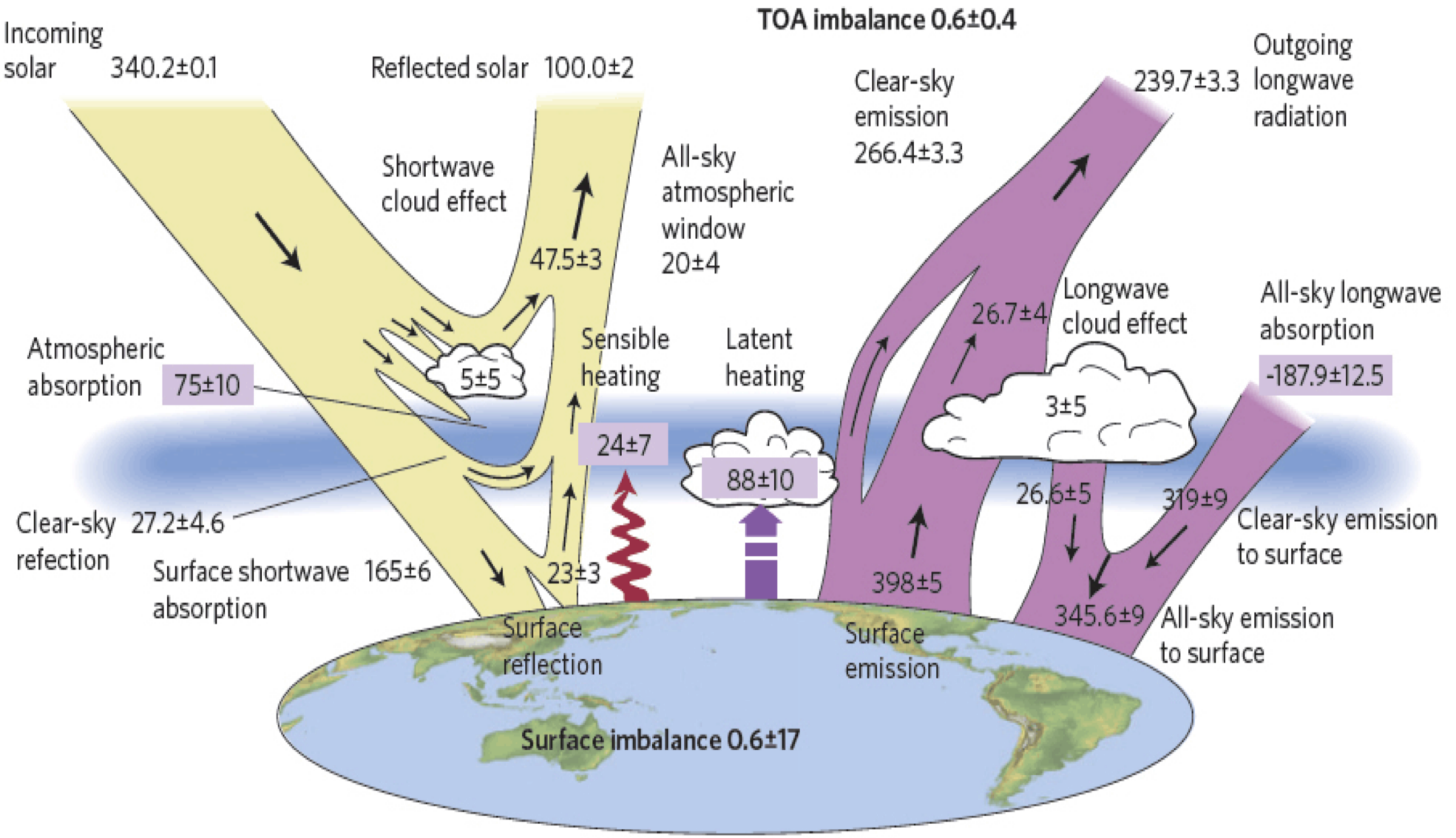
Ankur Desai
University of Wisconsin-Madison
19 Mar 2019
Carnegie Institute of Global Ecology
Stanford, CA







USGCRP, SOCCR2 report, 2018
IPCC 2014



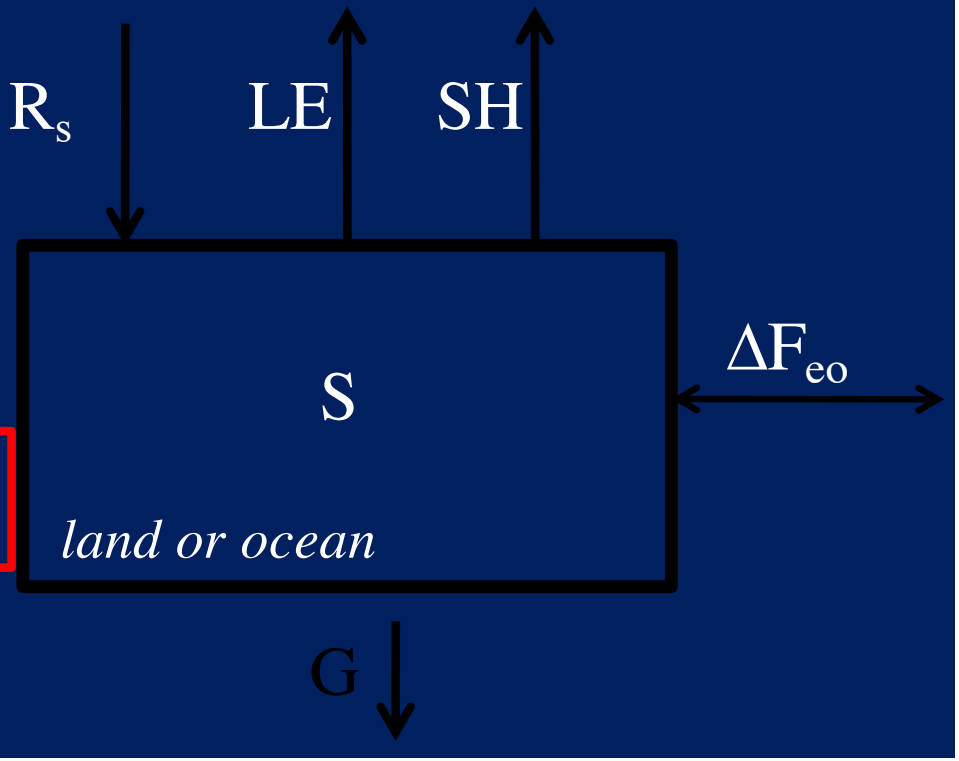
Stephens et al., 2012, Nature Geosci

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

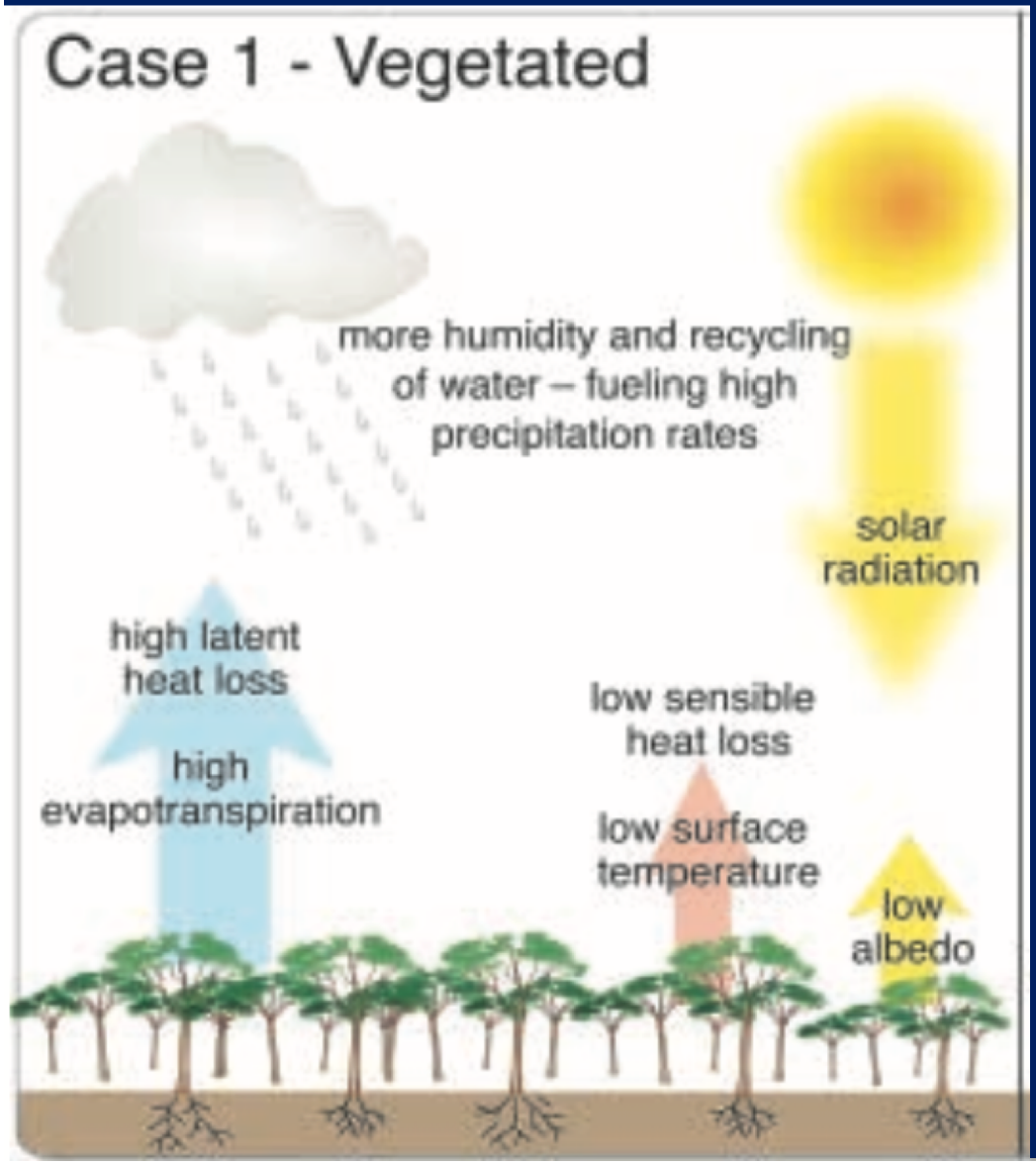
$$R_N - G = LE + SH + S + \Delta F_{eo}$$



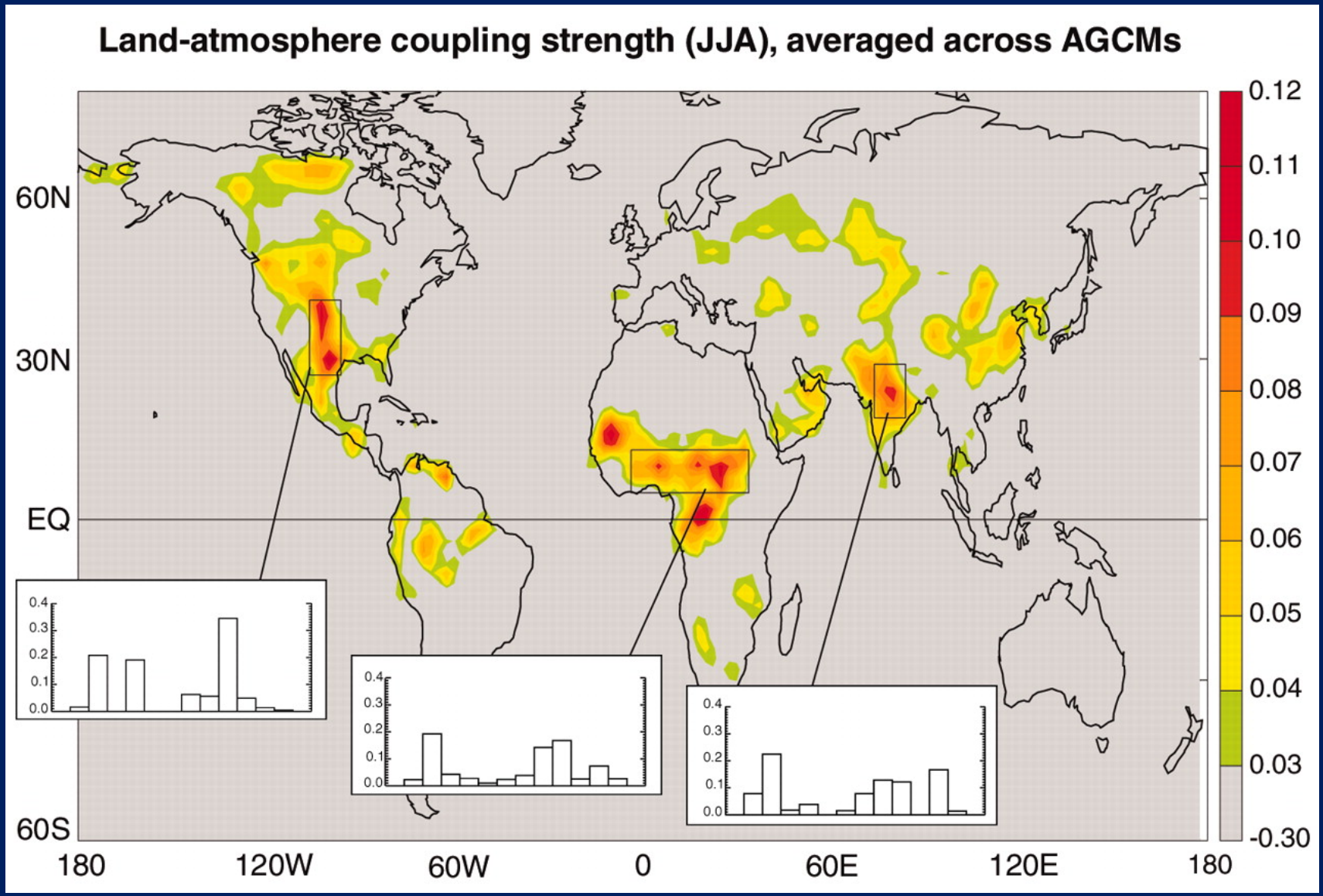
Green surprise? How terrestrial ecosystems could affect earth's climate

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

Frontiers in Ecology, 2003

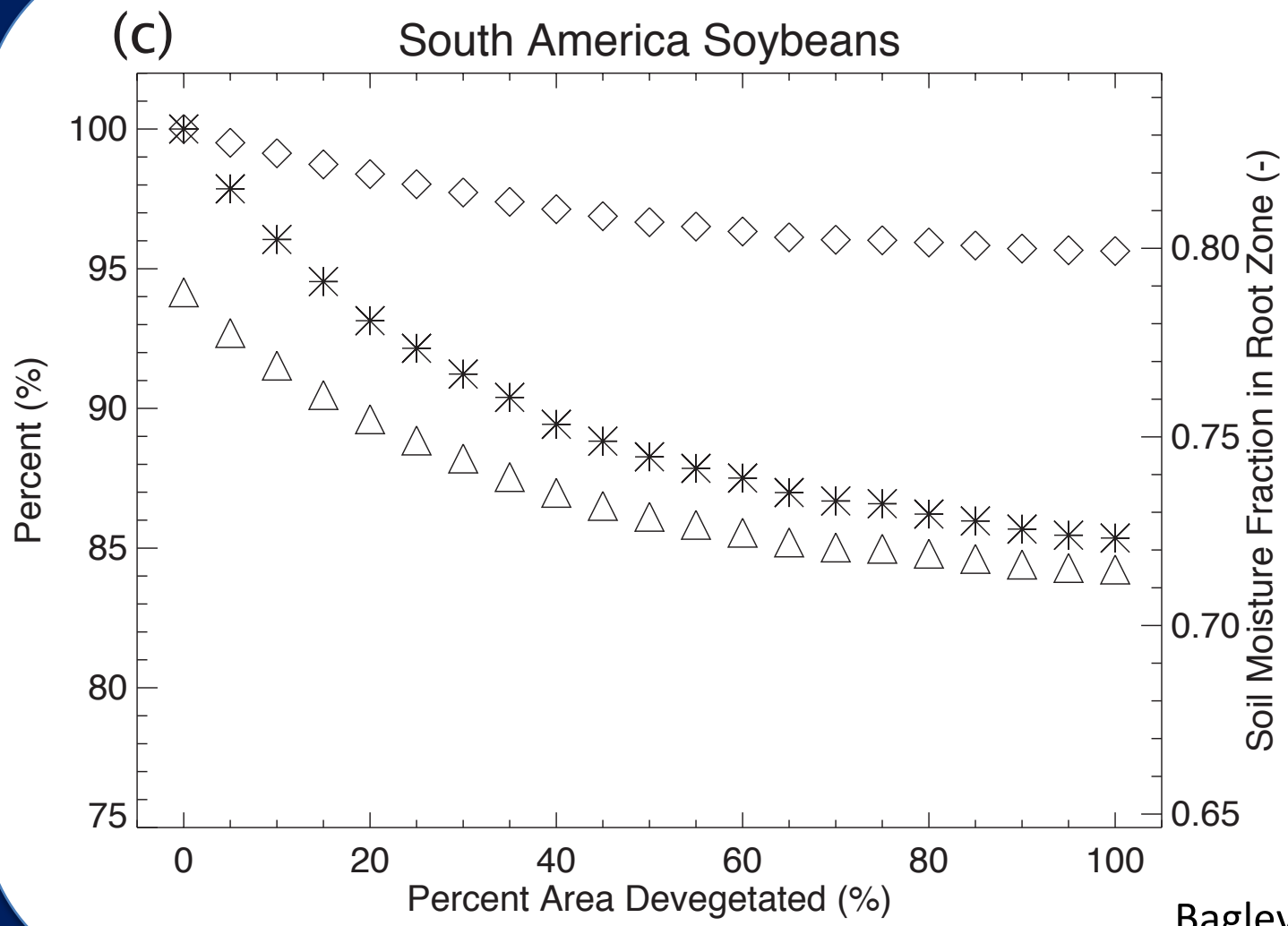


Koster et al., 2004



Potential Impact of Land Cover Change on Crop Yield

S. America Soybeans

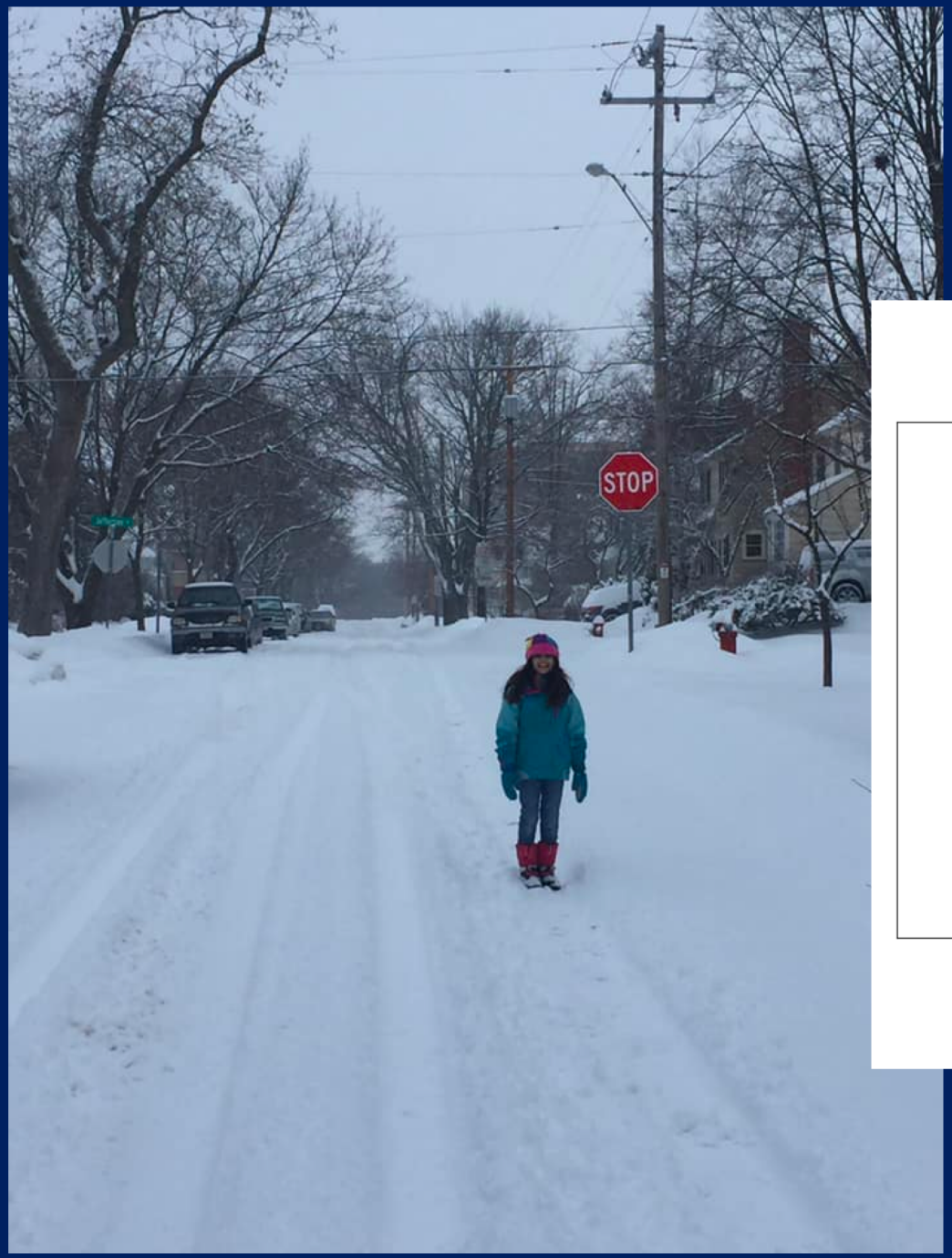


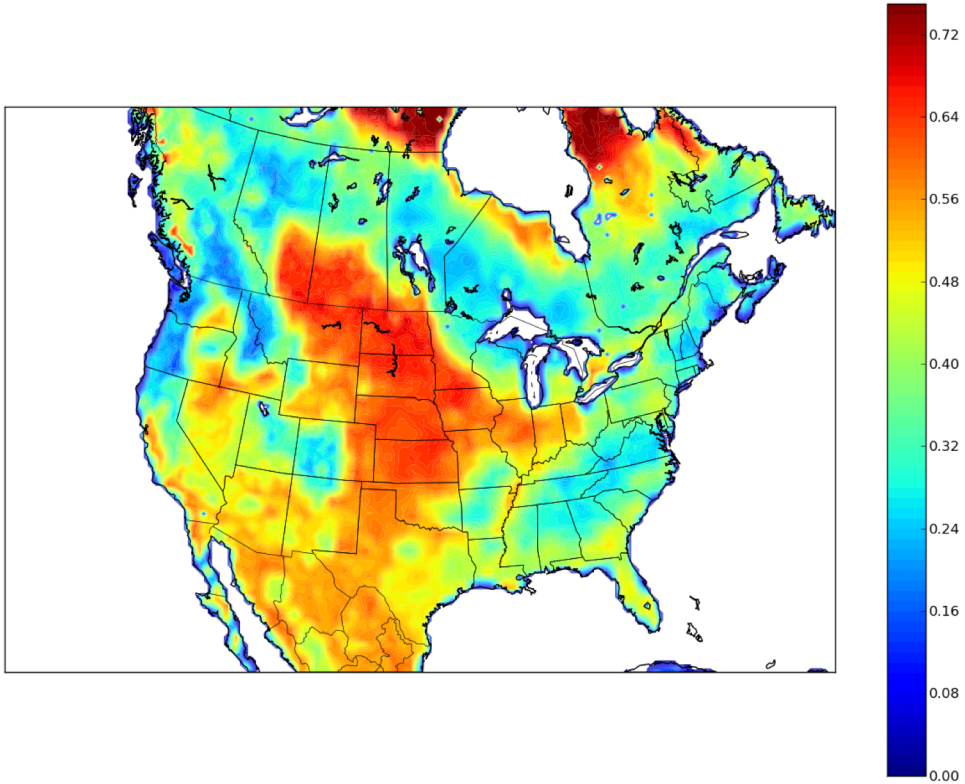
Soil moisture fraction

Crop Yield

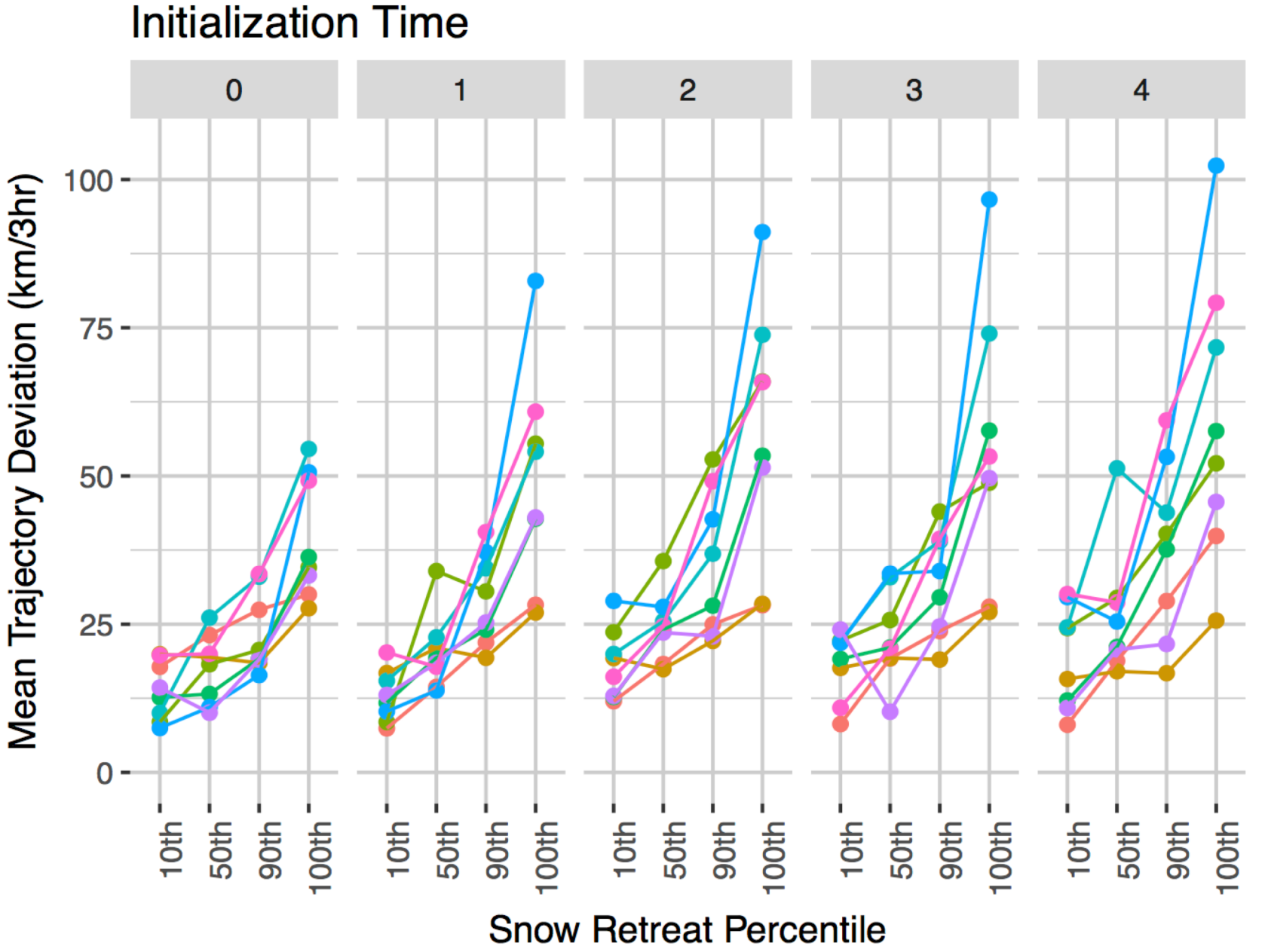
Precipitation

Bagley et al., 2012, ERL



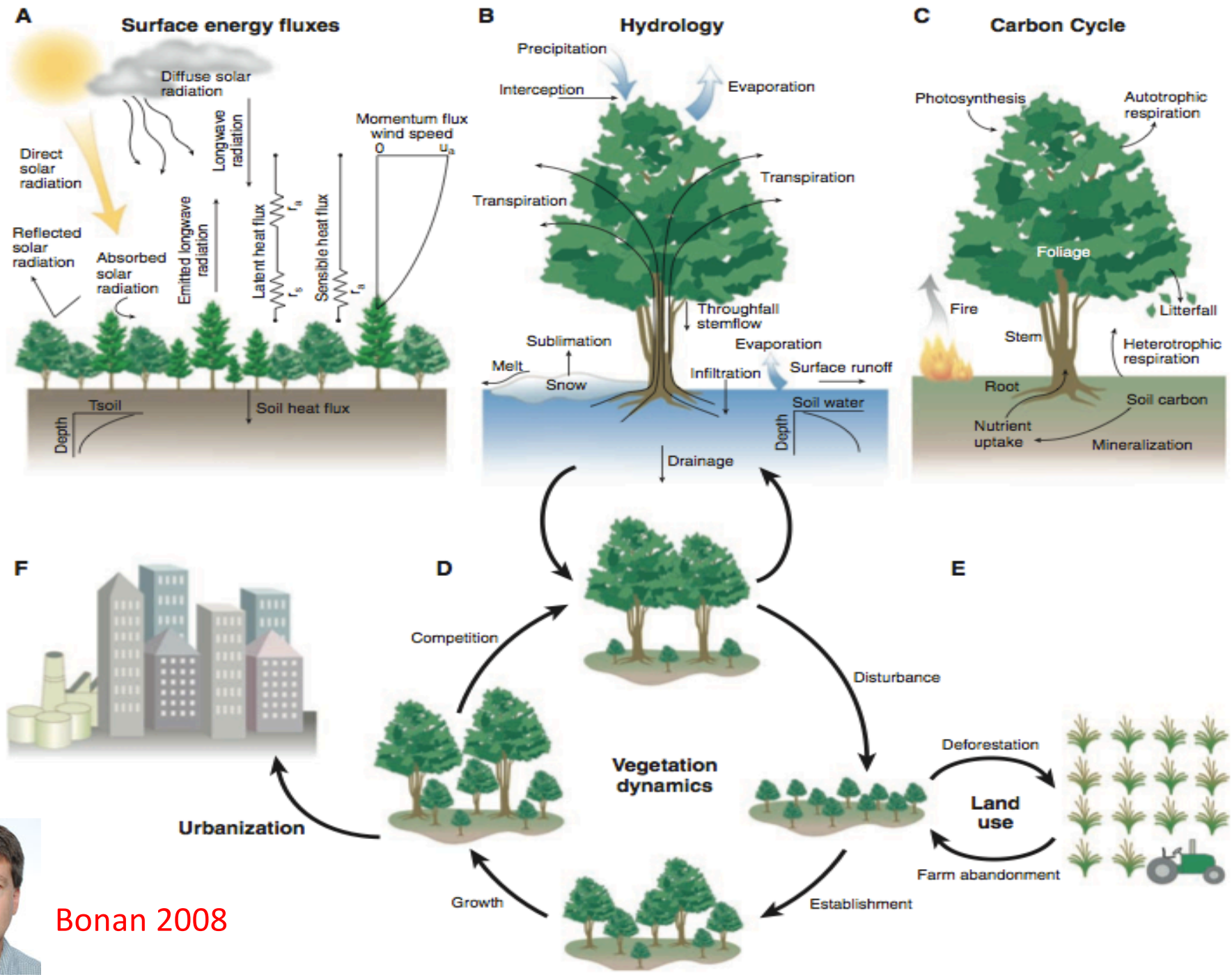


Clare et al., in prep, J Climate



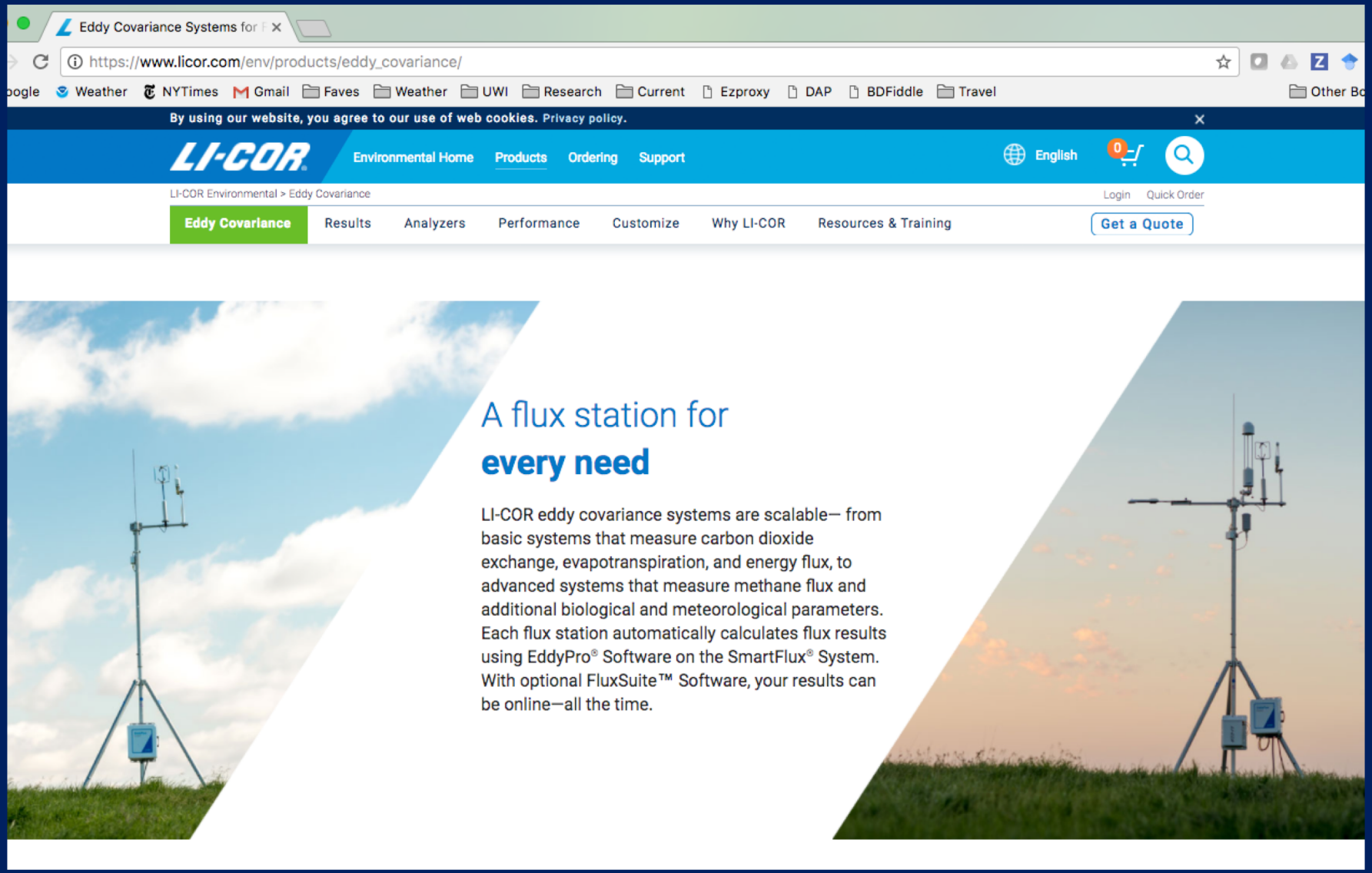
Rydzik and Desai, 2012; Clare et al ., in prep; figure by Michael Johnson

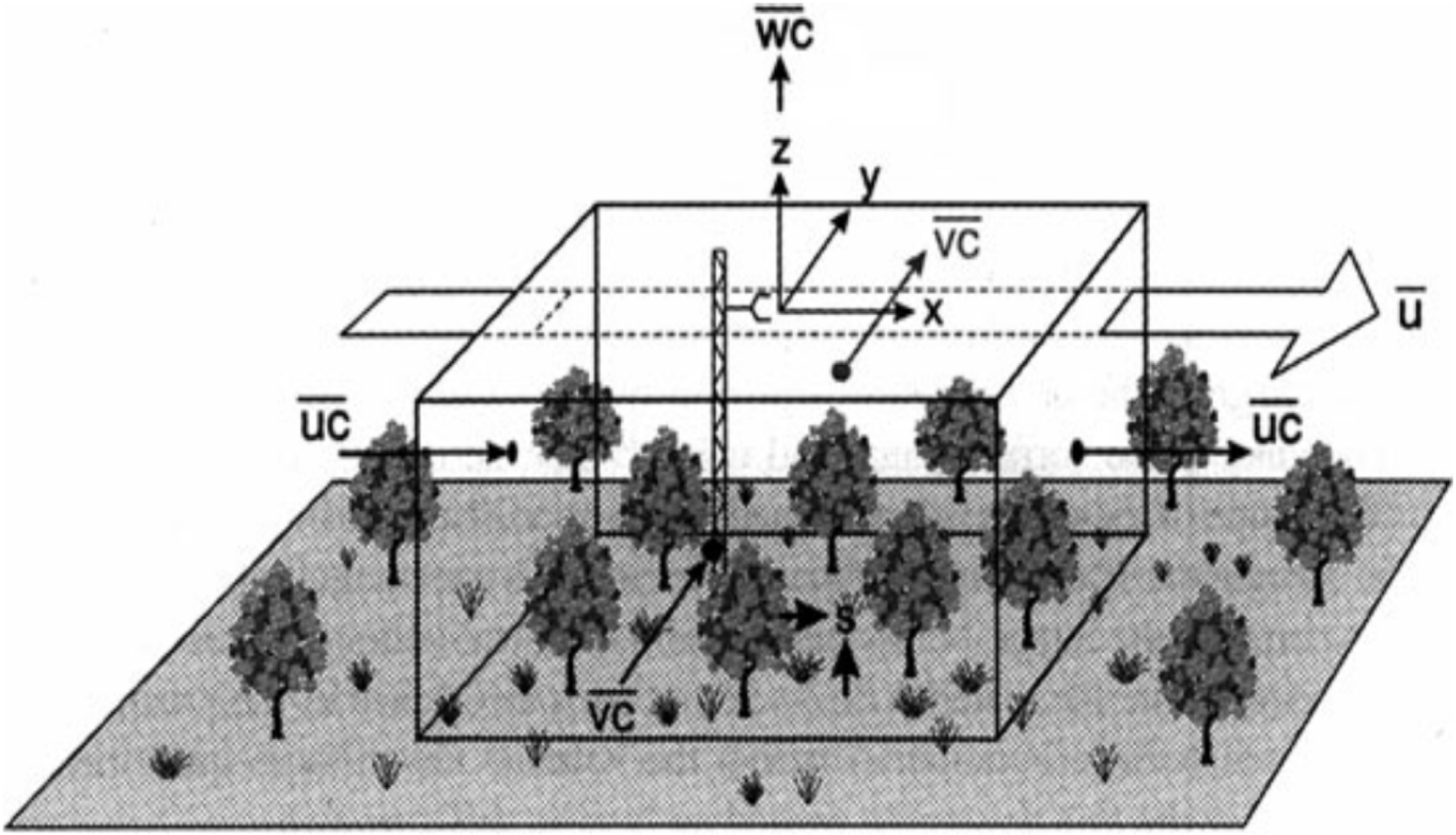
Forests in Flux



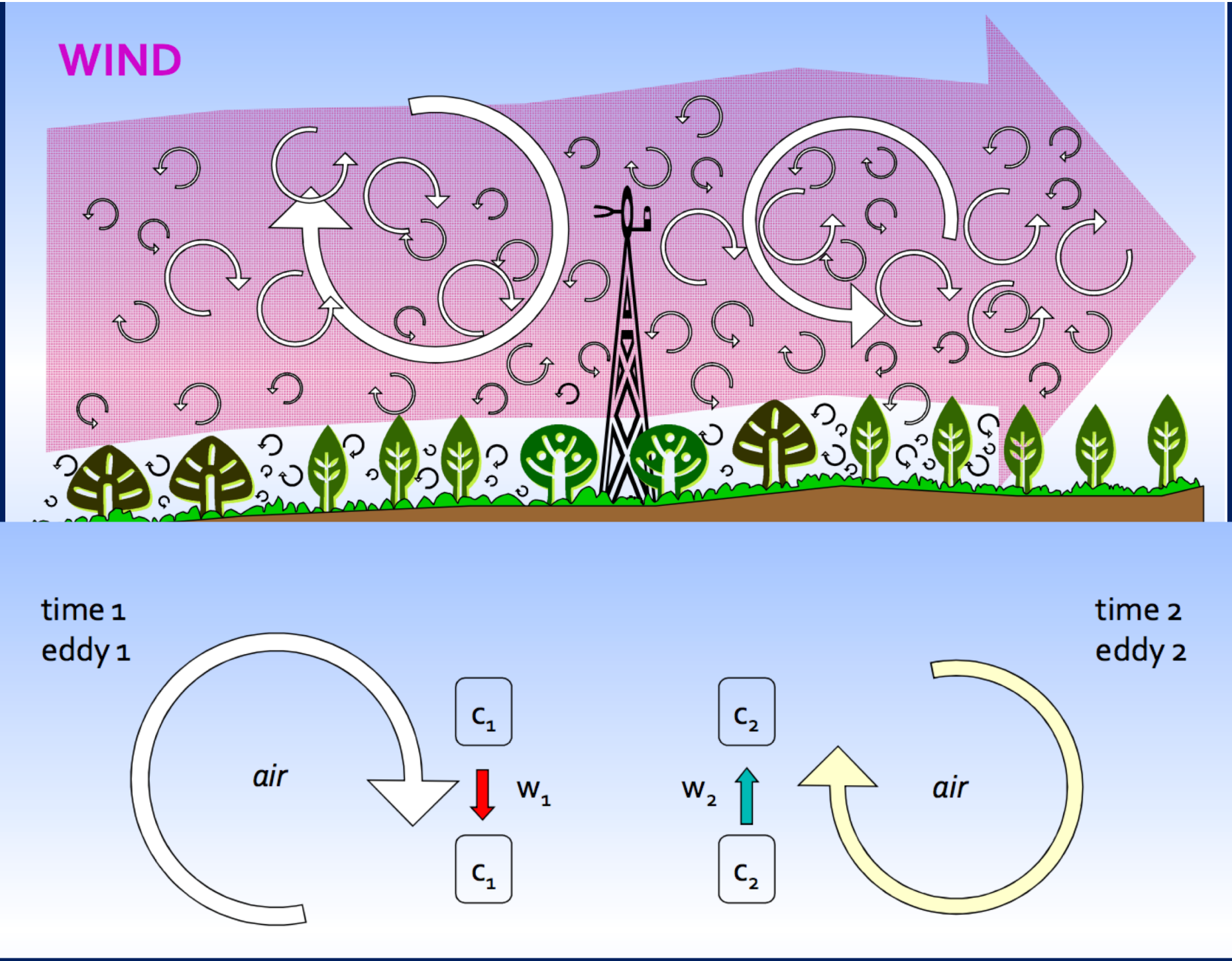
Bonan 2008

Enter eddy covariance flux towers

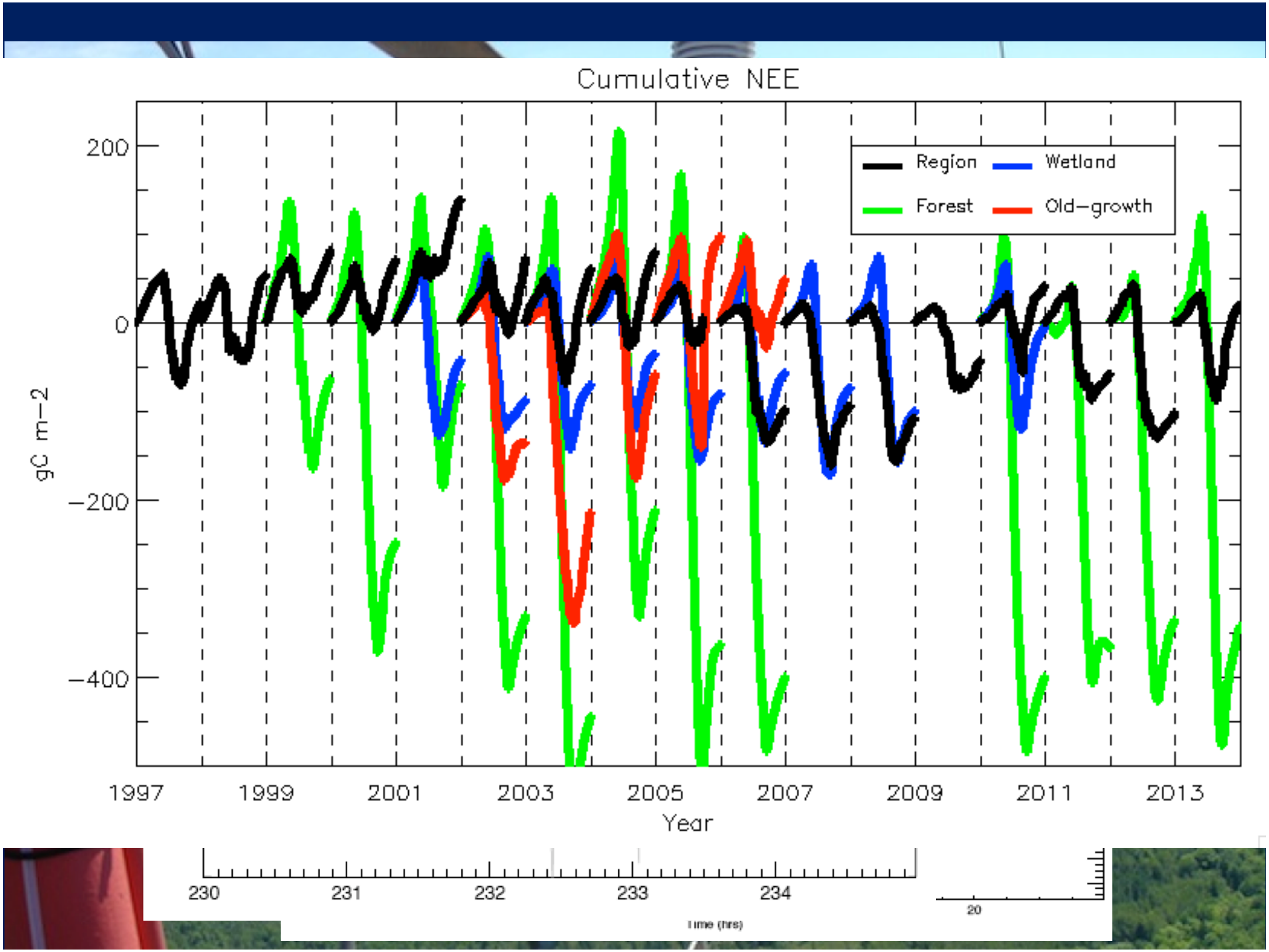




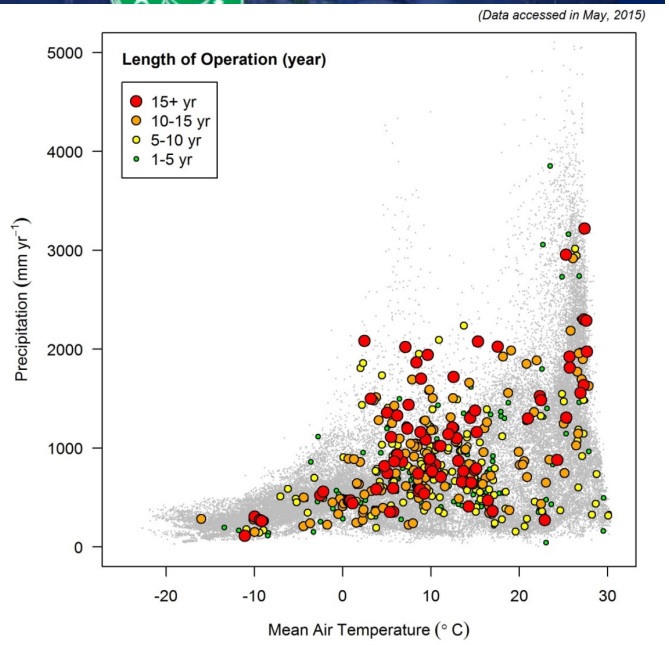
Finnigan et al (2003)



Burba and Anderson (2010)

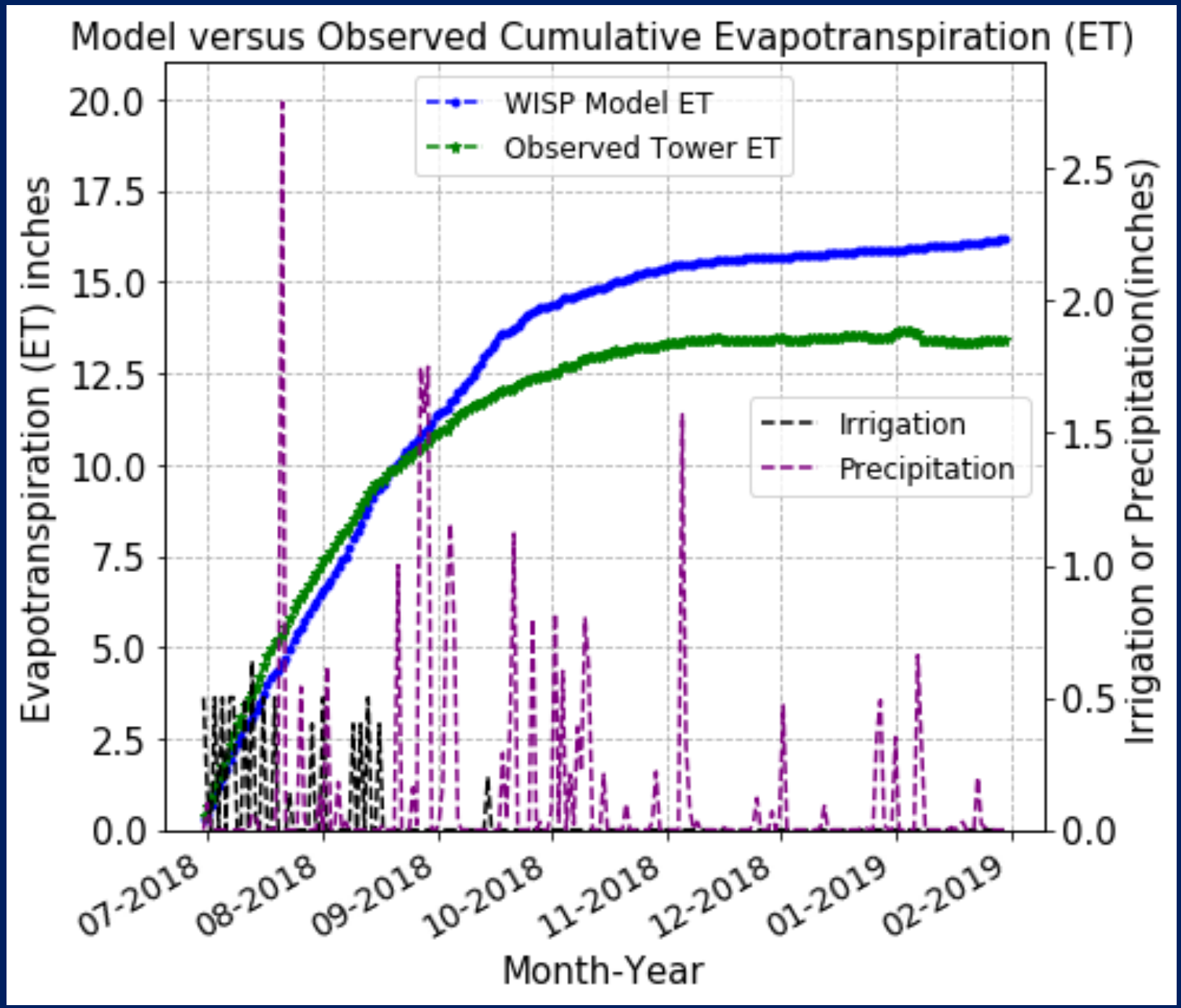

Cumulative NEE
Region
Wetland
Forest
Old−growth
200
0
−200
−400
gC m−2
1997
1999
2001
2003
2005
2007
2009
2011
2013
Year
230
231
232
233
234
Time (hrs)
20

2029 towers!
(Feb 2019)



George Burba, doi:10.13140/RG.2.2.25992.67844/1
Ameriflux: The Coalition of the Willing
Novick et al (2018) Agricultural and Forest Meteorology


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

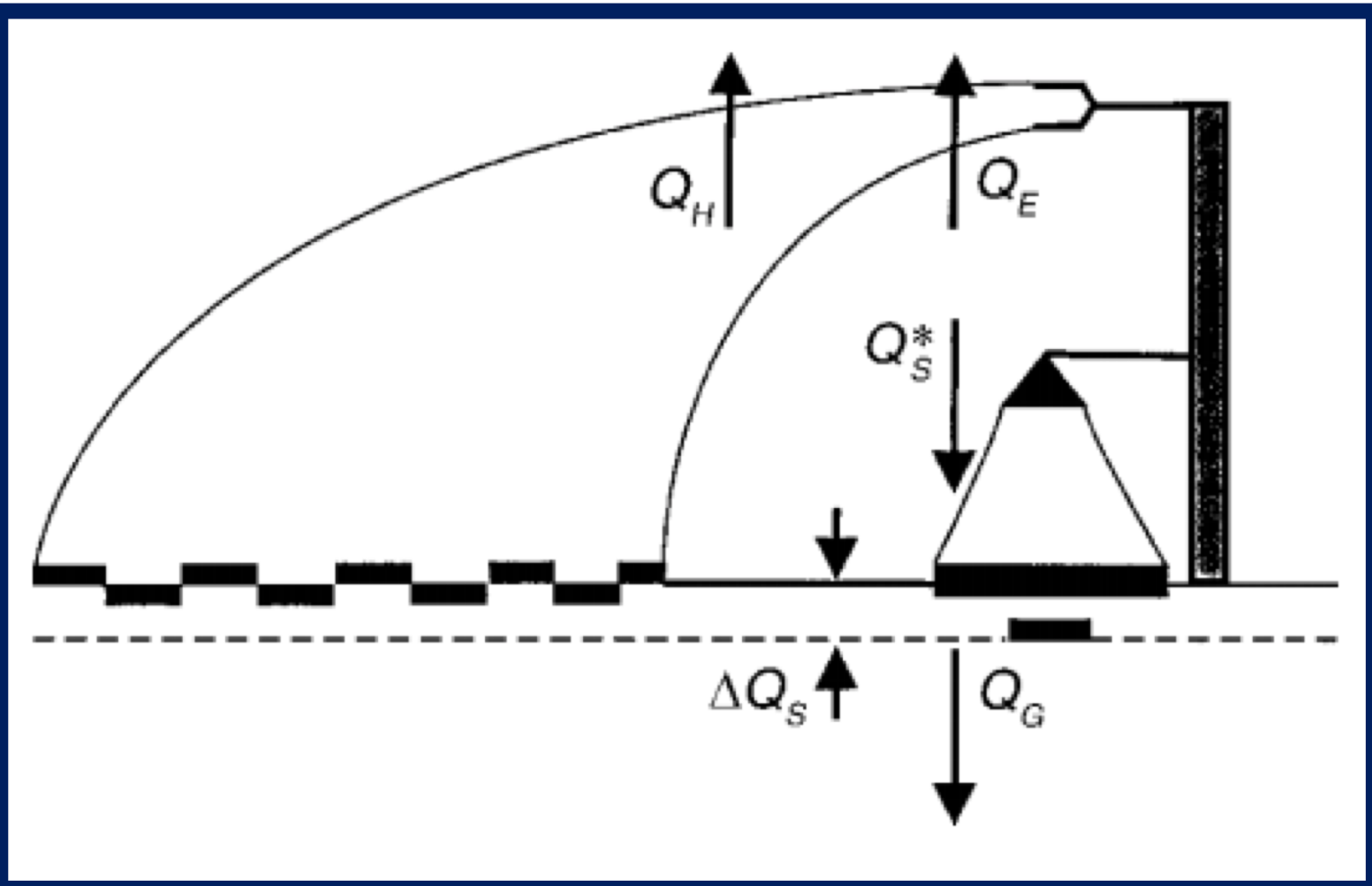

Model versus Observed Cumulative Evapotranspiration (ET)
WISP Model ET
Observed Tower ET
Irrigation
Precipitation
Evapotranspiration (ET) inches
Irrigation or Precipitation(inches)
Month-Year
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
2.5
2.0
1.5
1.0
0.5
0.0
07-2018
08-2018
09-2018
10-2018
11-2018
12-2018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

But…

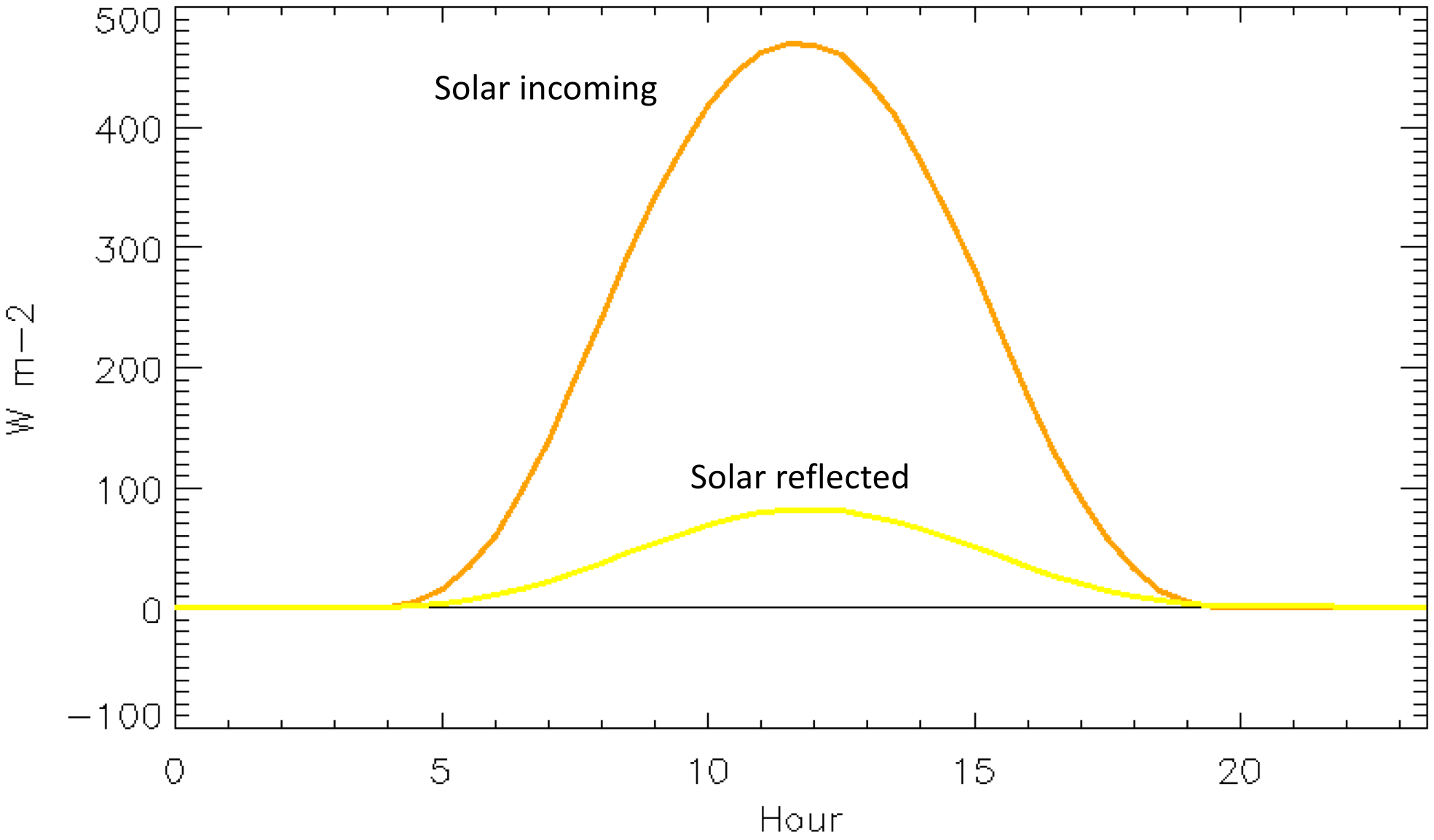
Ecological Applications, 18(6), 2008, pp. 1351–1367

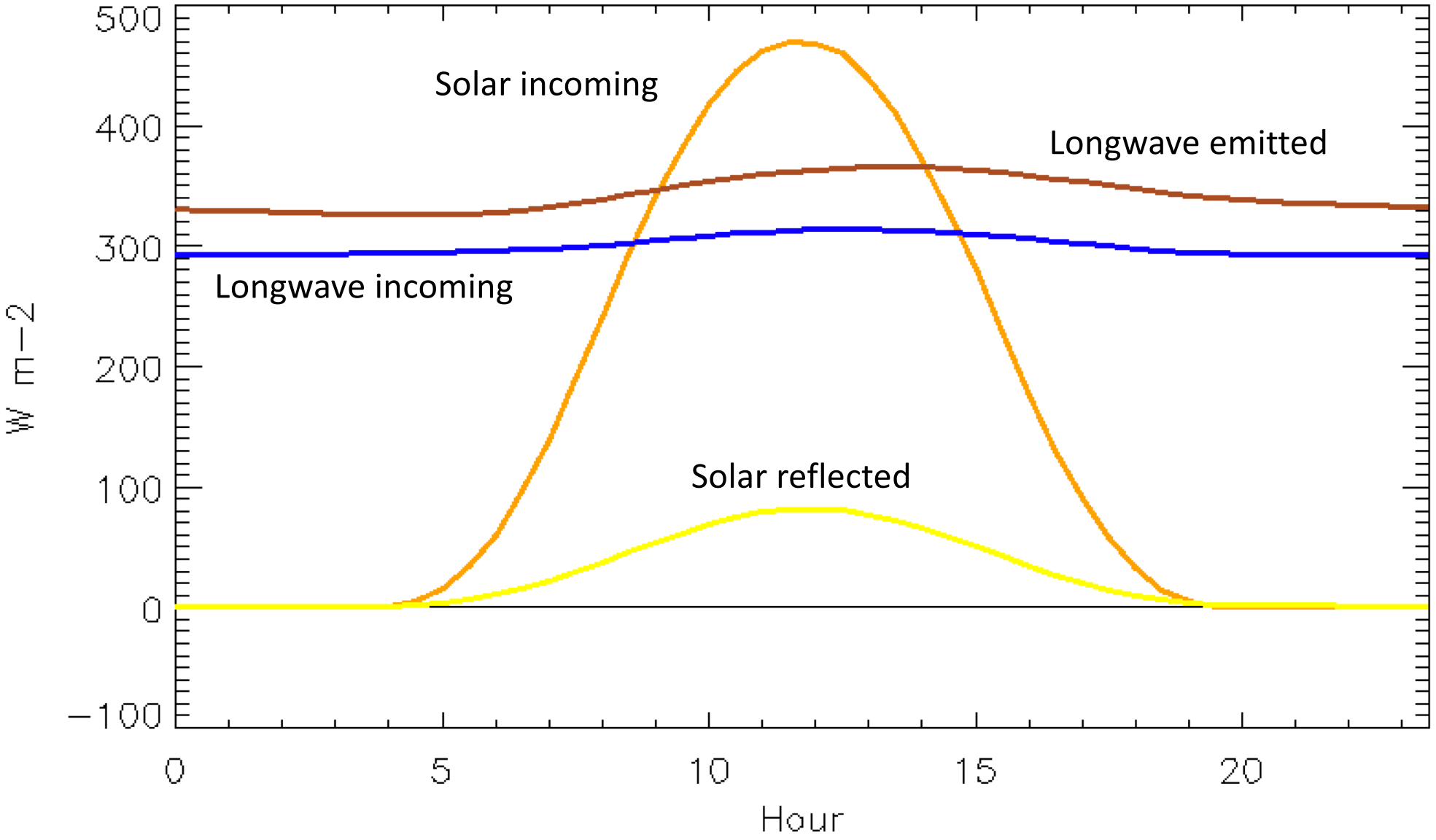
THE ENERGY BALANCE CLOSURE PROBLEM: AN OVERVIEW

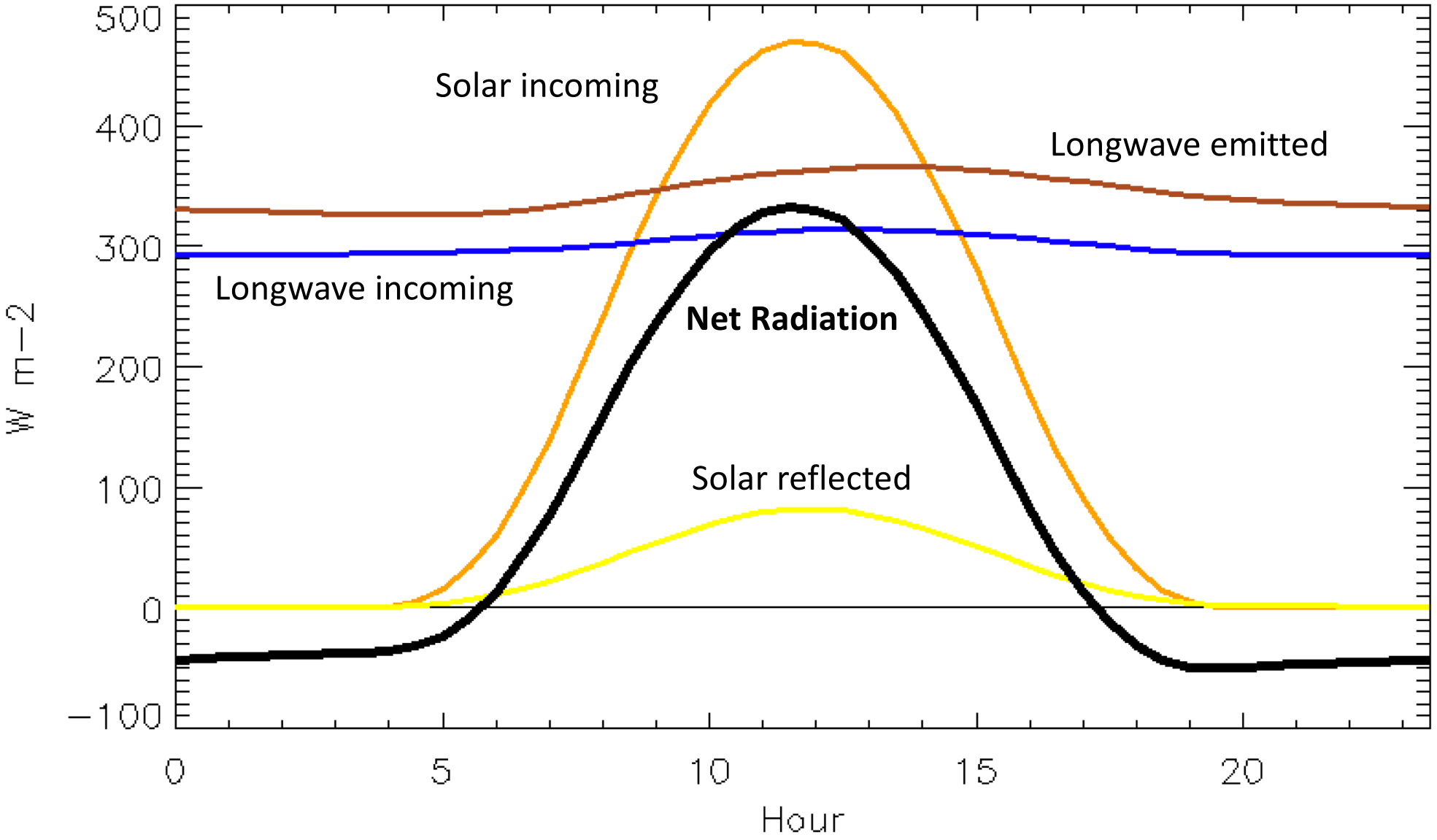
THOMAS FOKEN[1]

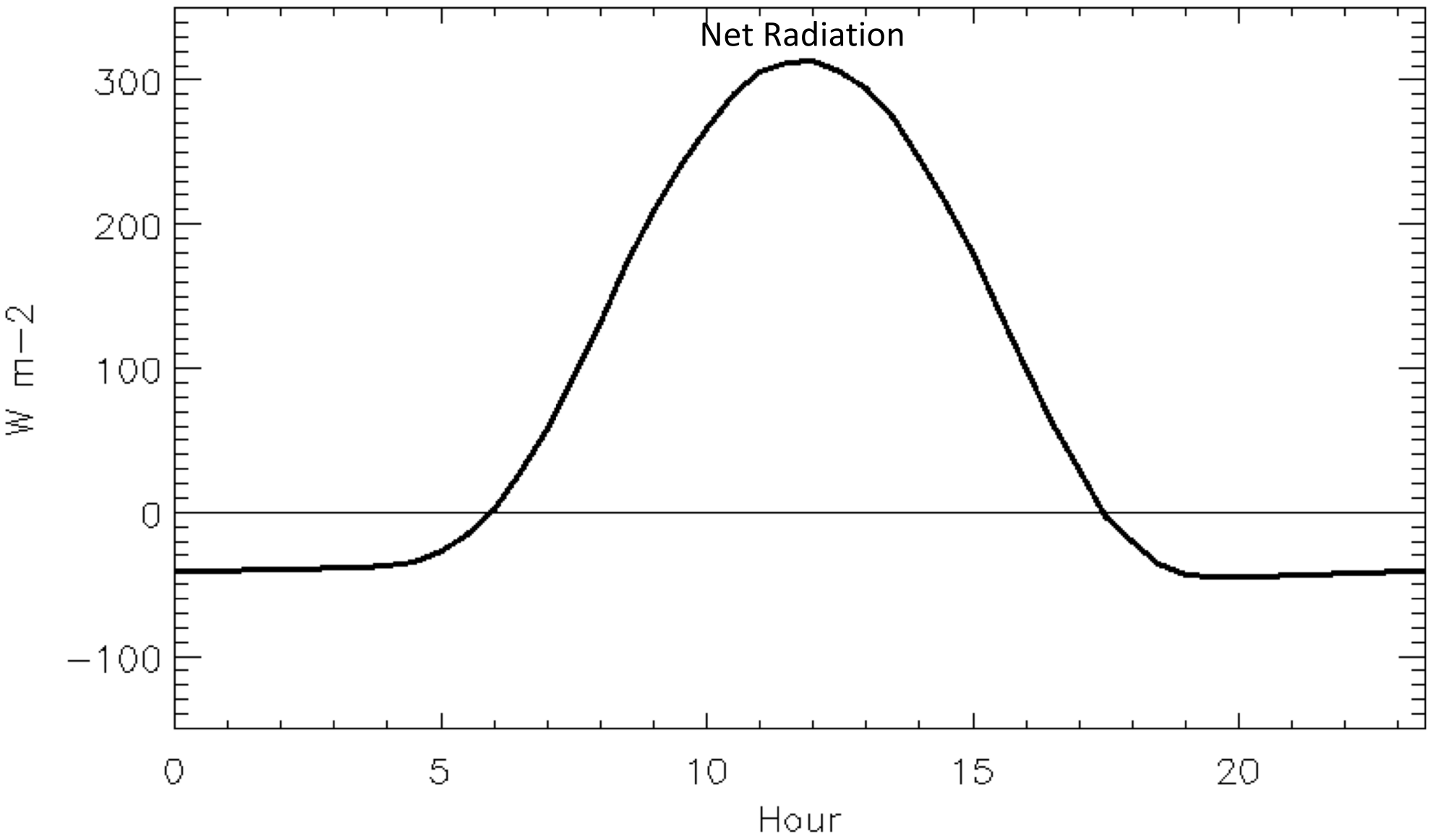


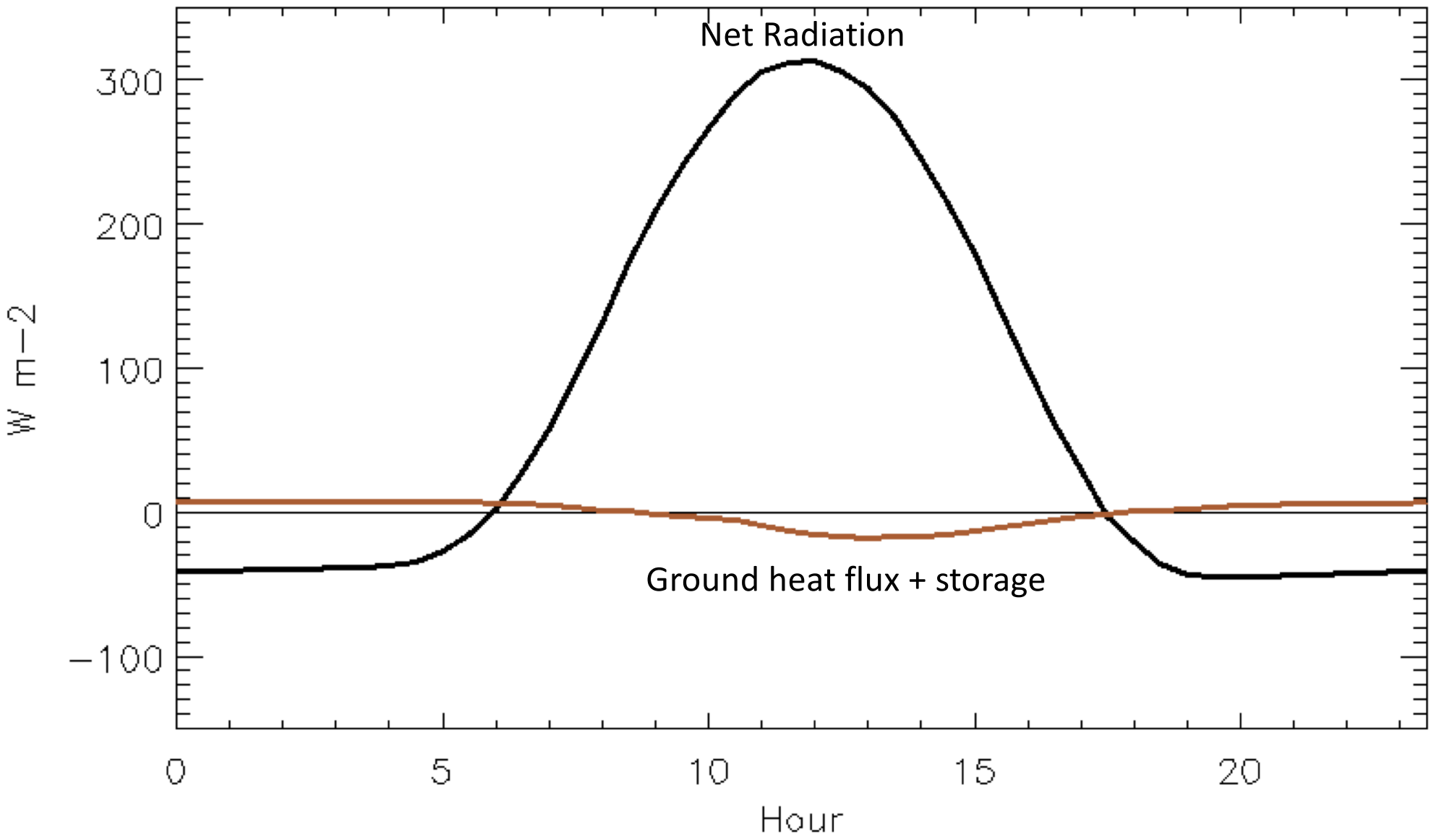

US-Syv (Sylvania)
Desai et al., 2005, Ag For Met

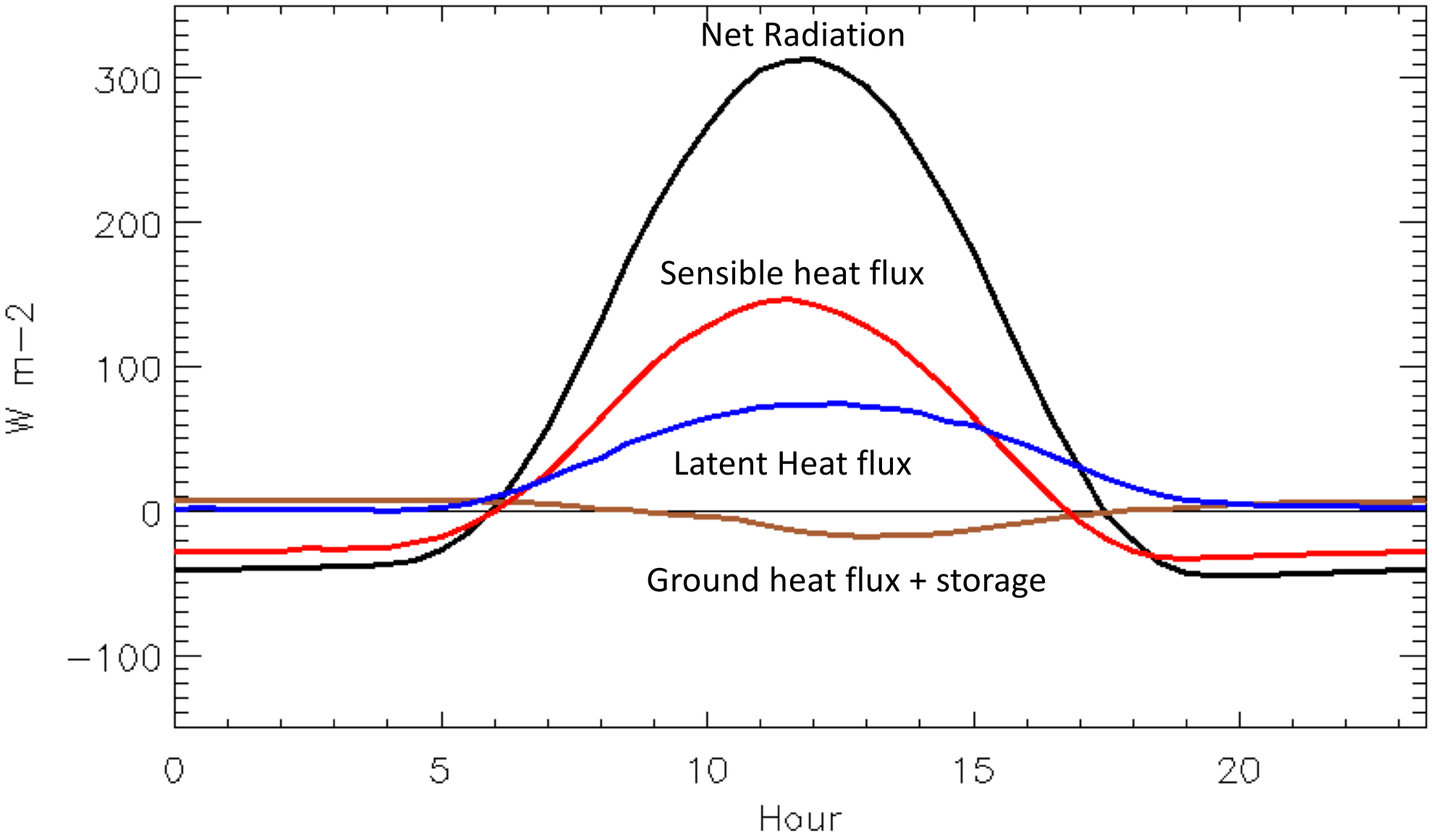

Solar incoming
Solar reflected
500
400
300
200
100
0
−100
W m−2
0
5
10
15
20
Hour

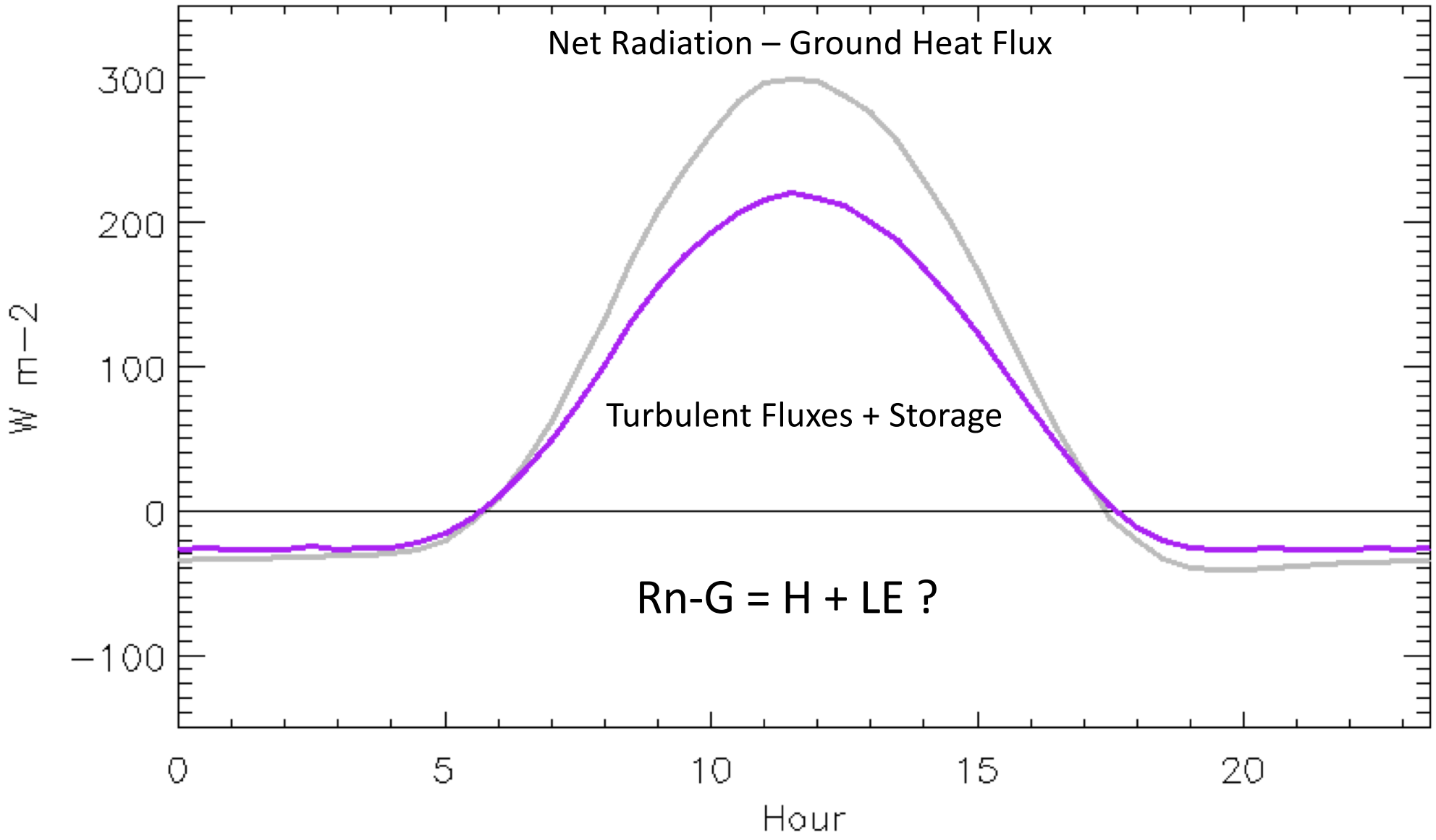

Solar incoming
Longwave emitted
Longwave incoming
Solar reflected
W m−2
500
400
300
200
100
0
−100
0
5
10
15
20
Hour

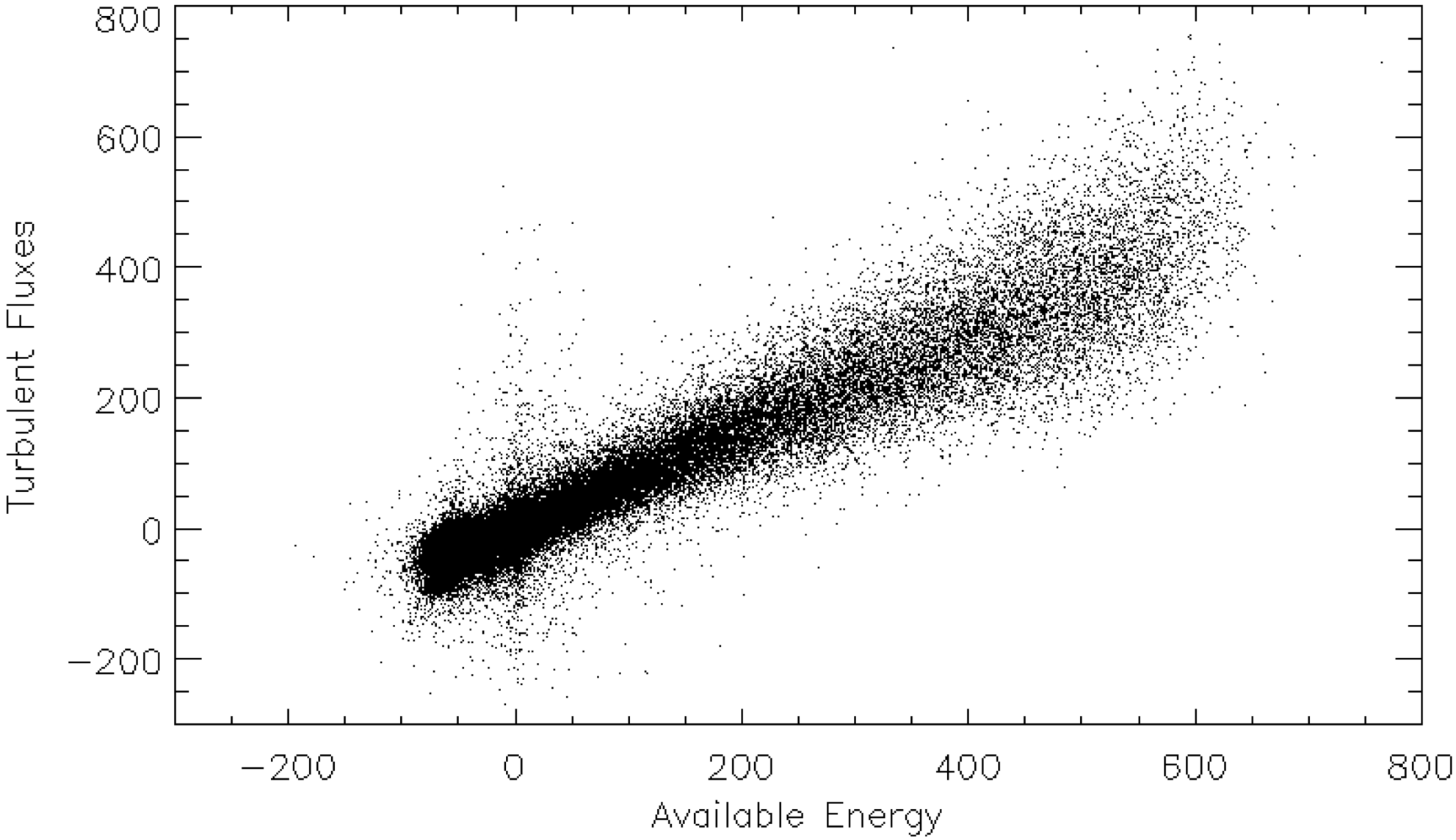

Solar incoming
Longwave emitted
Longwave incoming
Net Radiation
Solar reflected
500
400
300
200
100
0
−100
W m−2
0
5
10
15
20
Hour

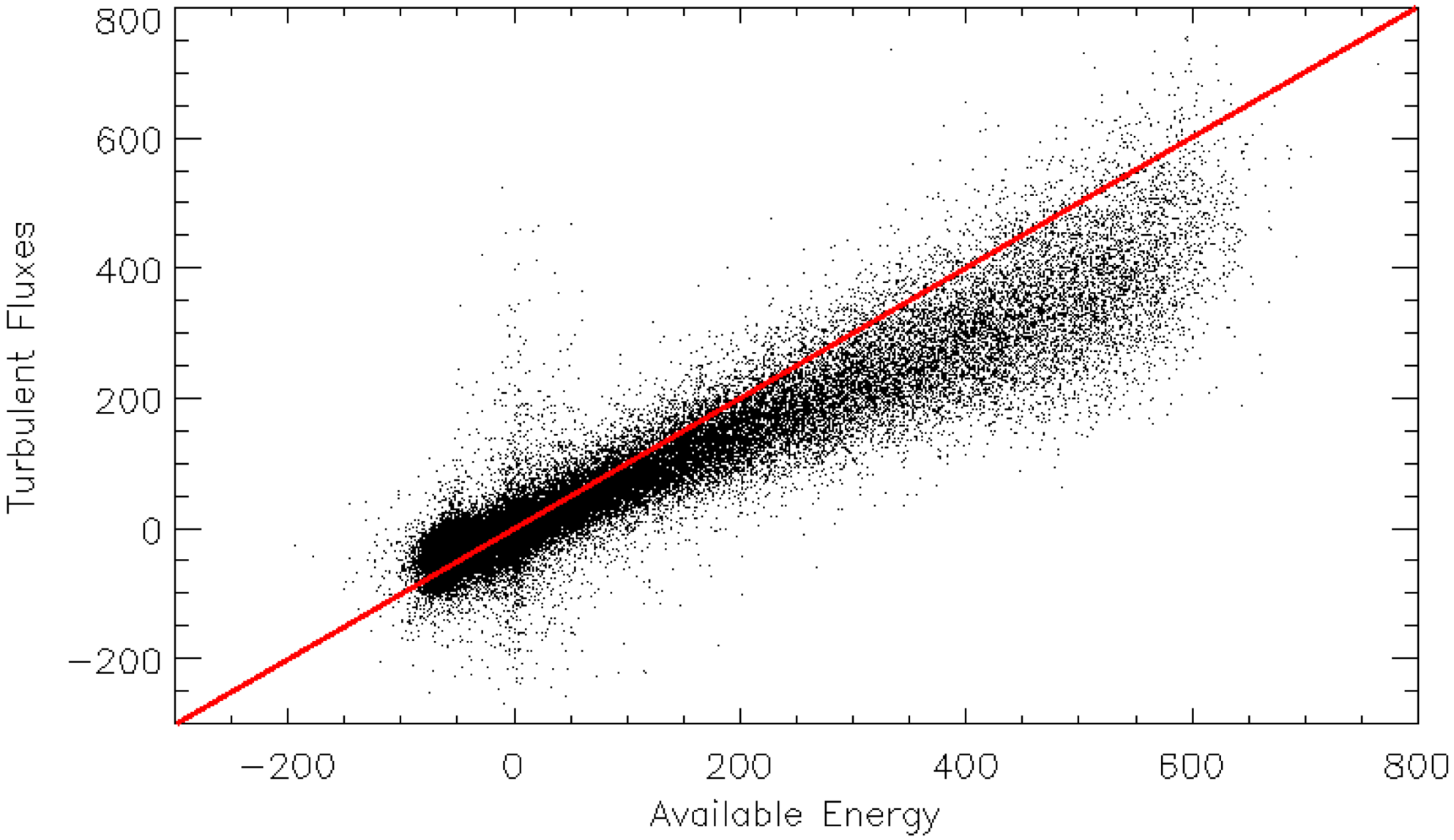

Net Radiation
300
200
100
0
−100
W m−2
0
5
10
15
20
Hour

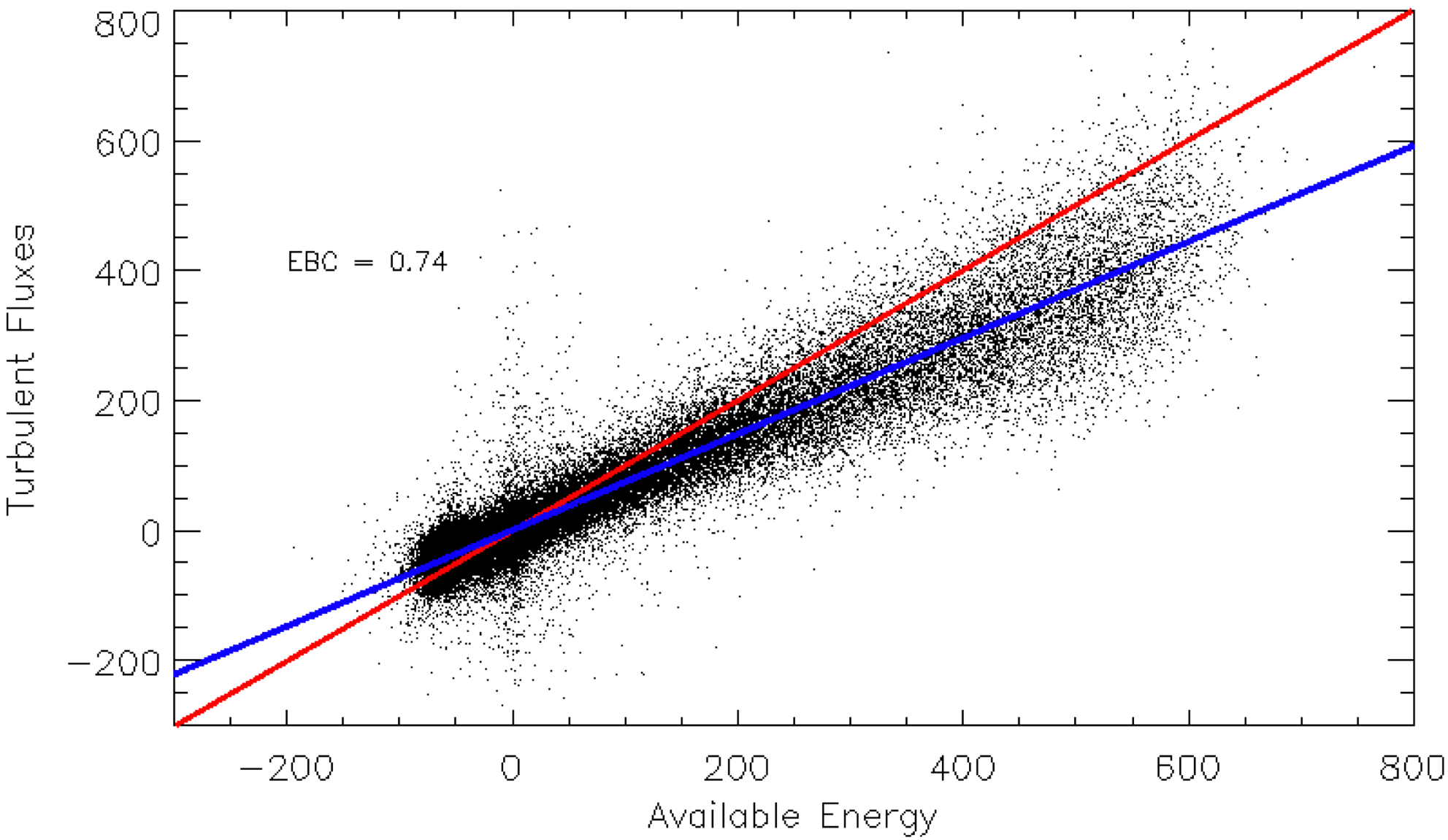

Net Radiation
Ground heat flux + storage
W m−2
300
200
100
0
−100
0
5
10
15
20
Hour


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


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


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


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

Energy Imbalance is Common But Variable in Space and Time

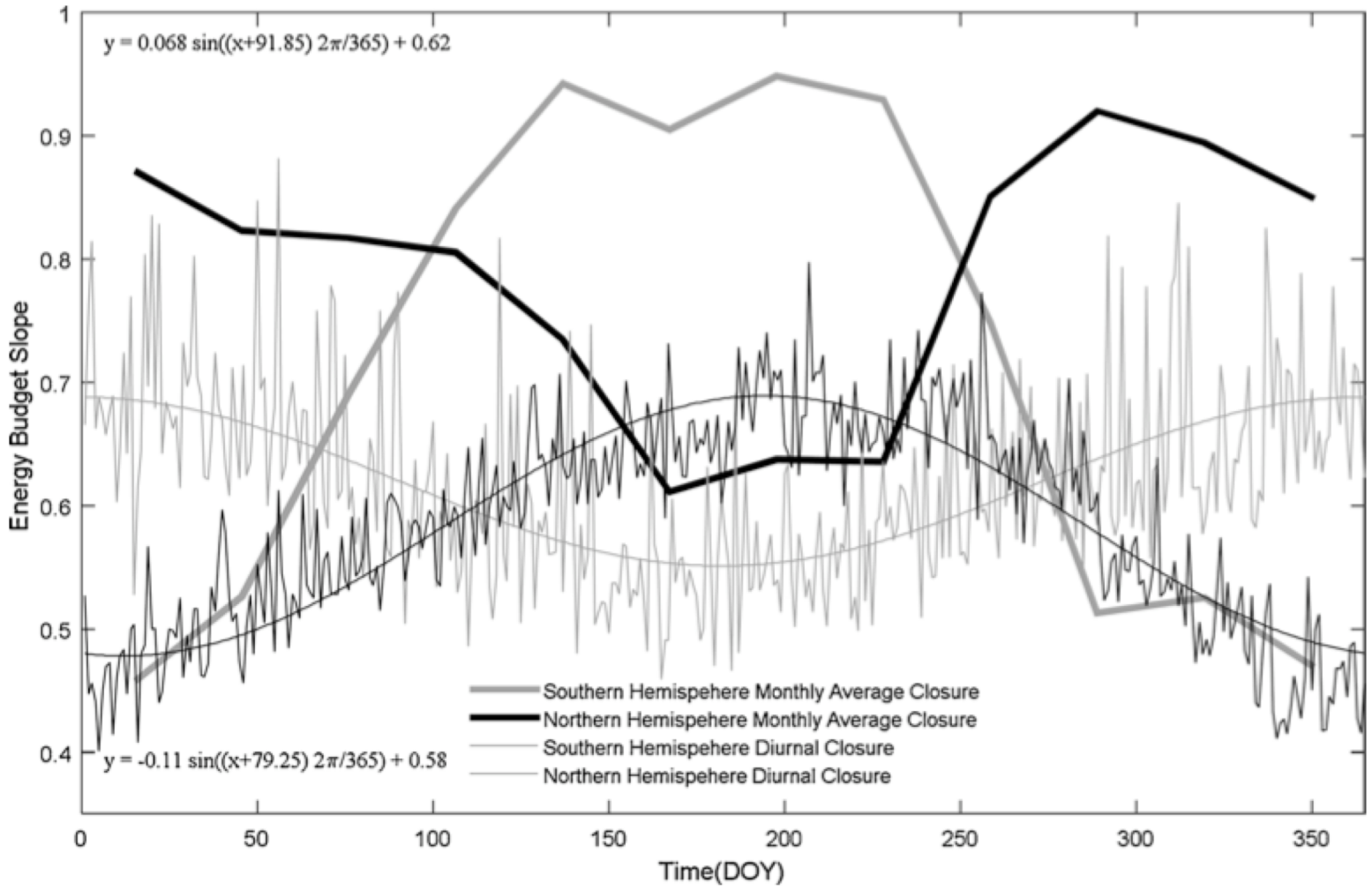


Fig. 7. Variation over an average year in FLUXNET2015 site energy closure, based on regression slope. Site separated by northern hemisphere (black, n = 132) and southern hemisphere (grey, n = 27). Bold lines shows monthly average regression energy closure at northern (bold black) and southern (bold grey)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

Reed et al., 2018, Ag For Met

WHY!?!?

Bad Instruments?

ELSEVIER

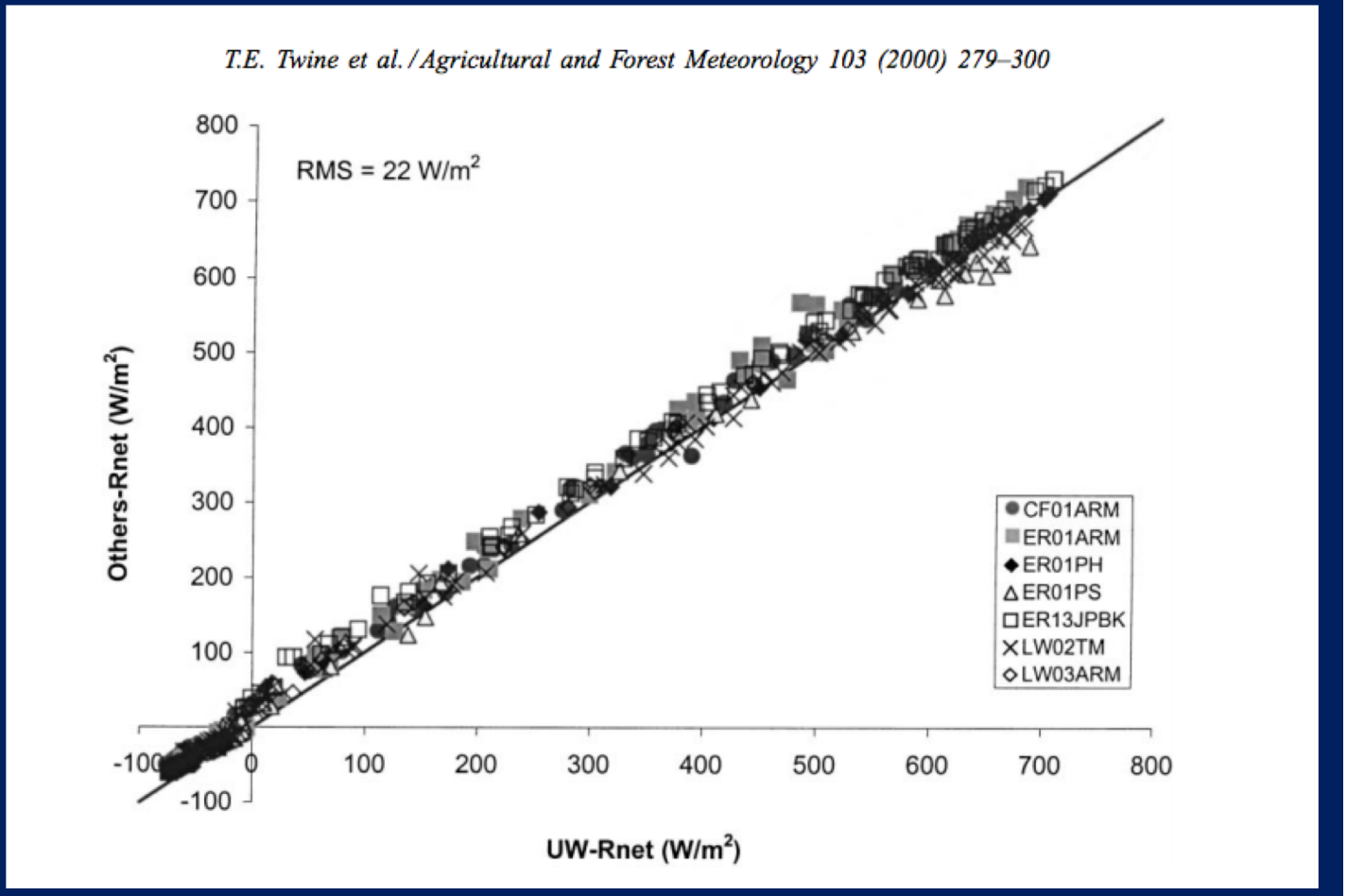
Agricultural and Forest Meteorology 103 (2000) 279–300

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/m^2

ARM
JPBK
PH
PS
mean

G (W/m^2)

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

Day of Year (fraction)

a)

RMS = 22 W/m^2

Others-LE (W/m^2)

UW-LE (W/m^2)

0
100
200
300
400
500

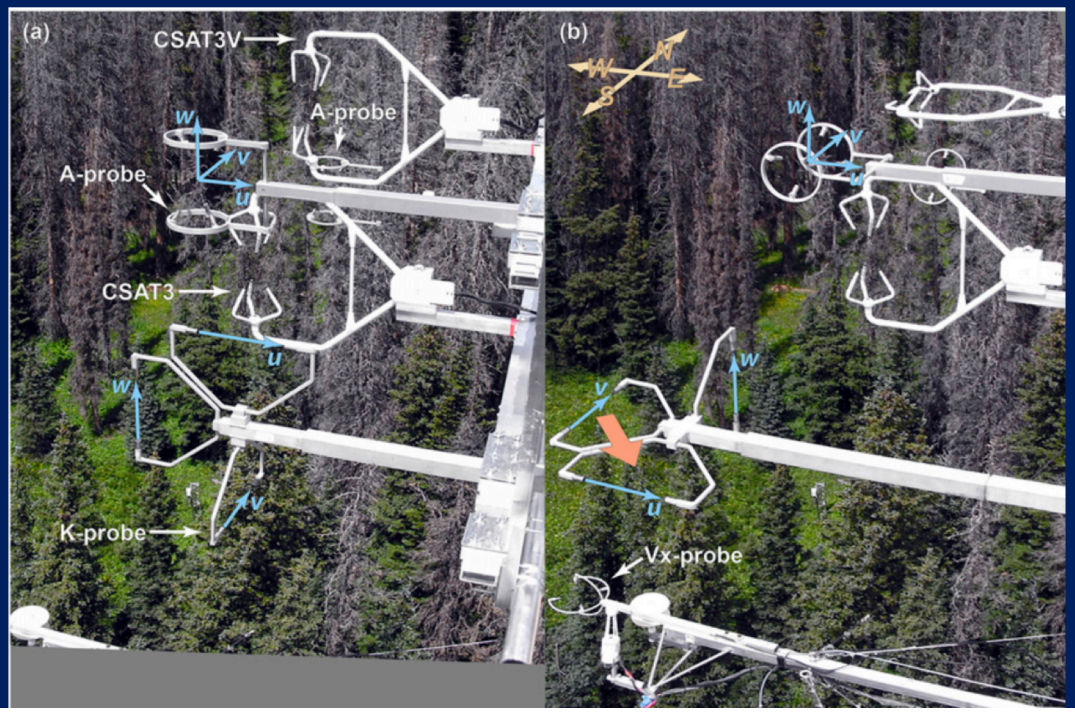
ER01JPBK172
ER01JPBK184
ER13JPBK

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

JOHN M. FRANK

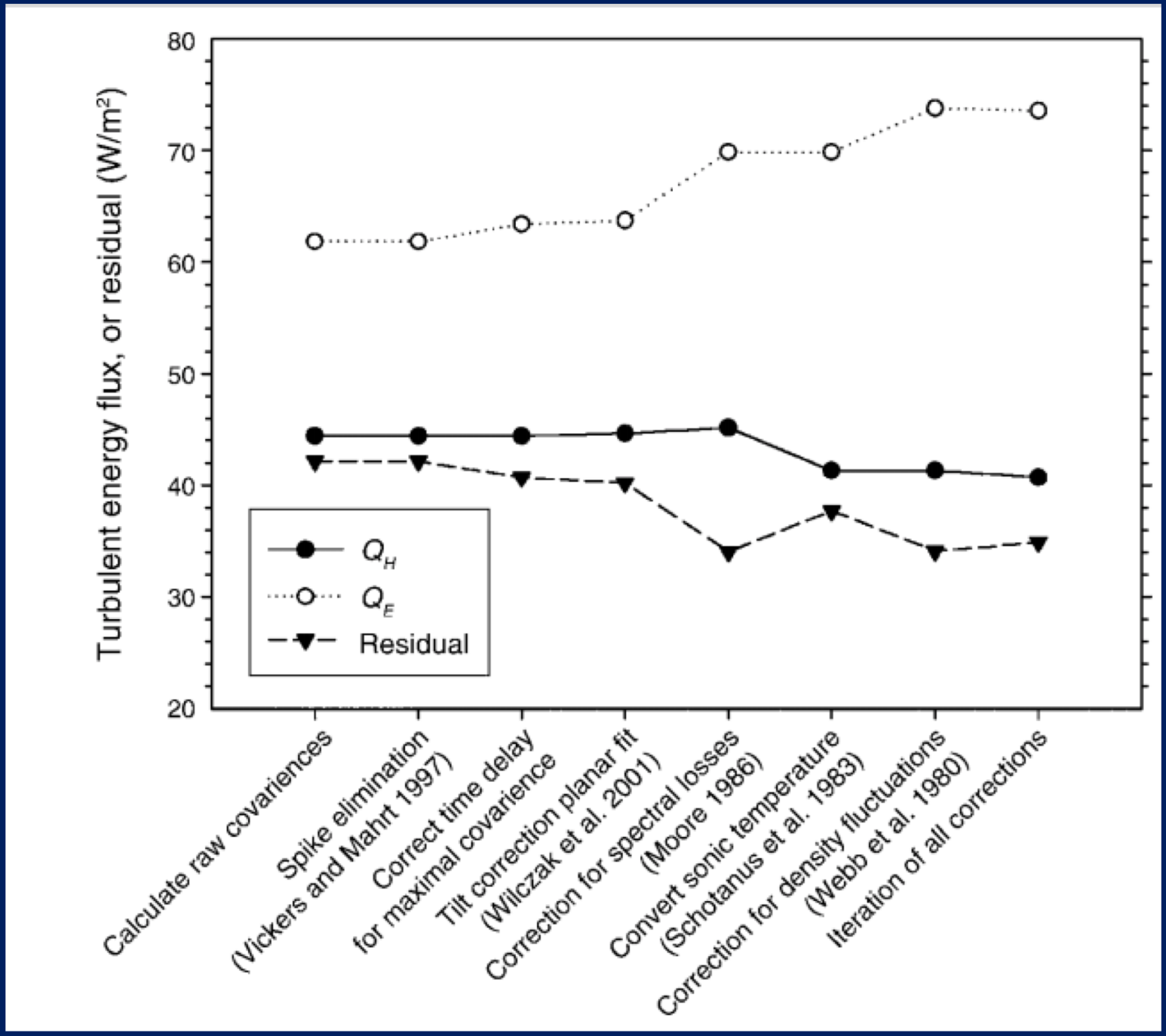
J. Atmos Ocean Tech, 2016

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



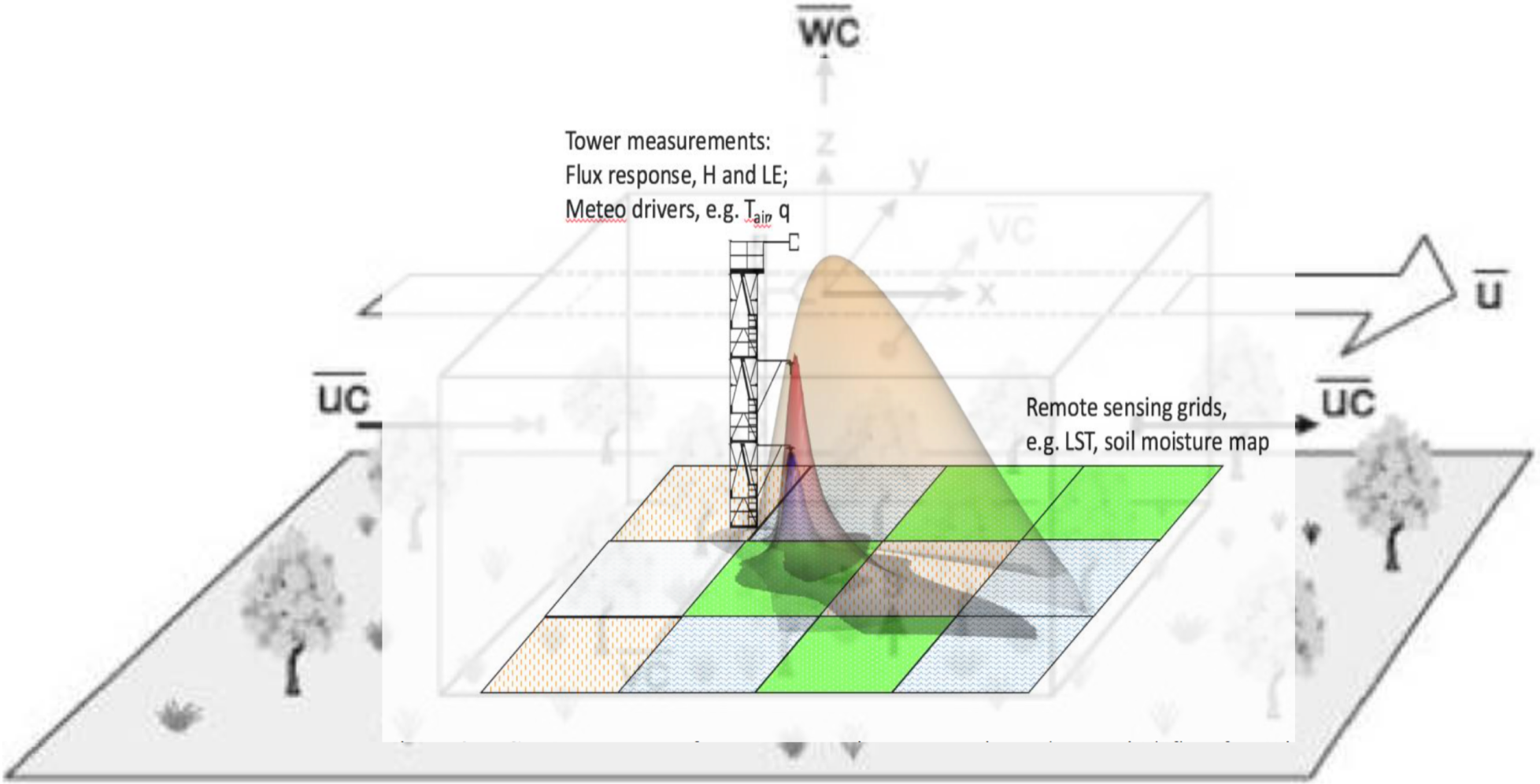
NO!

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

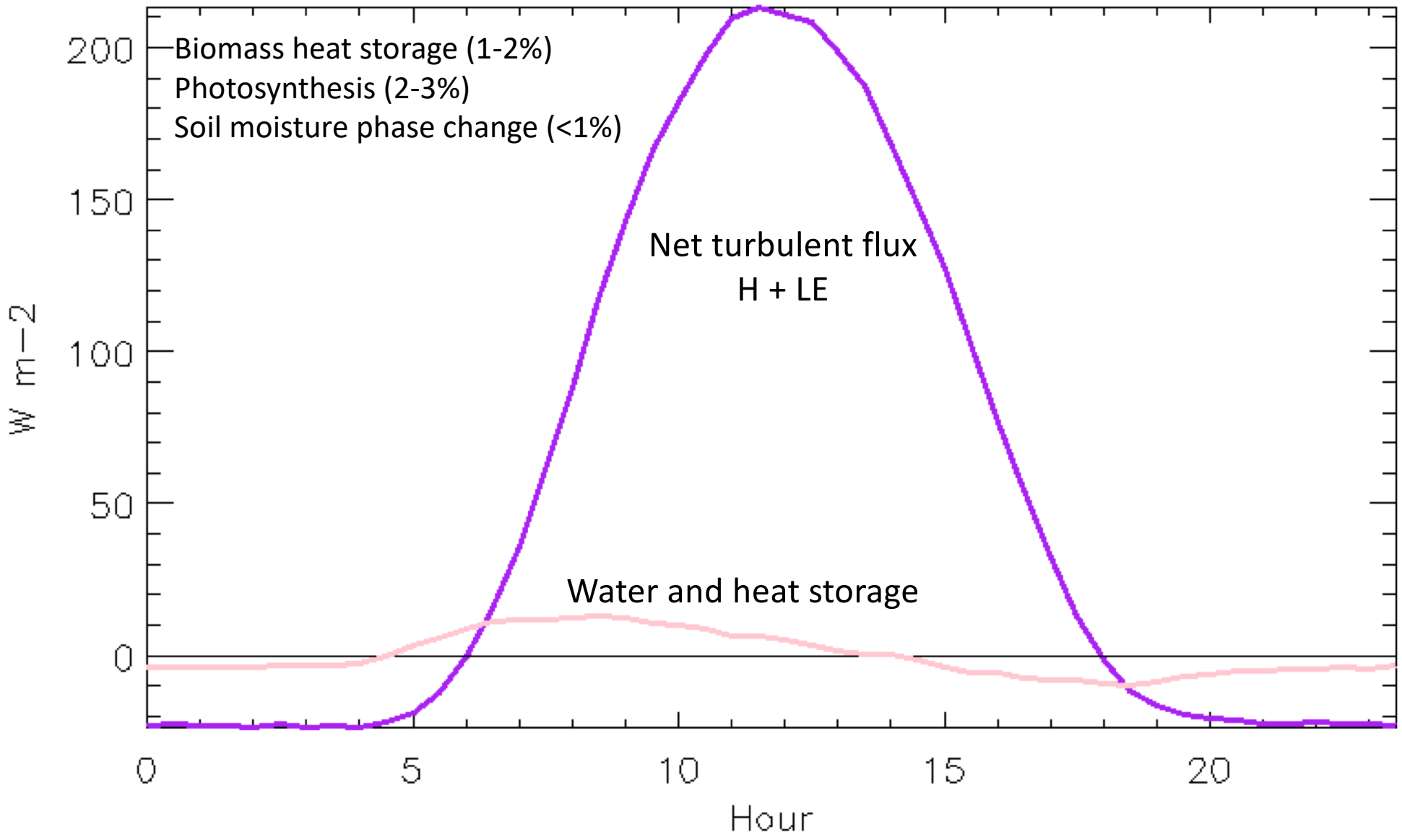
a


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

NO!

Towers too tall?

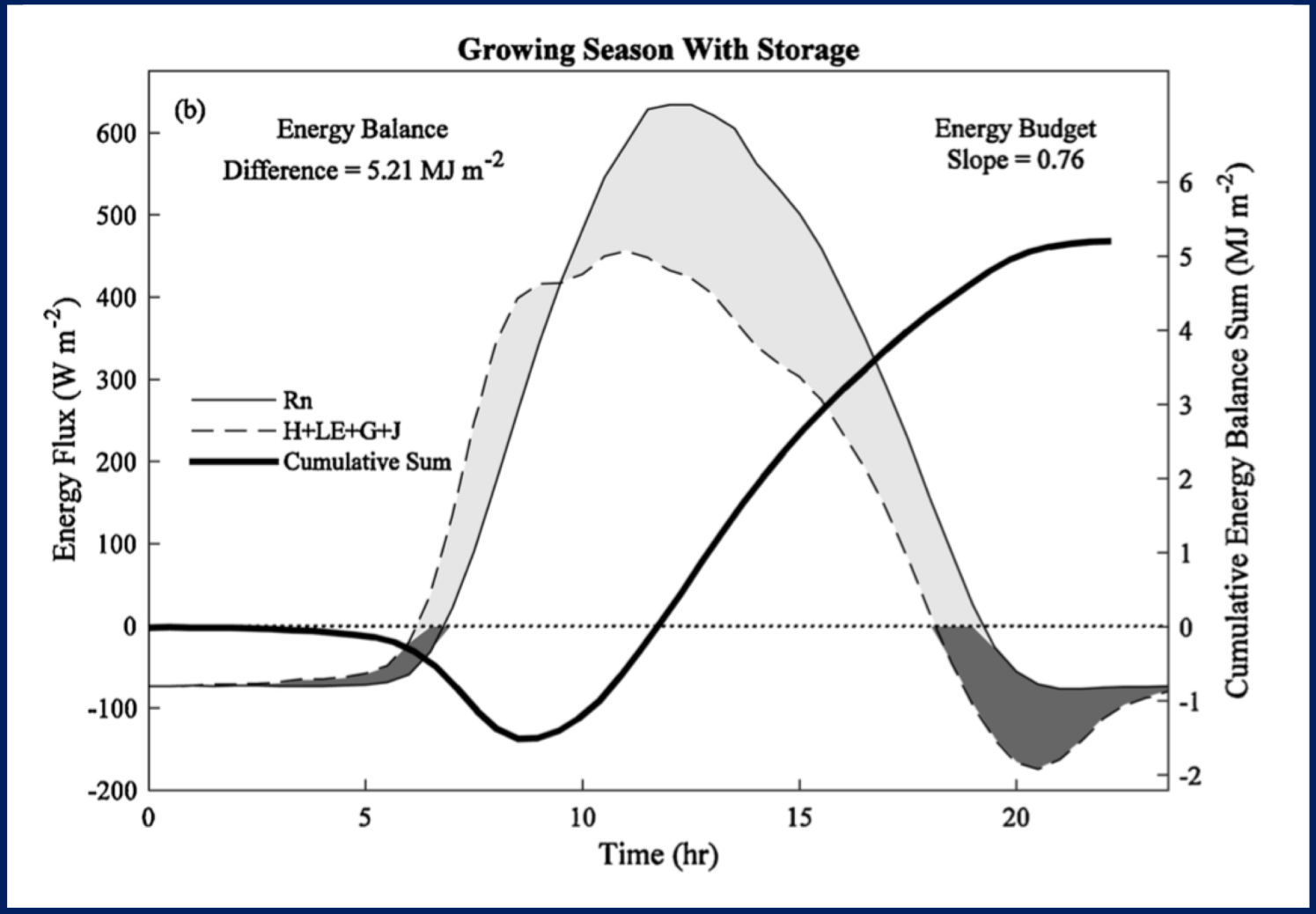
$$\int_0^h \overline{\frac{\partial c}{\partial t}}\,\mathrm{d}z + \overline{w'c'}(h) = \bar{S}$$


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?

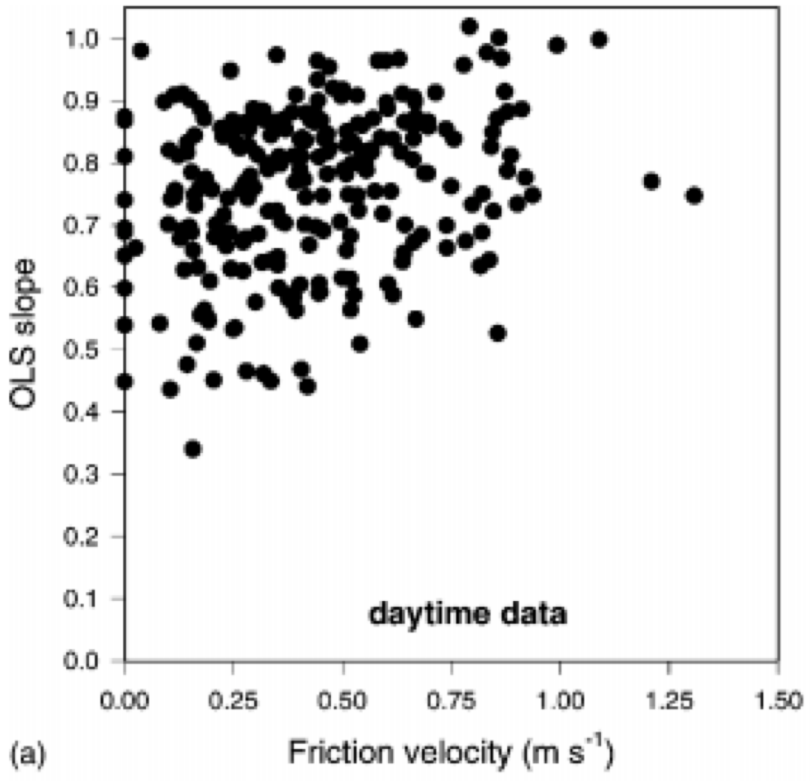
ELSEVIER

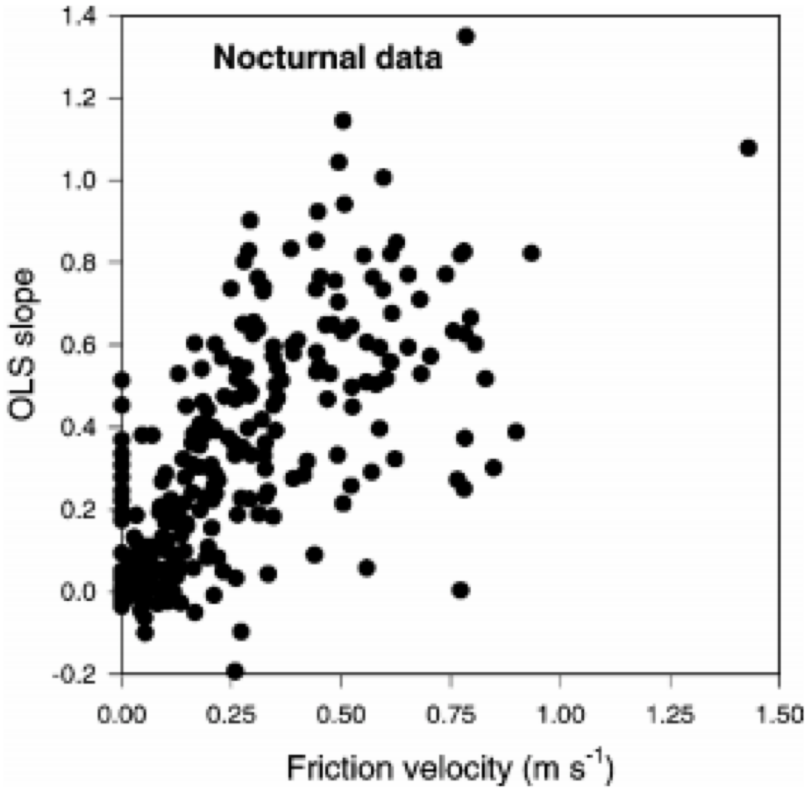
Agricultural and Forest Meteorology 113 (2002) 223–243

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]



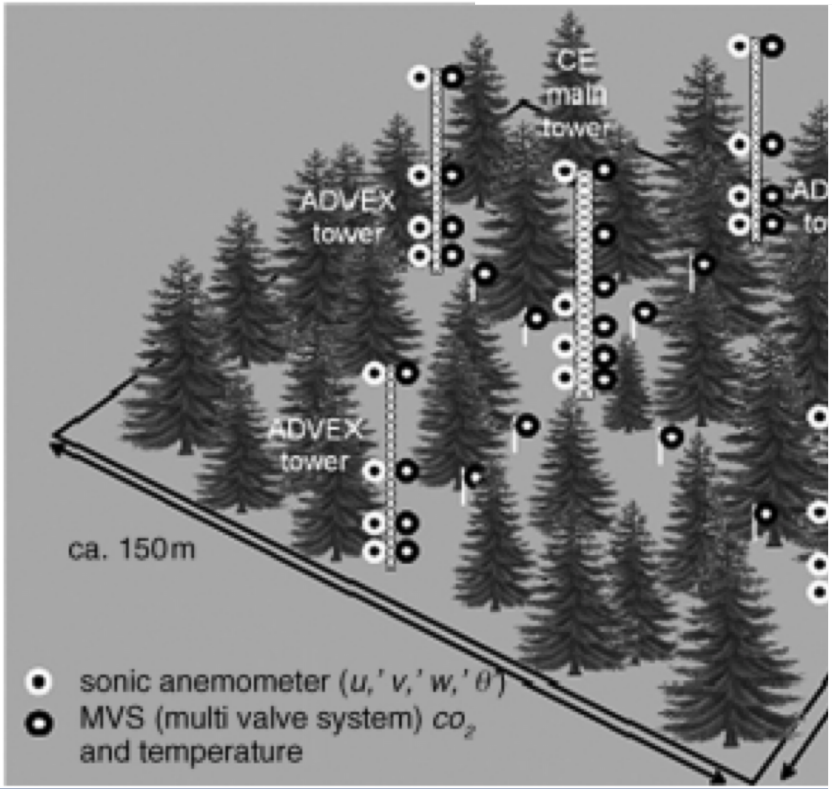


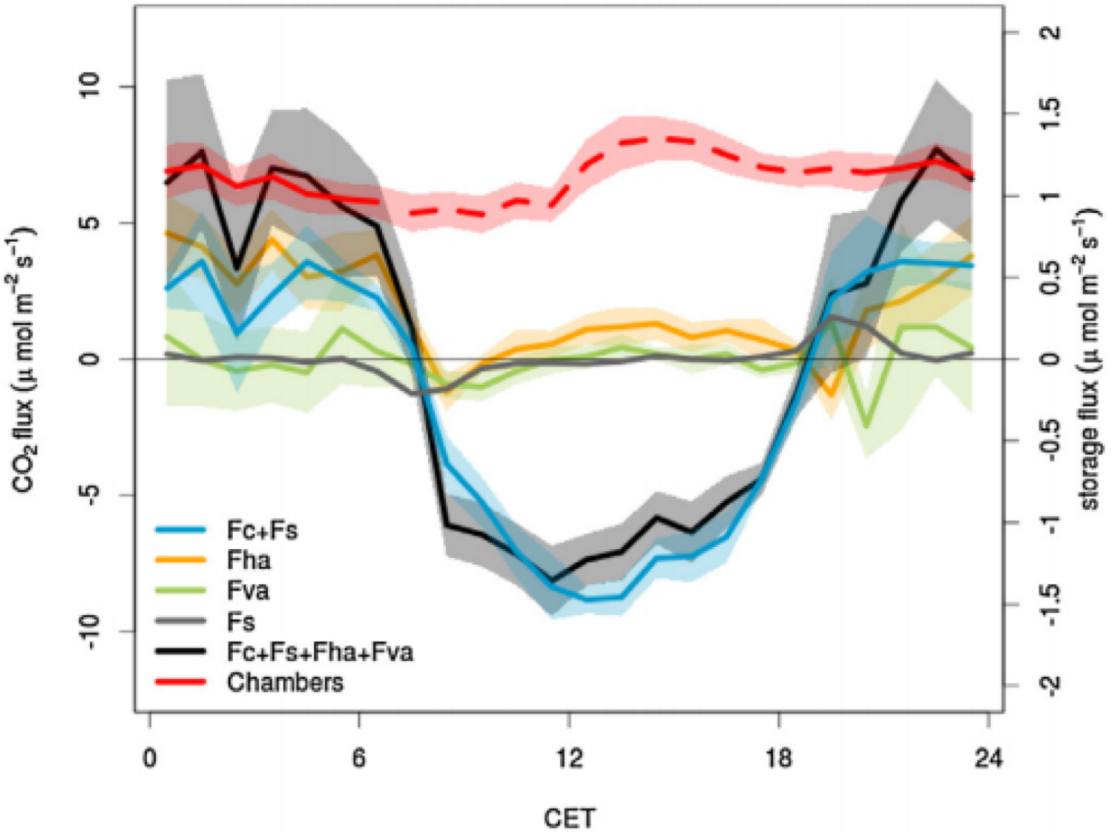
Comparison of horizontal and vertical advective CO_2 fluxes at three forest sites

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

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]

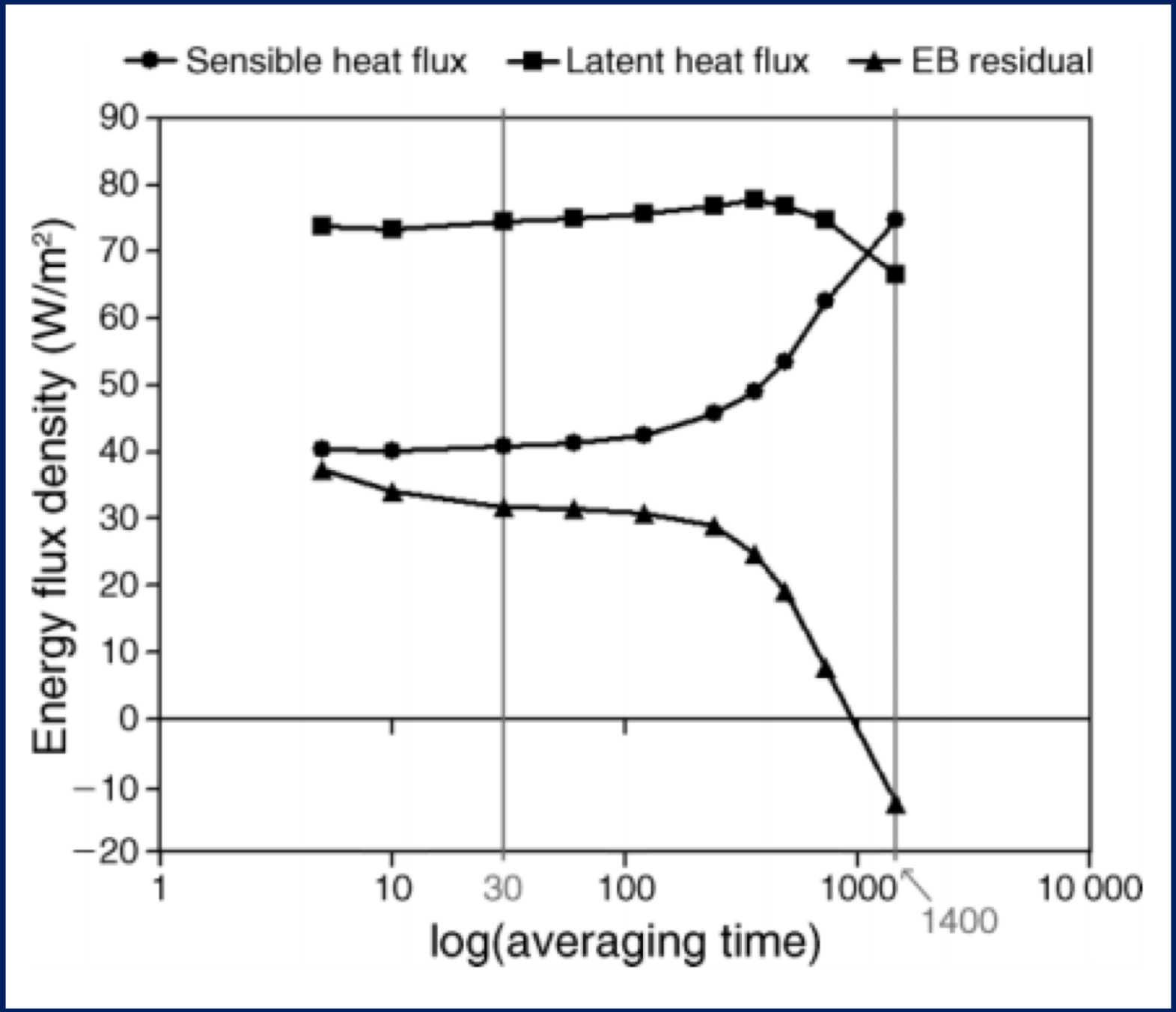




NO!

Mesoscale fluxes?

- Violation of assumptions:
  - Ergodicity
  - Homogeneity
  - Stationarity

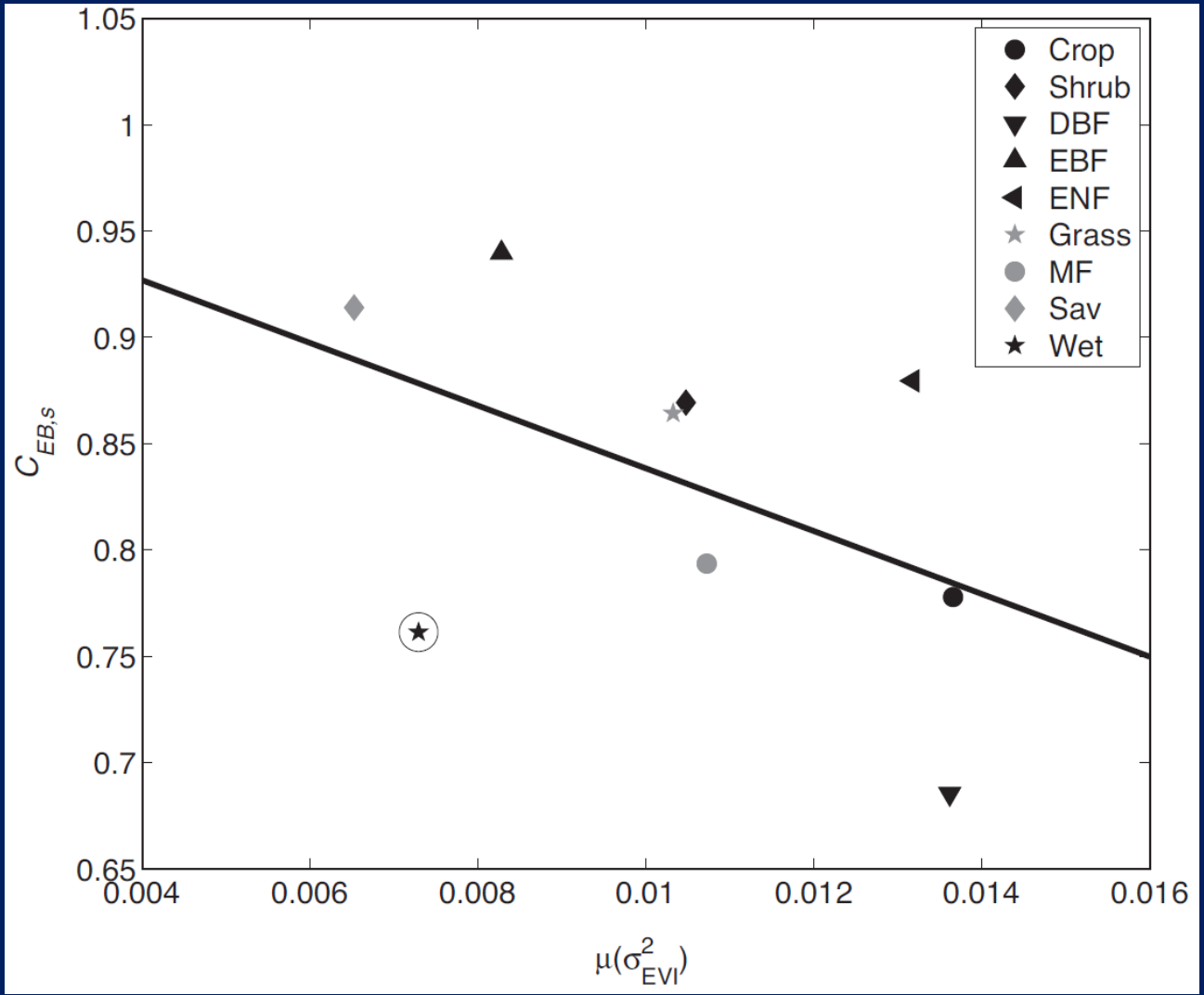

Sensible heat flux
Latent heat flux
EB residual
Energy flux density (W/m²)
90
80
70
60
50
40
30
20
10
0
−10
−20
1
10
30
100
1000
10 000
1400
log(averaging time)

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

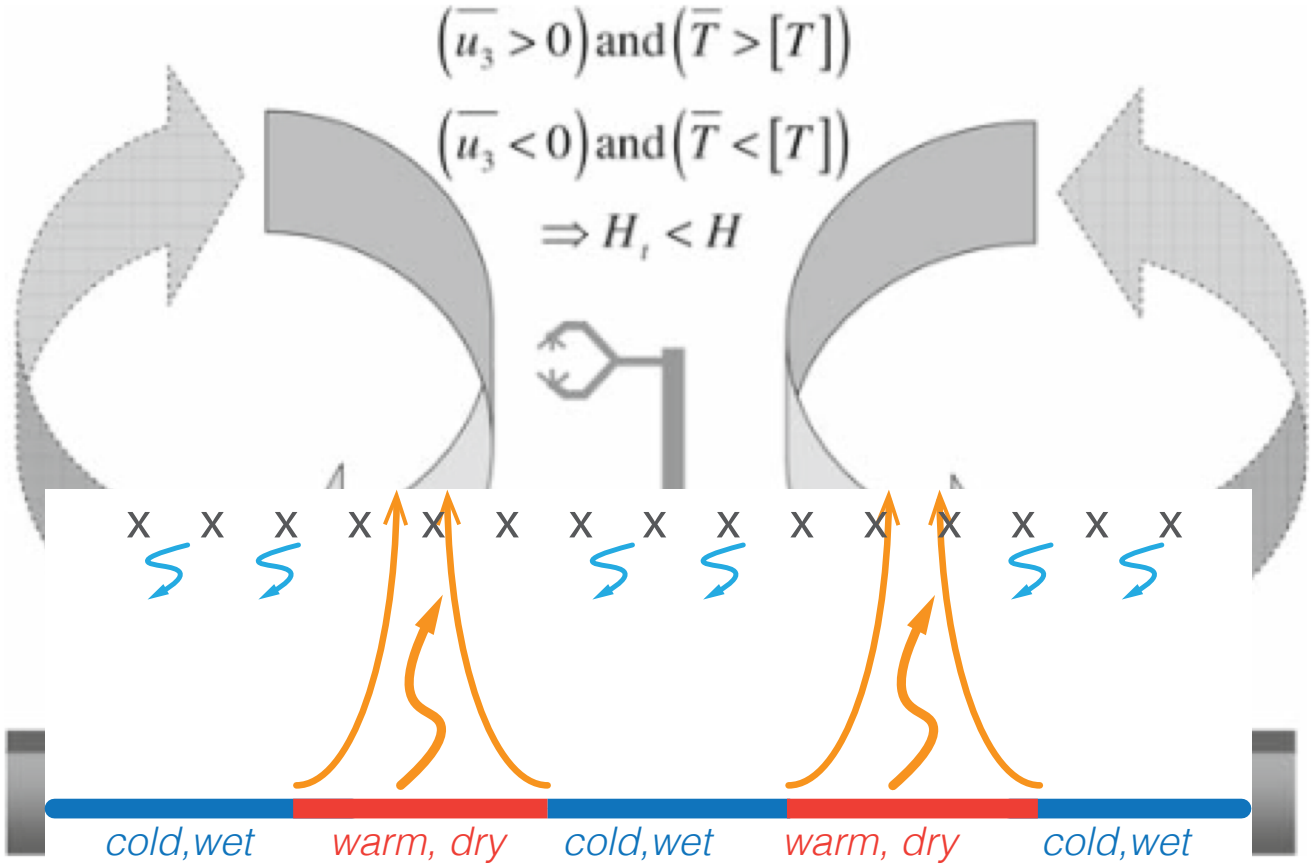


Fig. 1 Schematic showing how quasi-stationary eddies cause an underestimation of the total sensible heat flux H when using the temporal EC method to calculate H_t. The single-point sonic measurement in the centre is not able to resolve quasi-stationary eddies

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

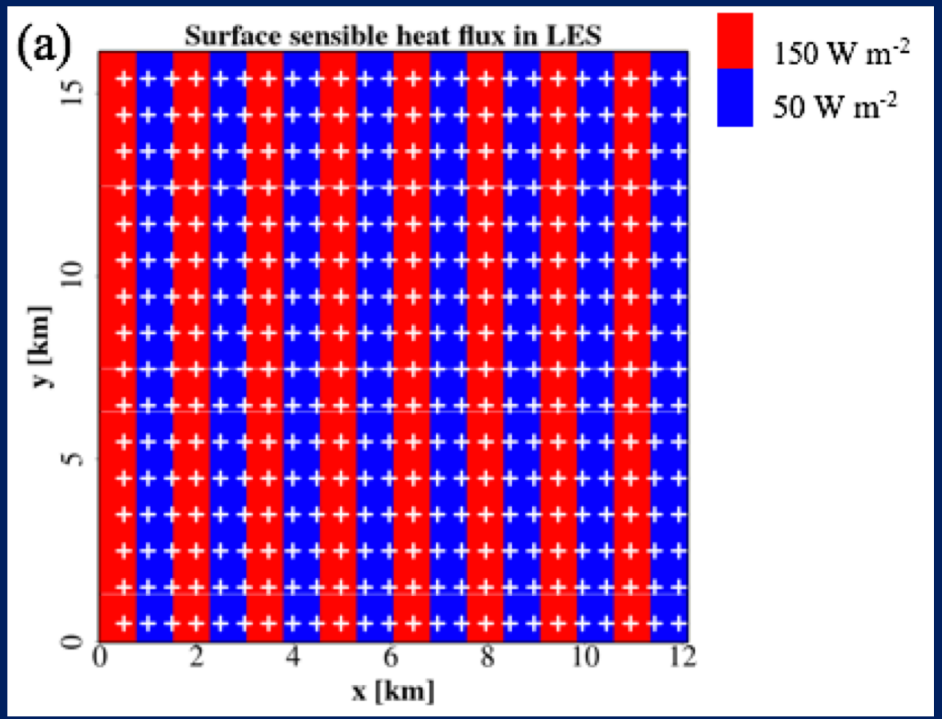
Authors: Ke Xu[1,2,*], Matthias Sühring[2], Stefan Metzger[3,1], David Durden[3], Ankur R Desai[1]

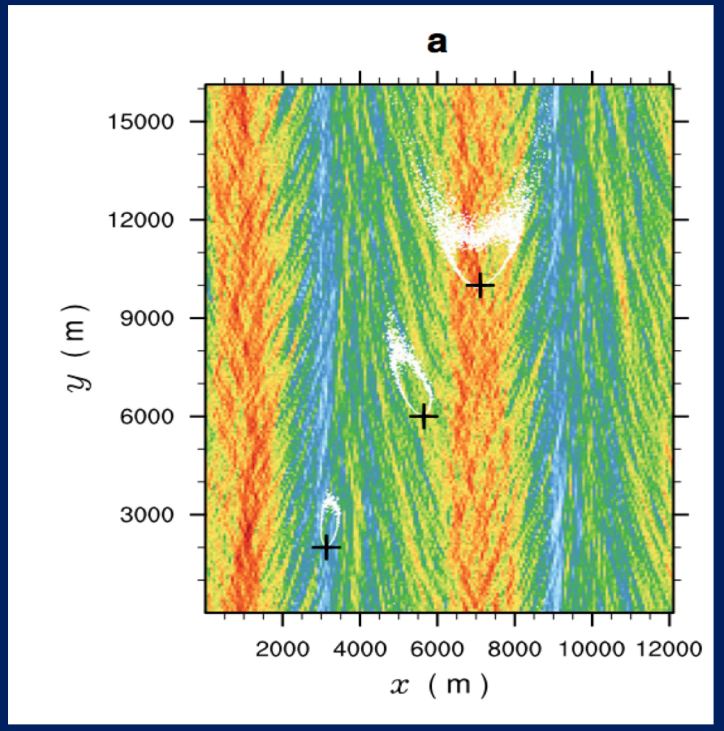
Boundary-Layer Meteorology
https://doi.org/10.1007/s10546-018-0387-x

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

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

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]

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

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

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

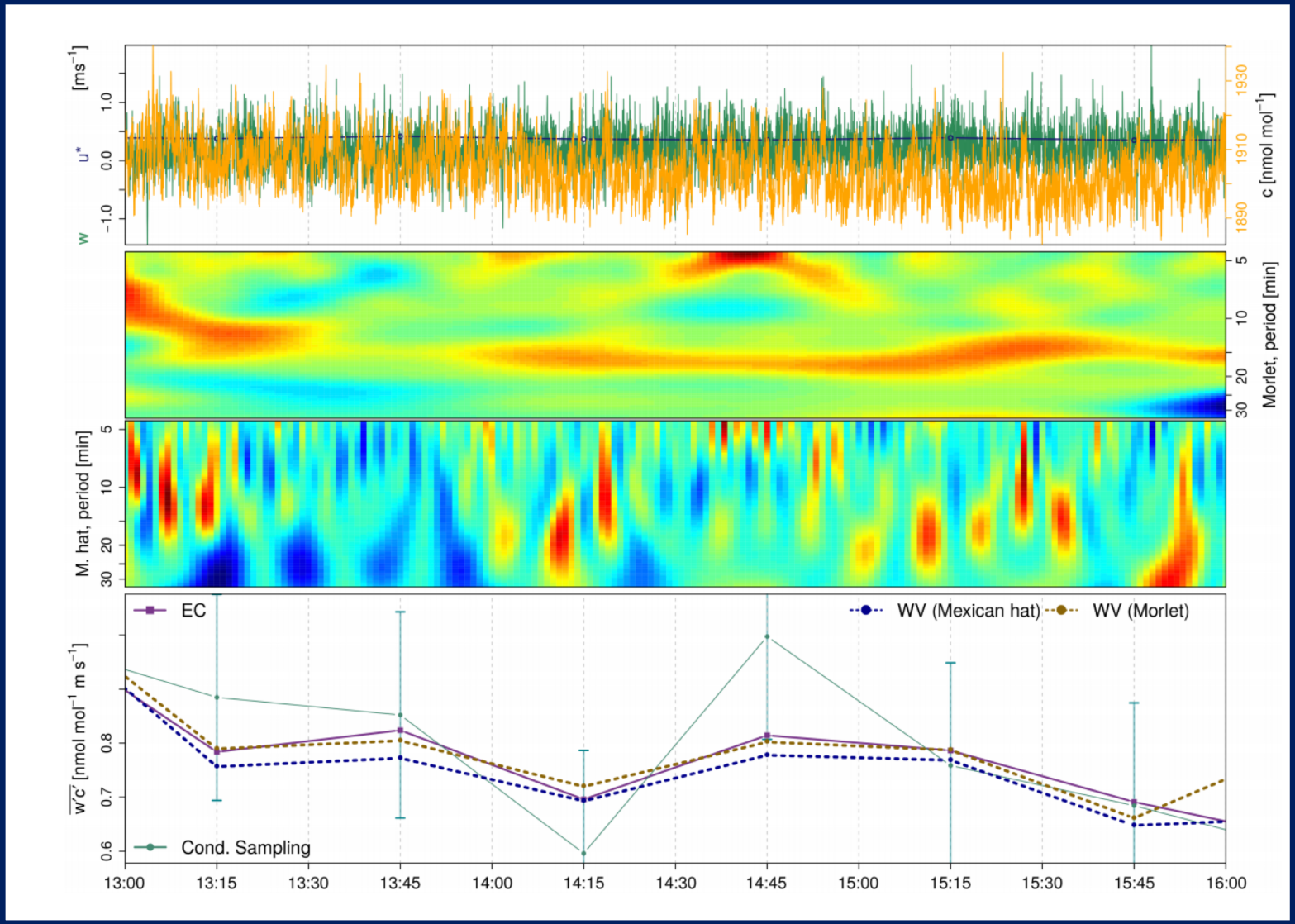
M. Mauder · R. L. Desjardins · E. Pattey · Z. Gao · R. van Haarlem

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

Flux calculation of short turbulent events – comparison of three methods

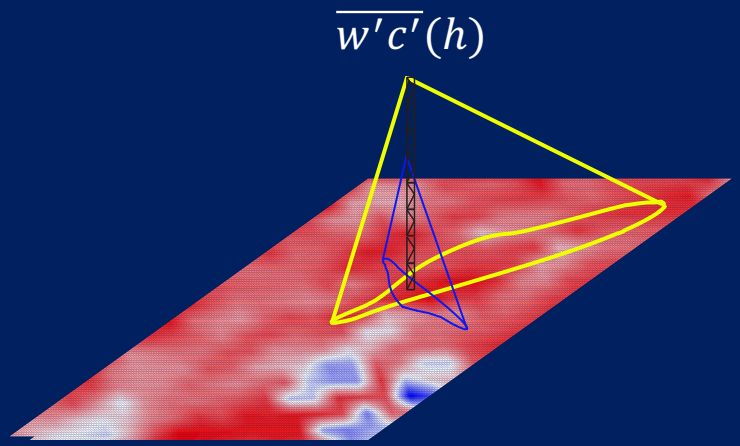
Carsten Schaller[1,2,a], Mathias Göckede[2], and Thomas Foken[1,3]

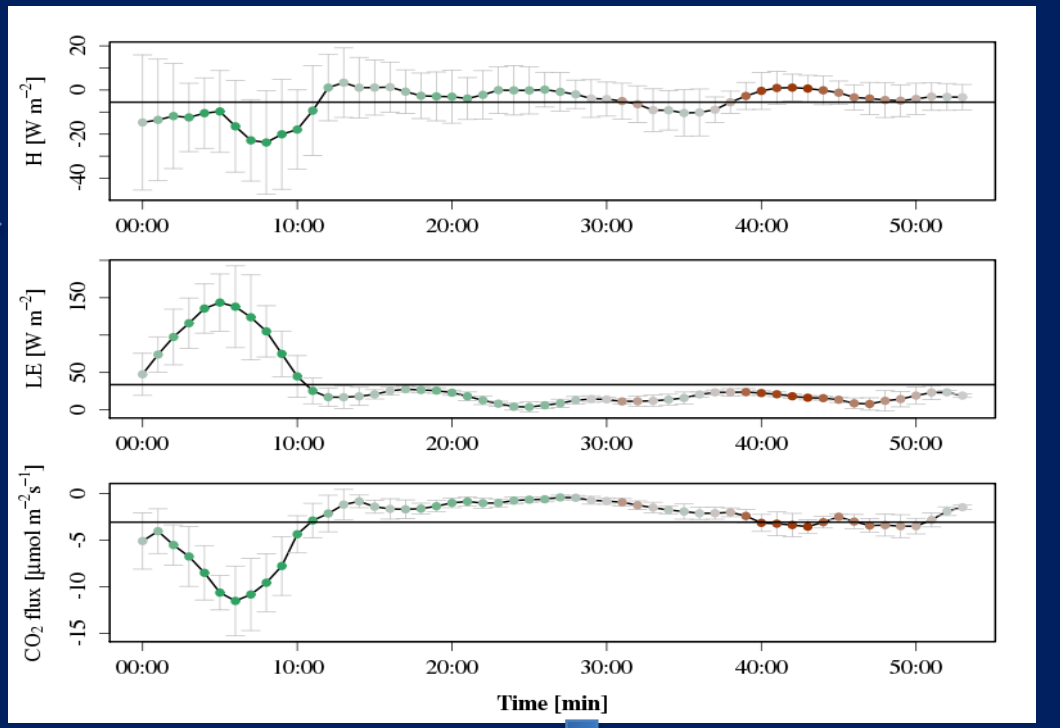
Atmos Meas Tech 2017



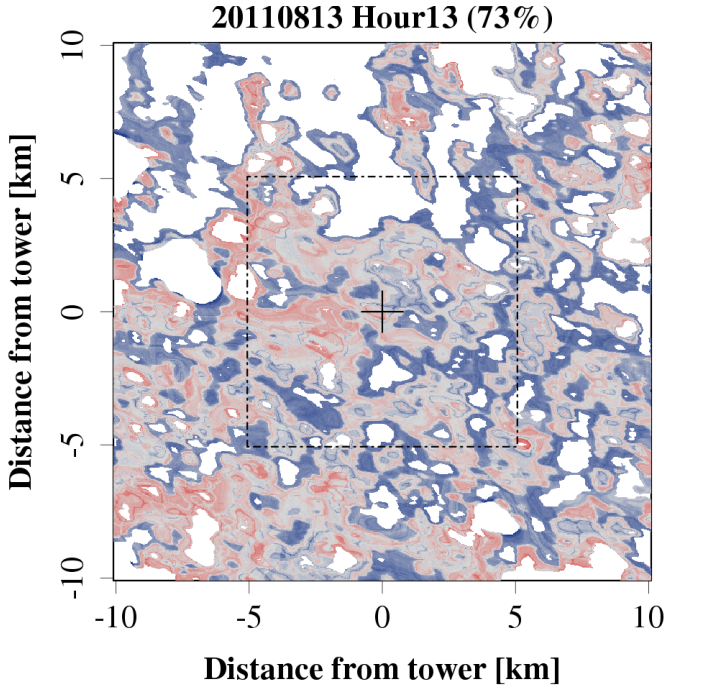
Environmental Response Function (ERF) scaling method

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

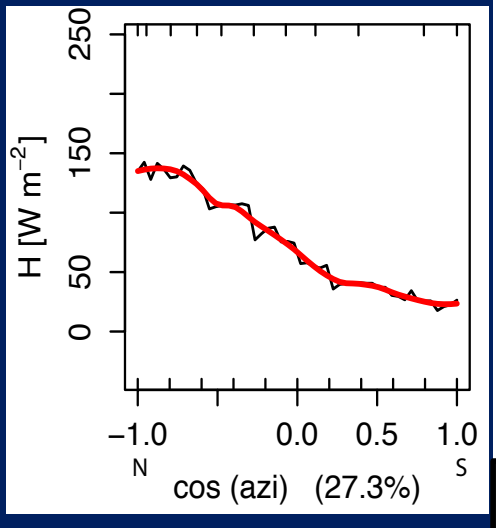


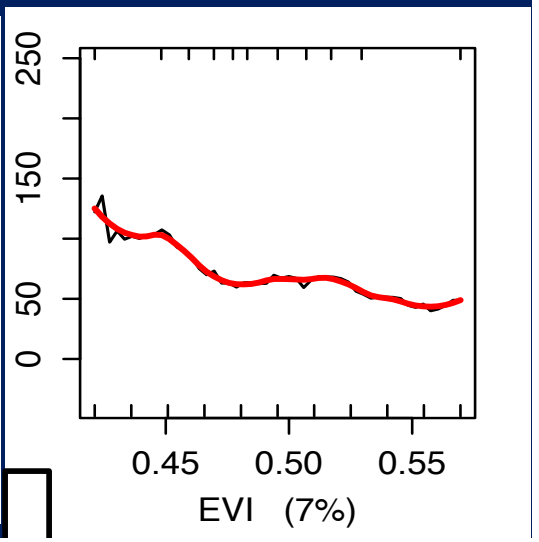


Domain-projected turbulent flux at measurement level



Extracted relationships





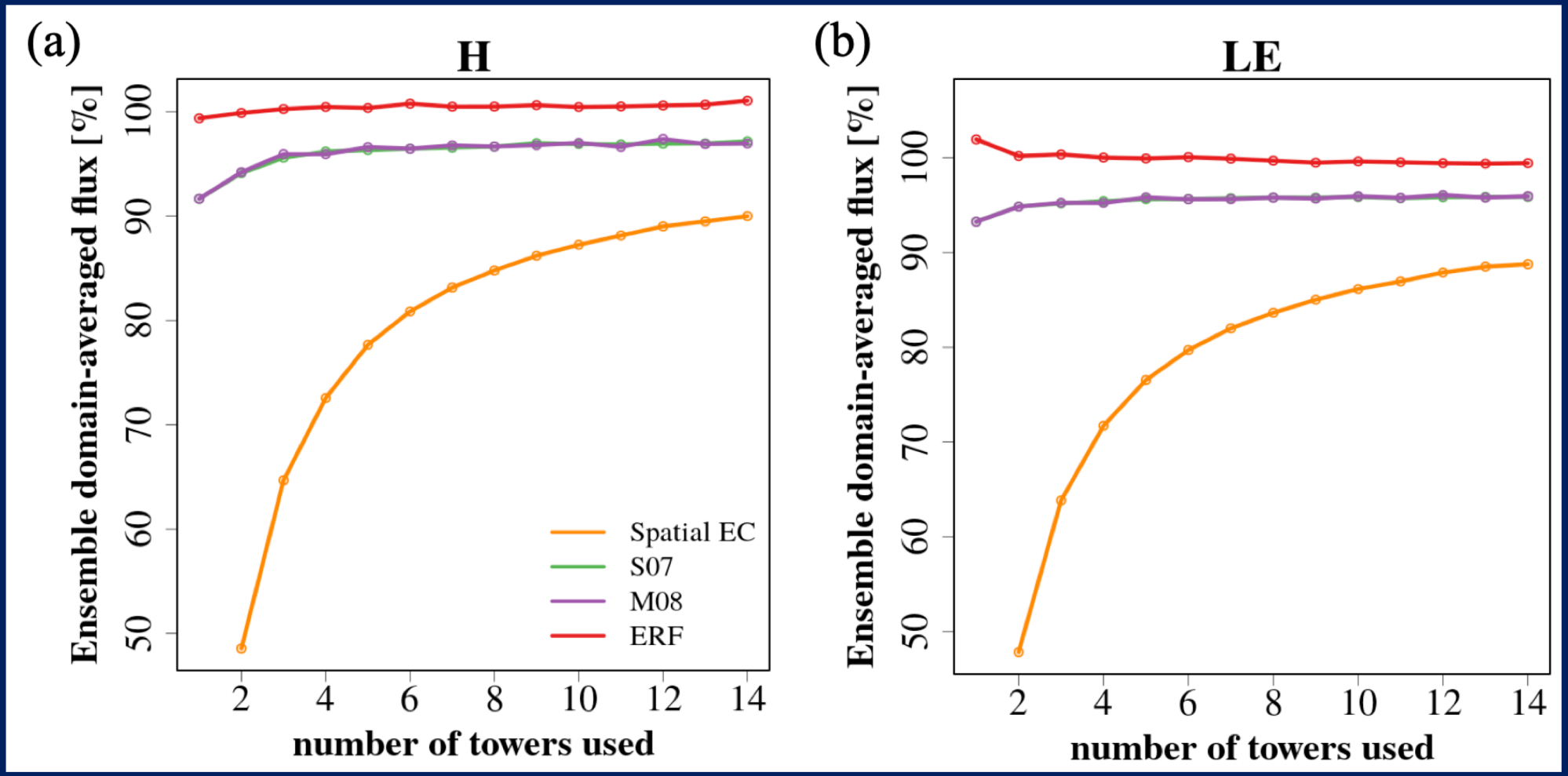


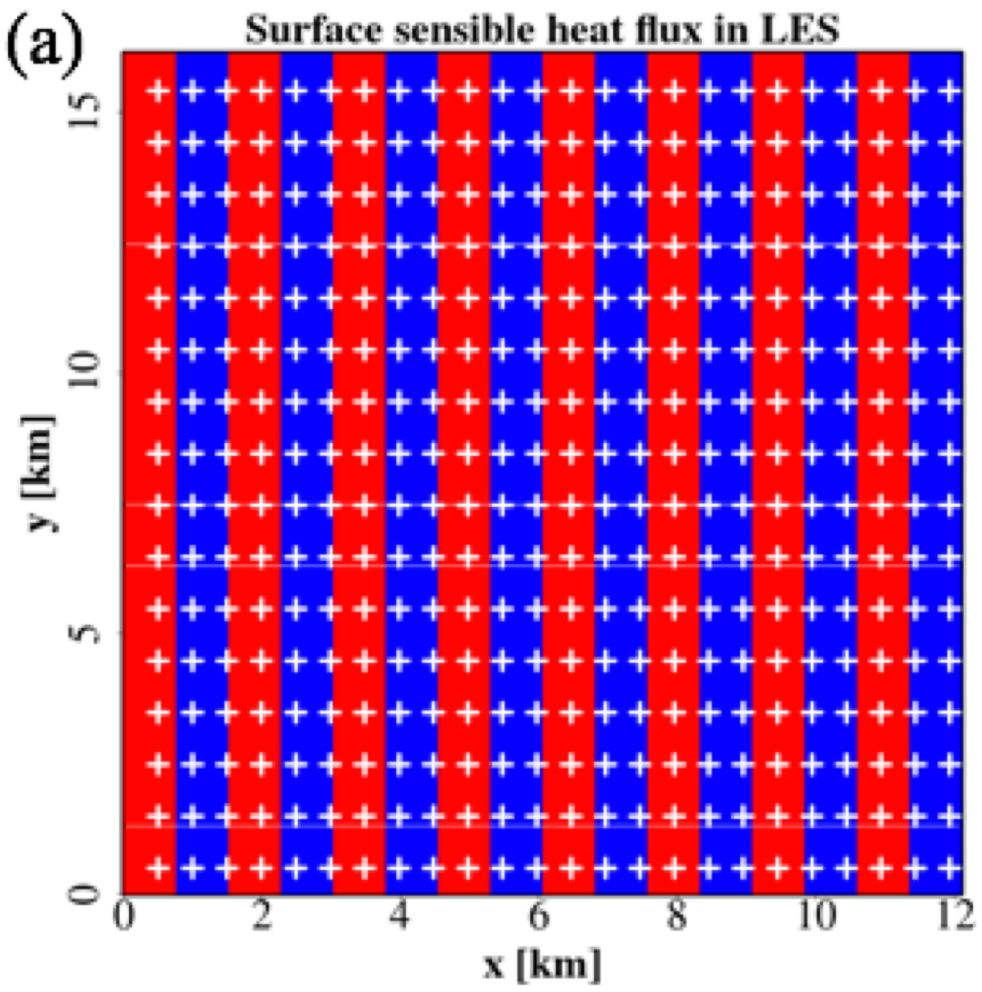
Fig. 3. Ensemble-averaged heat fluxes at 49 m using 1 to 14 virtual towers, randomly chosen from the 320 locations depicted in Figure 1, using different upscaling approaches: spatial eddy-covariance (spatial EC), spatio-temporal eddy-covariance approach (S07 and M08), and Environmental Response Function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

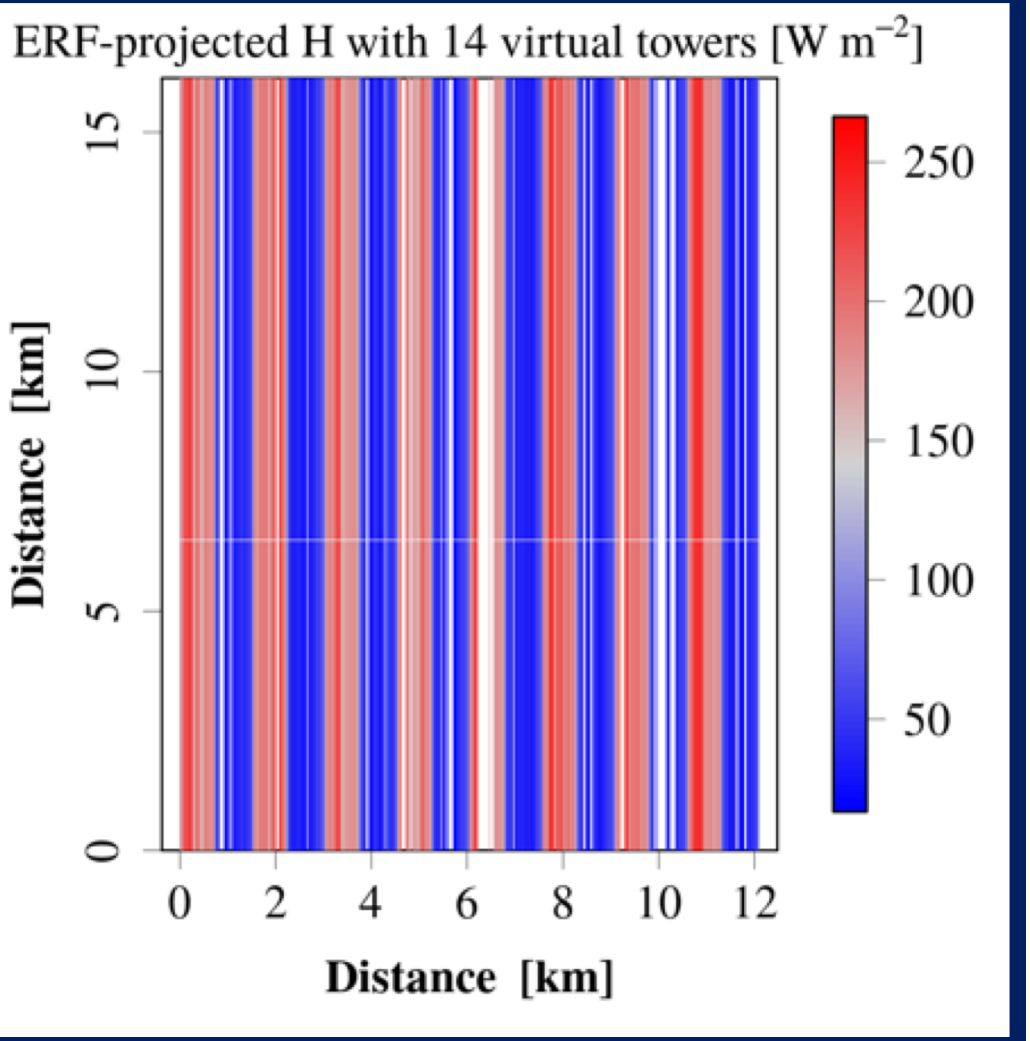
“Secondary circulation” = Mesoscale flux!

	Turbulent flux	Energy at long transporting scales	Atmospheric skewness	Sum
H	91.3%	8.4%	1.6%	101.3%
LE	93.8%	8%	-2.4%	99.4%
H + LE	92.7%	8.2%	-1.1%	99.8%

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
EGU

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

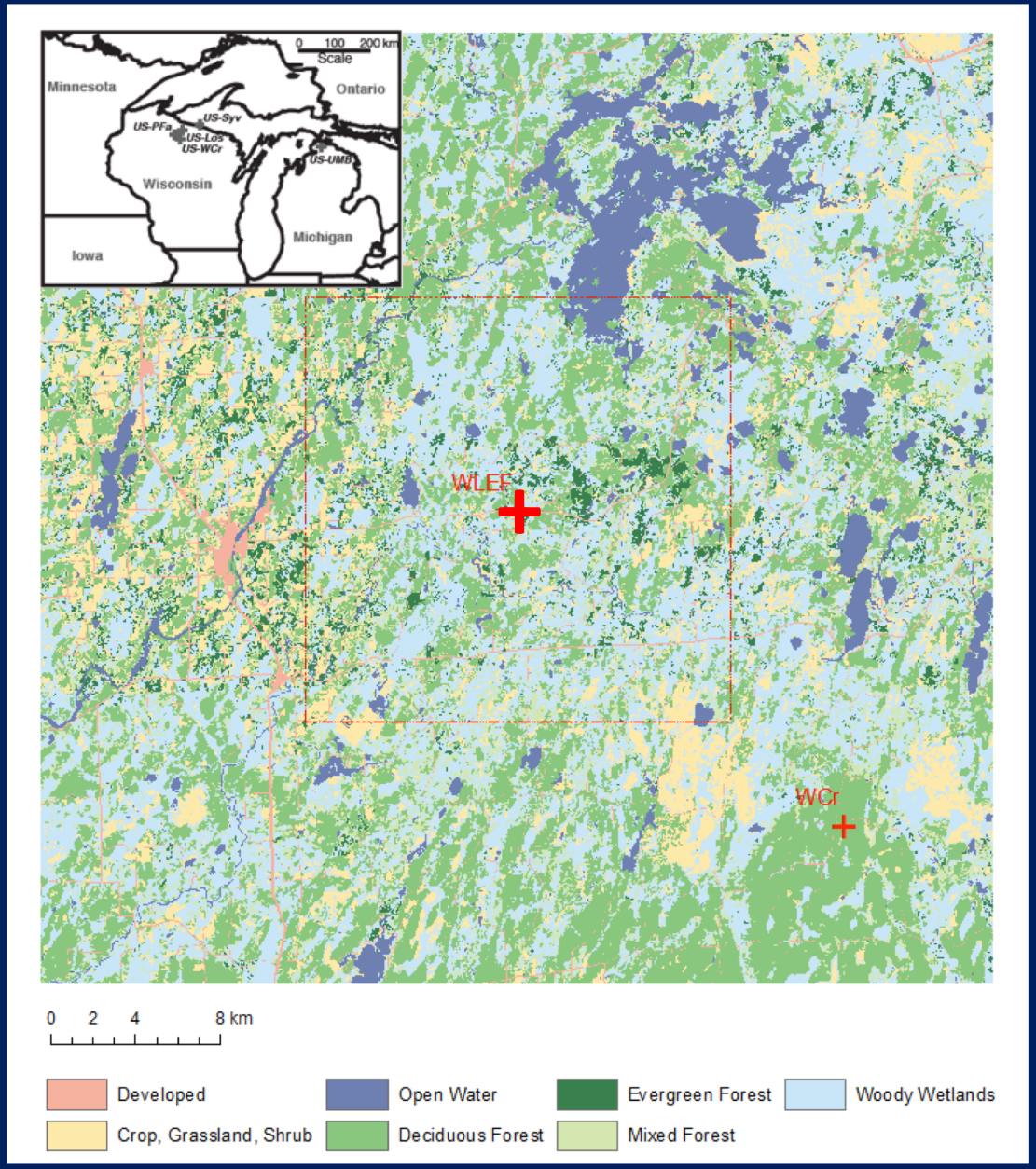
Stefan Metzger[1,2], David Durden[1], Cove Sturtevant[1], Hongyan Luo[1], Natchaya Pingintha-Durden[1], Torsten Sachs[3], Andrei Serafimovich[3], Jörg Hartmann[4], Jiahong Li[5], Ke Xu[2], and Ankur R. Desai[2]

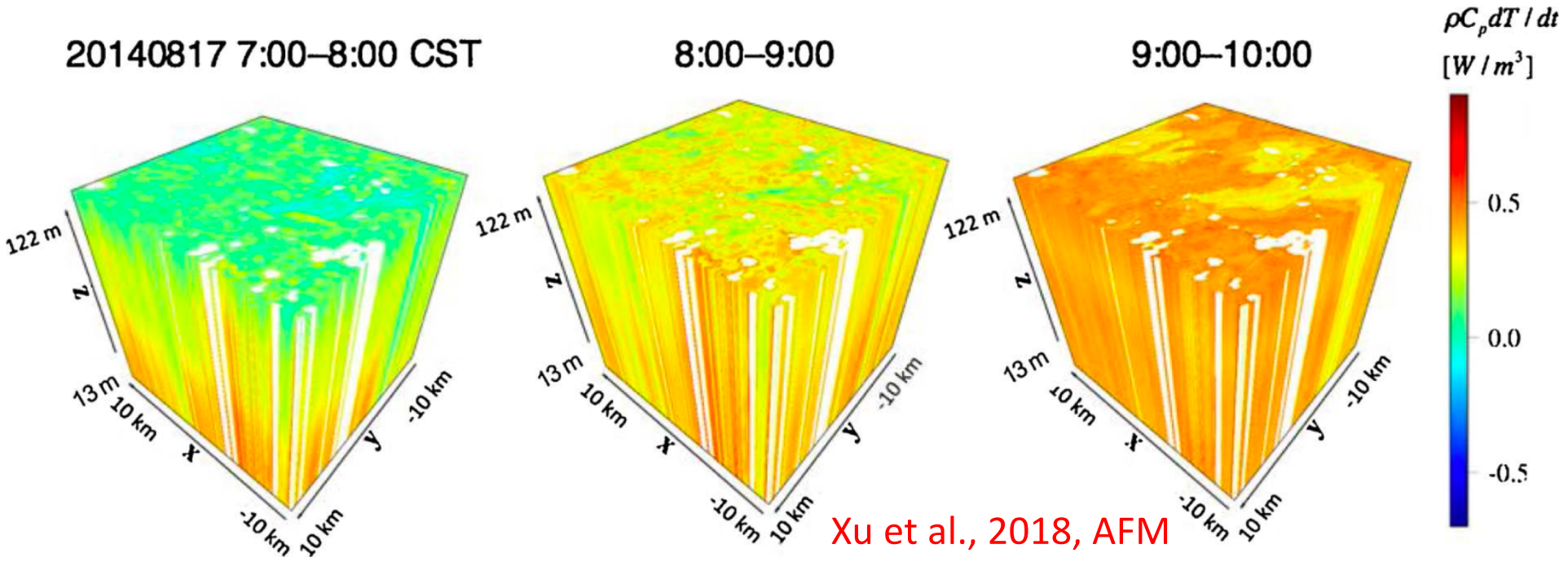
[1]National Ecological Observatory Network, Battelle, 1685 38th Street, Boulder, CO 80301, USA

Park Falls/Chequamegon National Forest region, WI

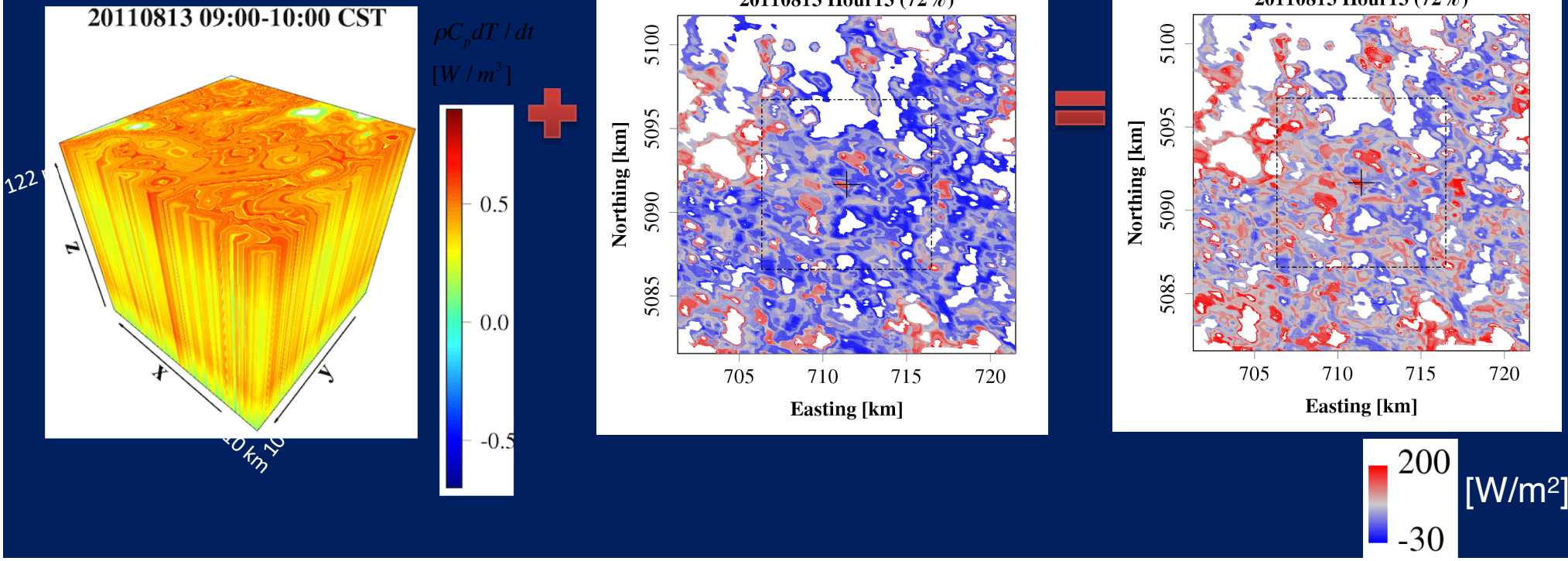
Tall Ameriflux Park Falls WLEF tower; Measurement in 2011 Aug at 30, 122 m.

Credit: Matt Rydzik (U Wisconsin)



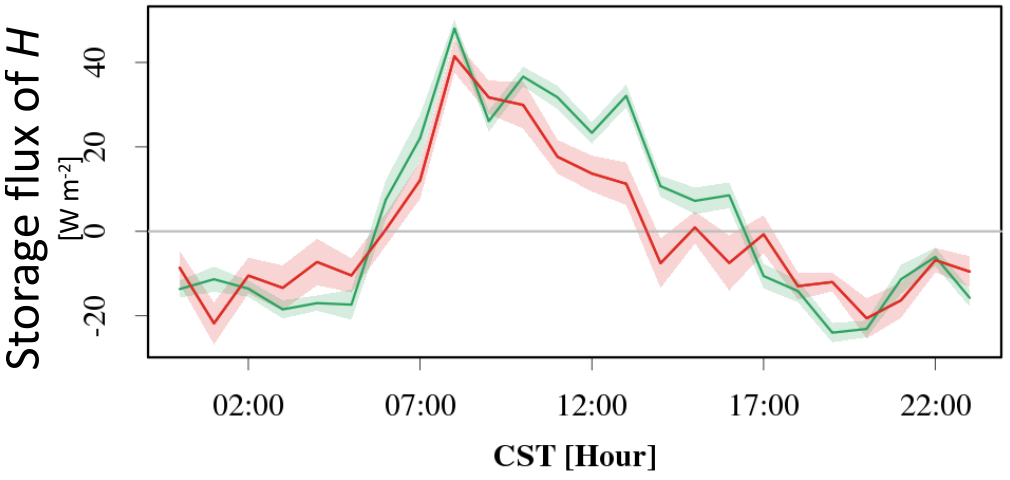


Xu et al., 2018, AFM

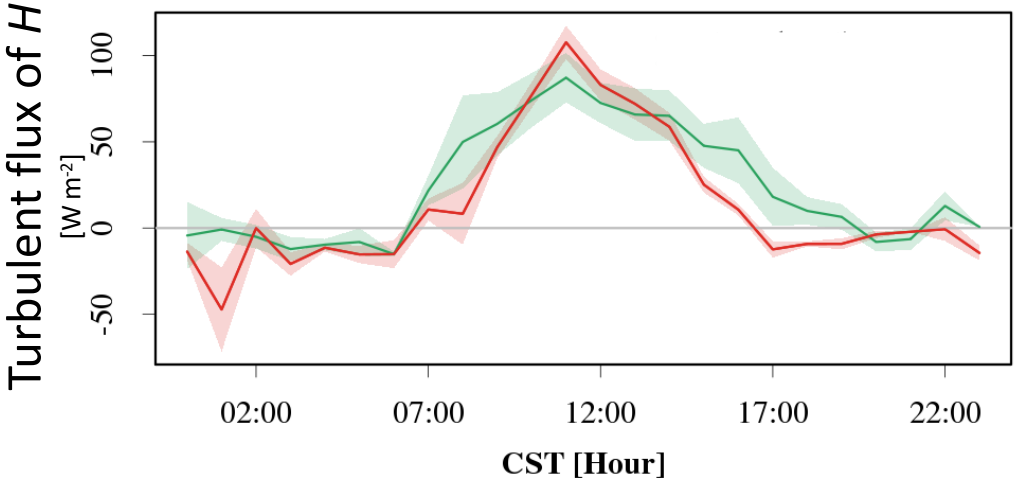


Does rectified surface atmosphere exchange help ?

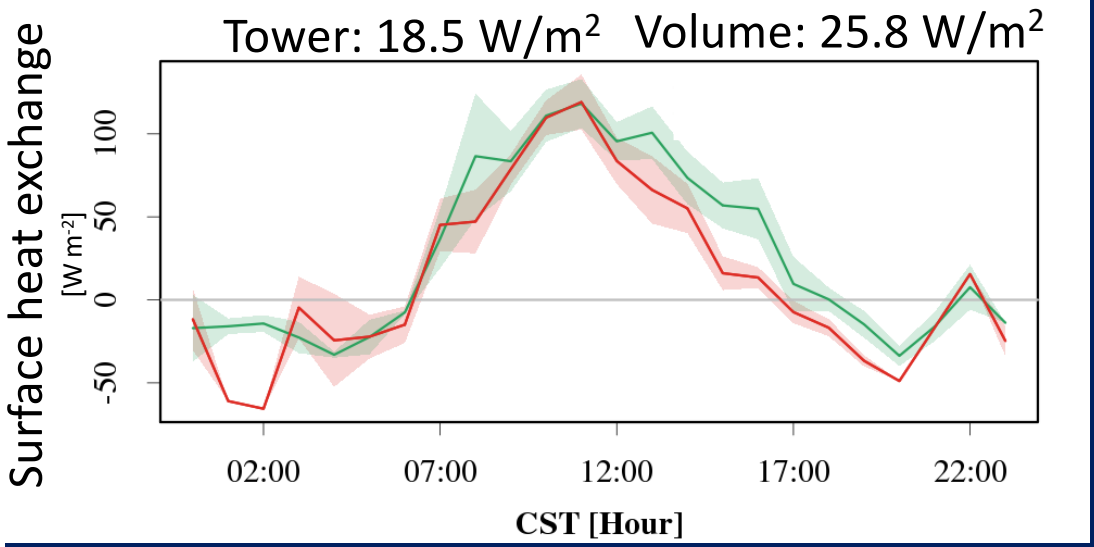
Tower: -0.3 W/m^2 Volume: 2.4 W/m^2



Tower: 19.4 W/m^2 Volume: 24.1 W/m^2



Tower: 18.5 W/m^2 Volume: 25.8 W/m^2



tower-observed

volume-rectified

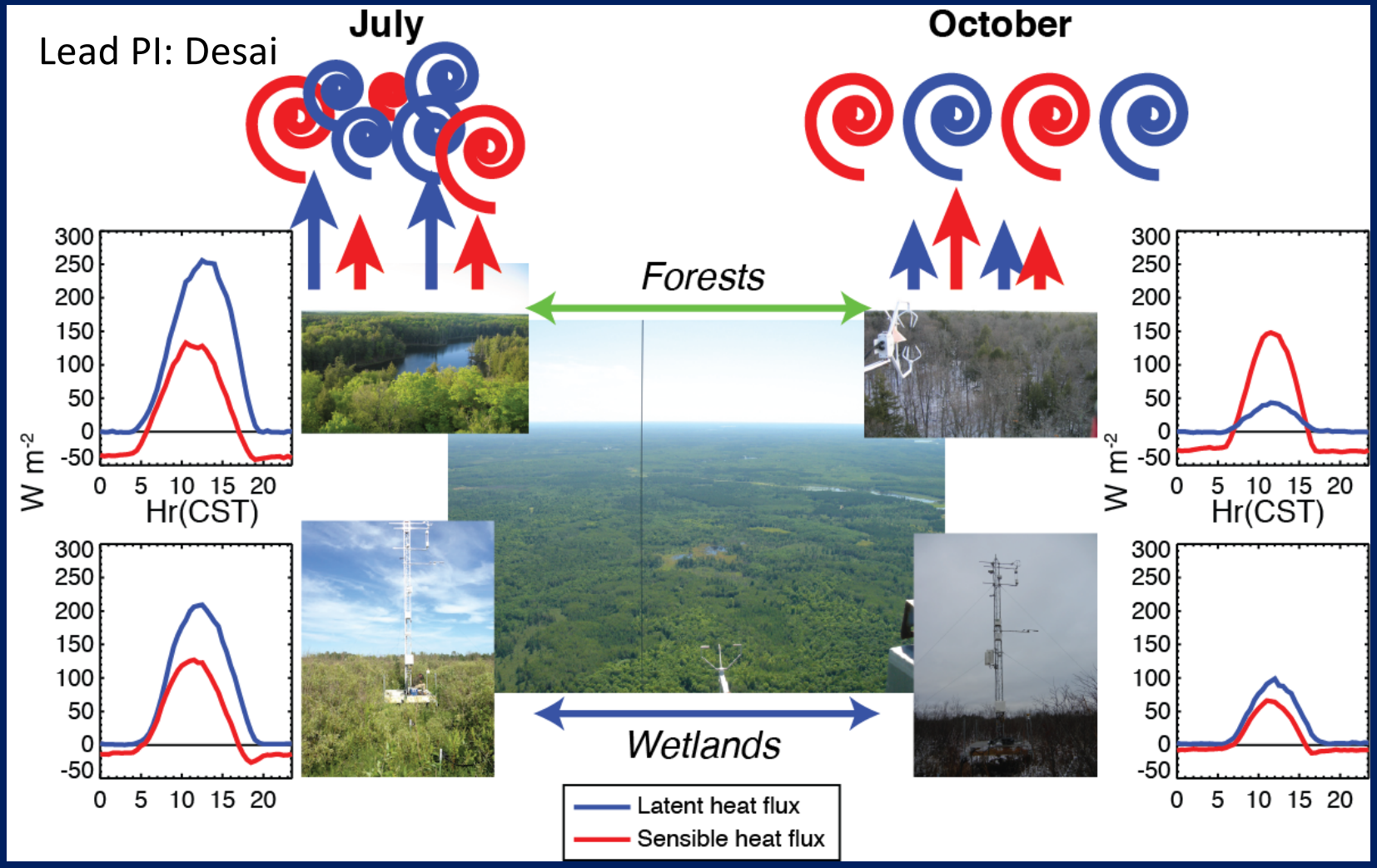
volume-rectified energy flux is + 7.3 W/m^2

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

Lead PI: Desai



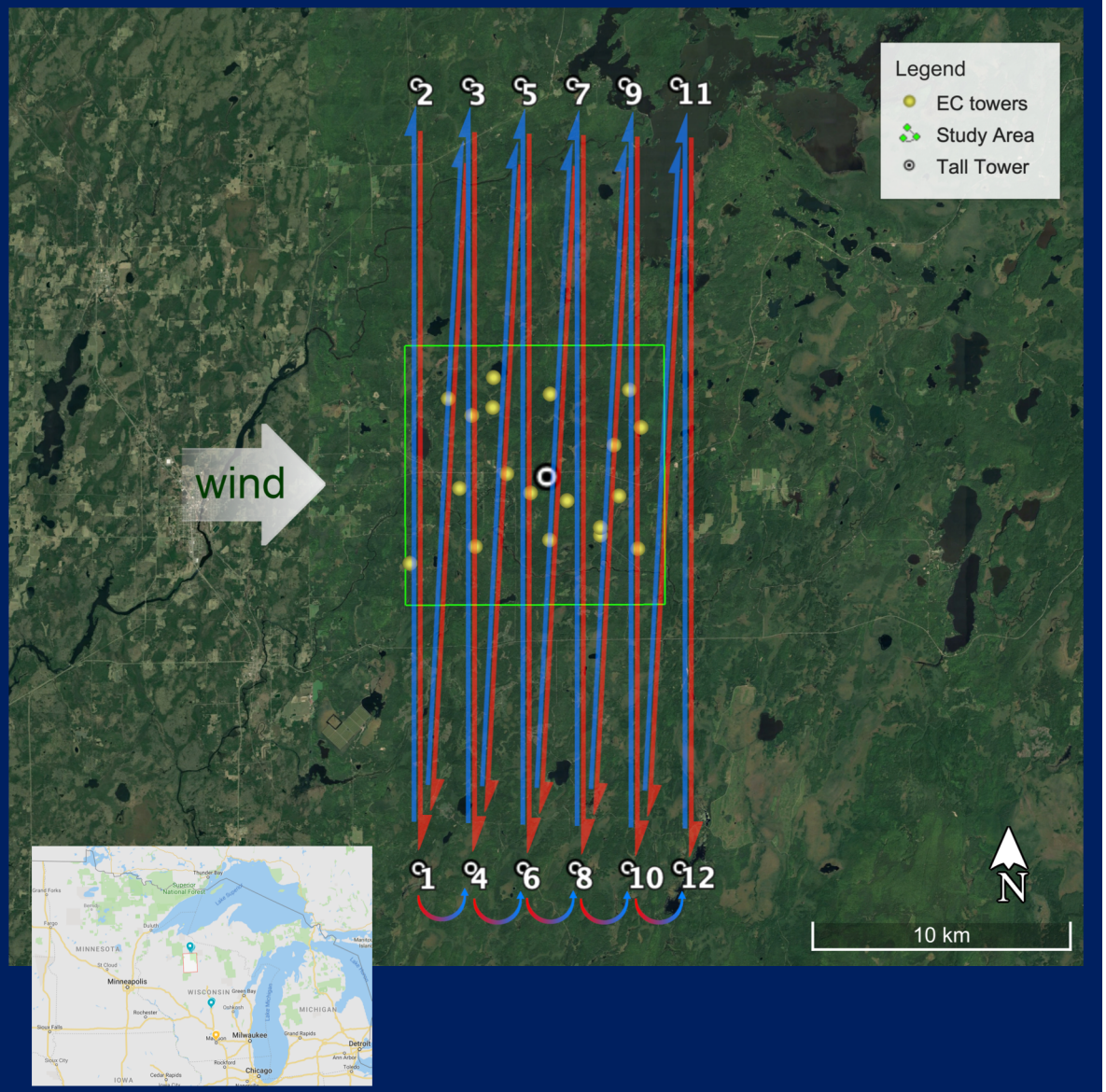
Experimental Design

- 10 km x 10 km (green box)
- July-Oct 2019

- 1 very tall tower (black dot)
- 8 in situ atmospheric profilers
- 19 eddy flux towers (yellow dots)

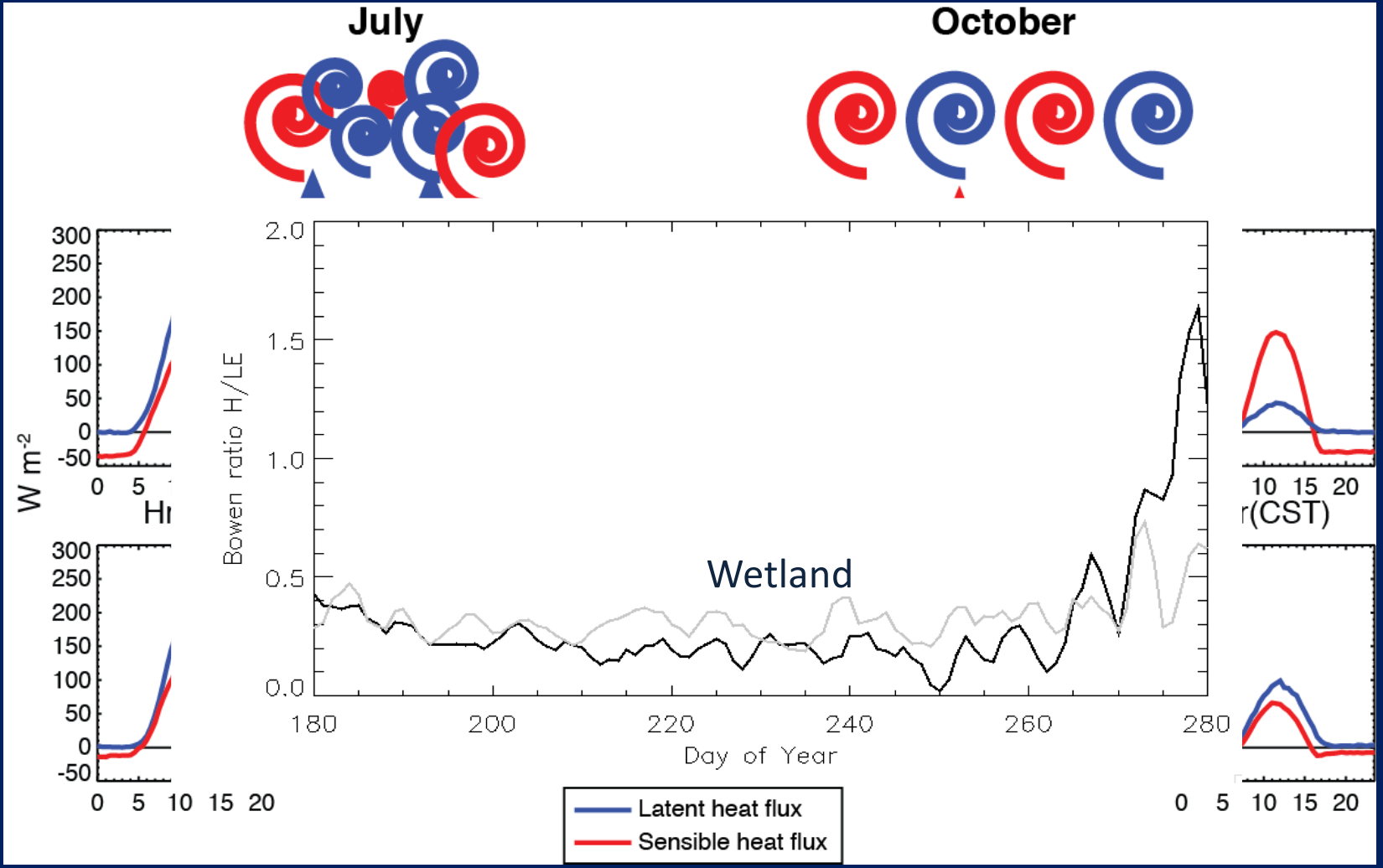
- Weekly sampling of NPP and phenology
- Monthly hyperspectral and seasonal LiDAR mapping of domain

- 3 week-long intensives (Jul-Sep)
- Flux and PBL profiling aircraft at 100 and 400 m (red/blue lines)
- 3-hourly radiosondes
- LES simulations in each

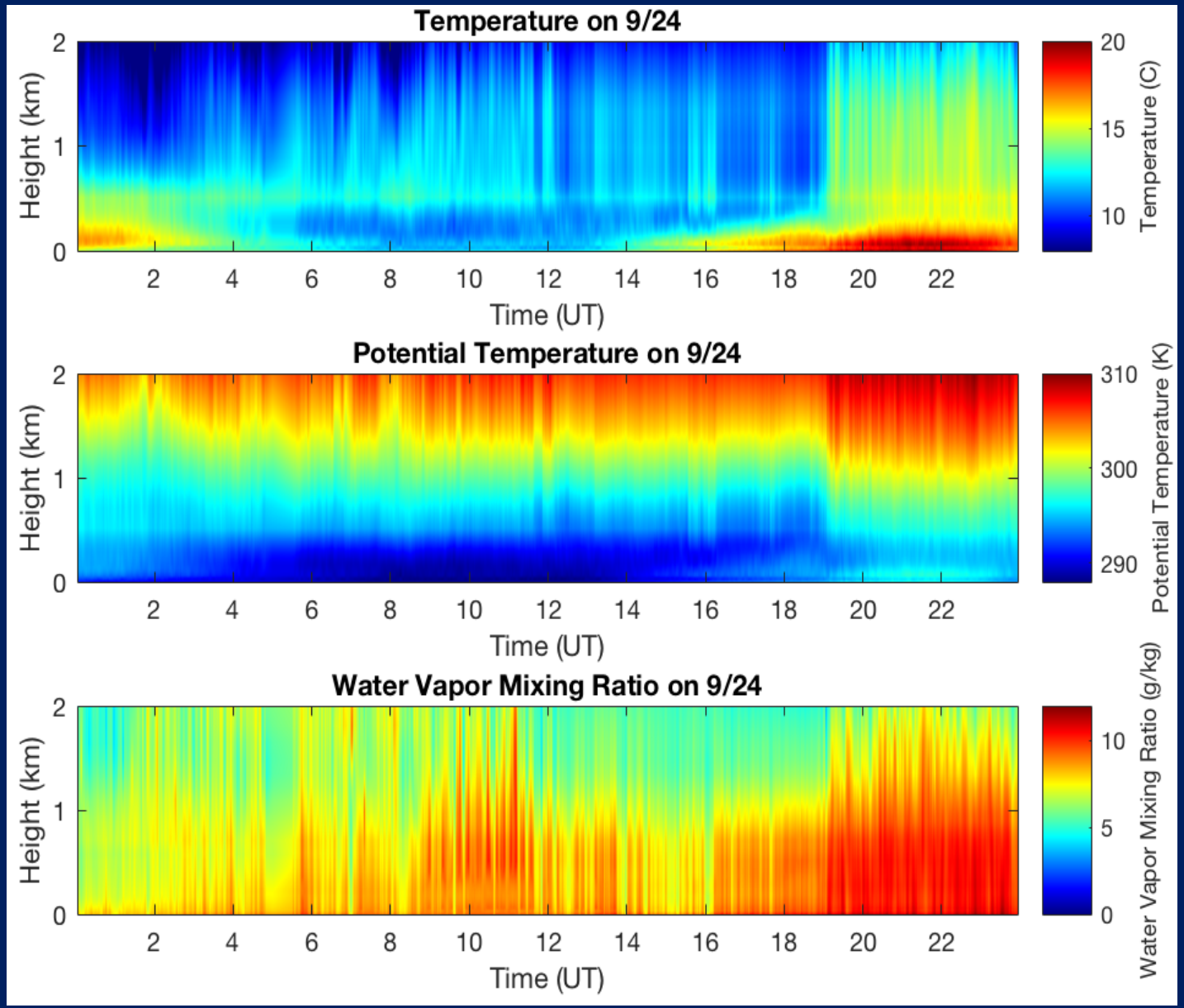



Legend
EC towers
Study Area
Tall Tower
NW4_lake_1
NW1_pine_1
NE1_pine_2
NE3_hardwood_1
NW3_tussock_1
NW2_poplar_1
NE4_cedar_1
NE2_larch_1
NW5_grass_1 (ISS)
Tall Tower
SW2_poplar_3
SW4_hardwood_3
SE5_aspen_2
SE2_maple_1
SE3_aspen_1
SE4_tussock_2
SE1_lake_2
SW3_hardwood_2
SE6_pine_3
SW1_poplar_2
N
Google Earth
5 km

July-October allows us to sample landscape as it evolves from homogenous LE (transpiration) driven, to patchier H and LE patterns depending on ecosystem



AERI (Atmospheric Emitted Radiance Interferometer)
at the US-PFa WLEF tall tower in Sept 2016



Photograph courtesy of Vanda Grubisic, Desert Research Institute

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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@profdesai
Photo: J Thom