Don’t we have enough flux towers already?

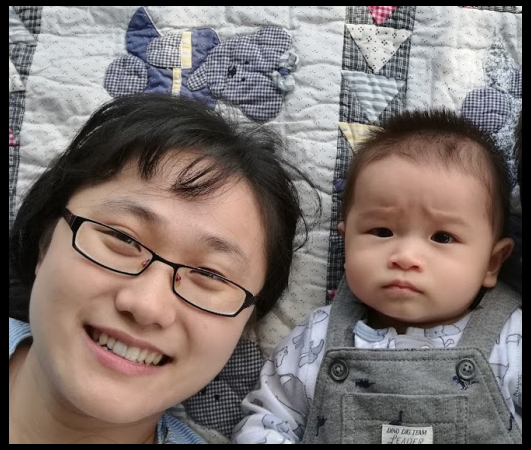
Ankur R Desai
Dept of Atmospheric and Oceanic Sciences
University of Wisconsin-Madison

UC-Davis
ATM290 Seminar

NO

But...

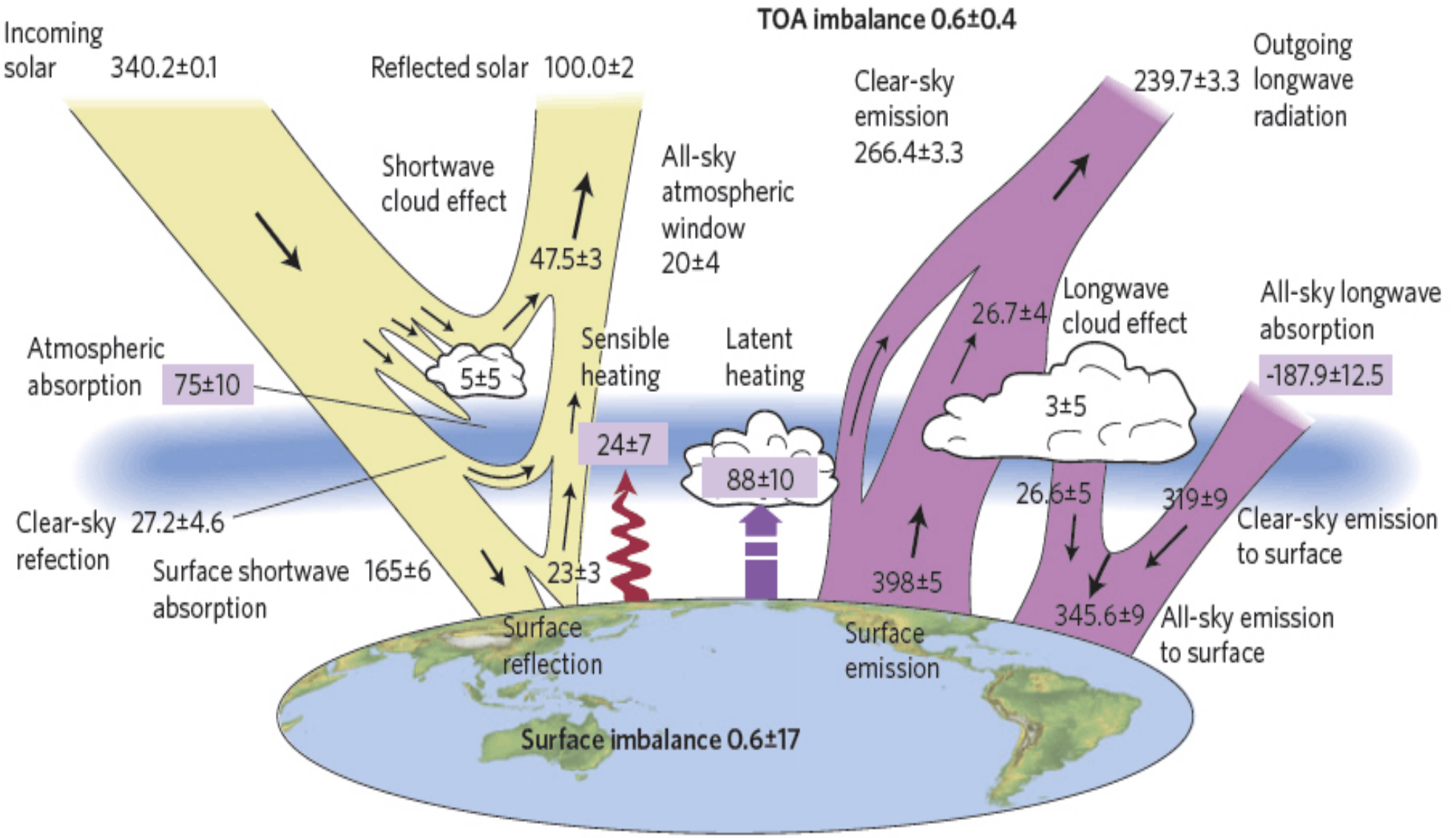
Acknowledge



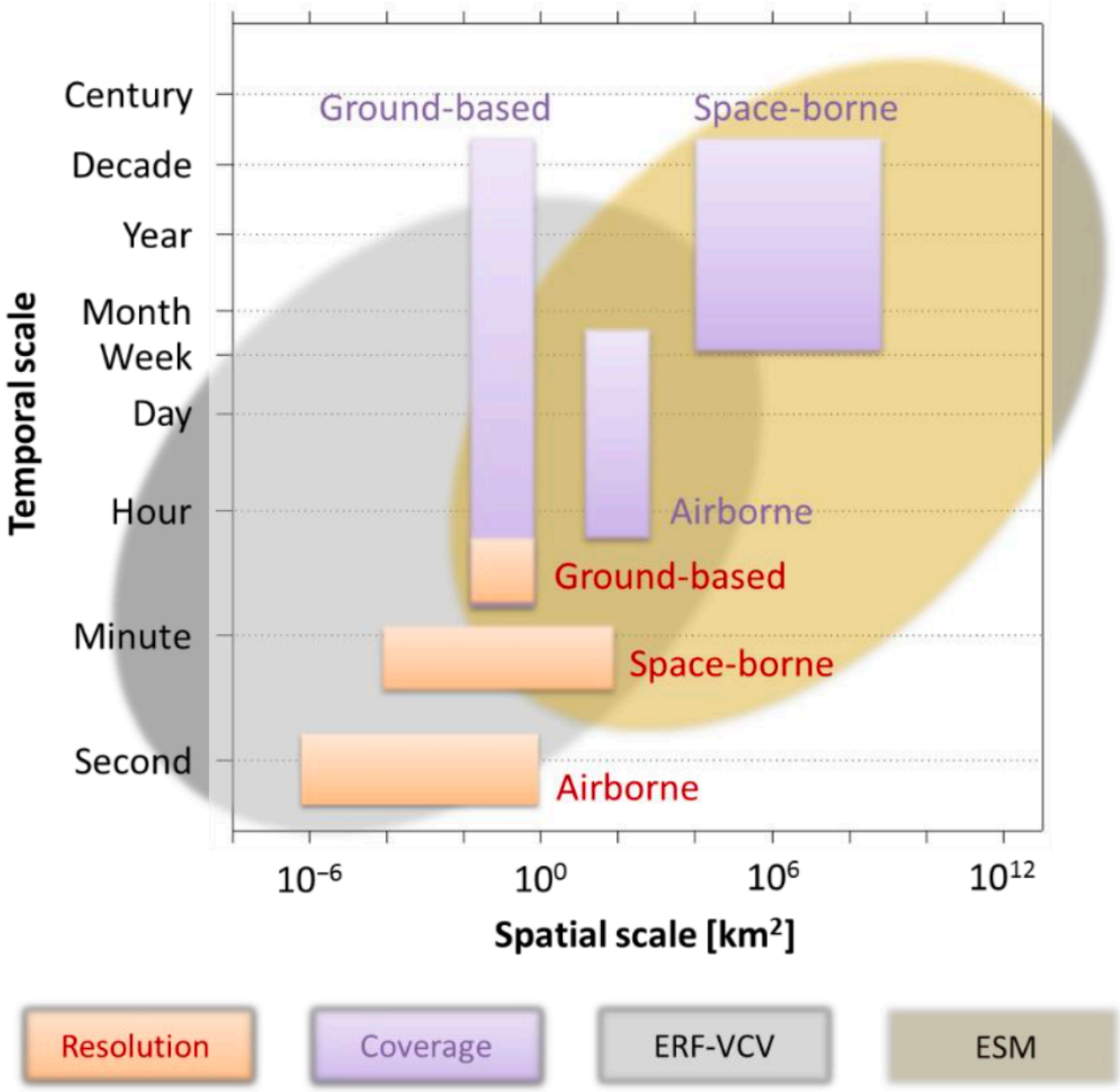
Ke Xu, Ph.D. Candidate, UW AOS
Expected defense March 2018
LOOKING FOR A POST-DOC

Stefan Metzger, Staff Scientist
National Ecological Observatory Network (NEON)
Battelle Ecology

ACT I: The Eddy Flux Story

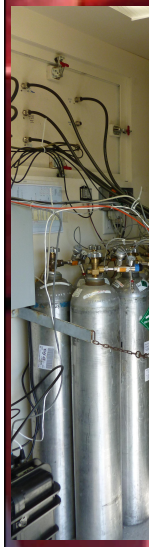


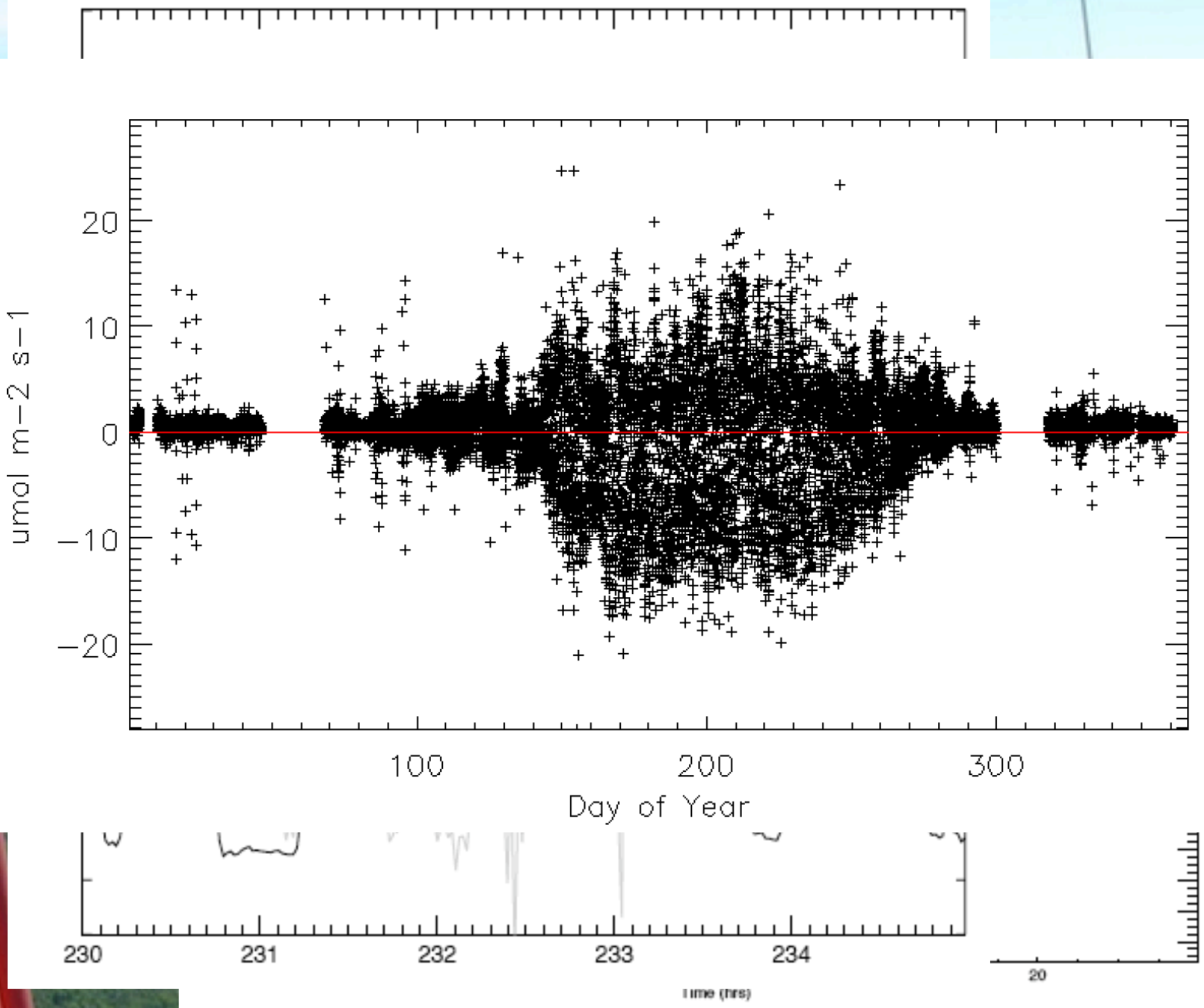
Stephens et al., 2012, Nature Geosci


Century
Decade
Year
Month
Week
Day
Hour
Minute
Second
Temporal scale
Ground-based
Space-borne
Airborne
Ground-based
Space-borne
Airborne
10^{-6}
10^{0}
10^{6}
10^{12}
Spatial scale [km^2]
Resolution
Coverage
ERF-VCV
ESM

Thermistor, hygrometer,

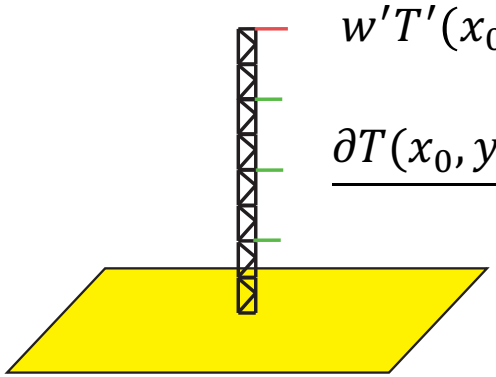
Infi
ana





Full net surface-atmosphere exchange in a box

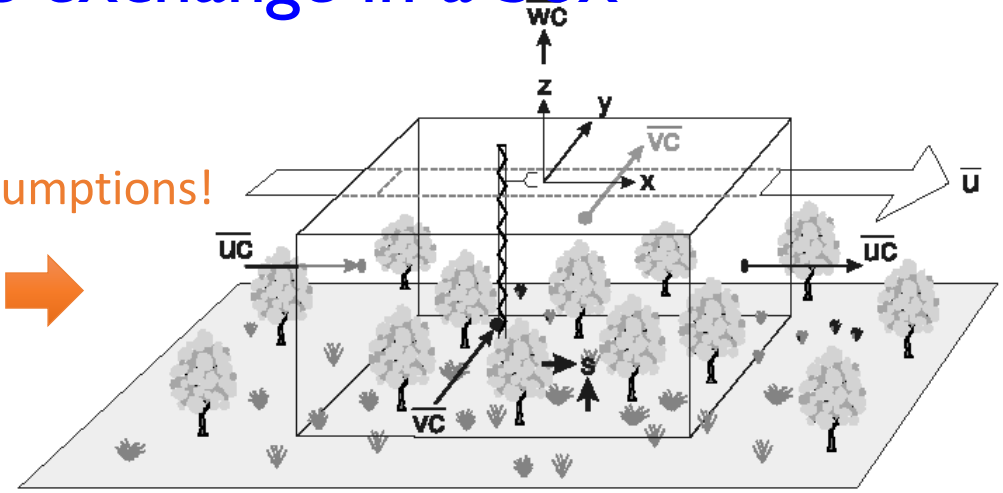
Eddy Covariance



$$w'T'(x_0, y_0, h)$$

$$\frac{\partial T(x_0, y_0, (z_1 \dots z_m))}{\partial t}$$

3 Assumptions!



modified after Finnigan (2004)

Assumption 1:

storage change $\int_0^h \frac{\partial \bar{c}}{\partial t} dz$ <- $\int_0^h \left[\frac{1}{4L^2} \int_{-L}^{+L} \int_{-L}^{+L} \frac{\partial \bar{c}}{\partial t} dx\, dy \right] dz$

Assumption 2:

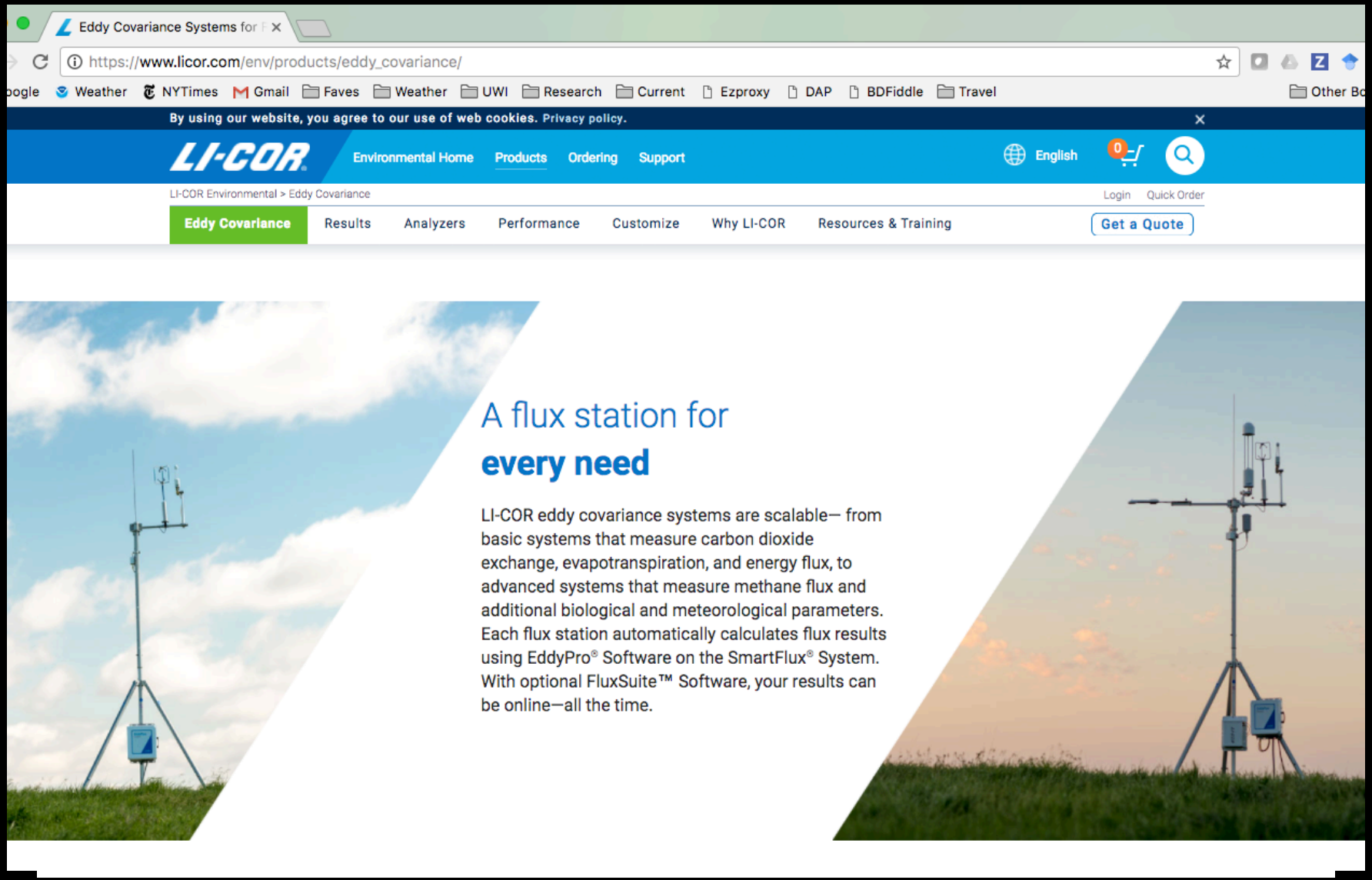
horizontal transport 0 <- $\int_0^h \left[\frac{1}{4L^2} \int_{-L}^{+L} \int_{-L}^{+L} \left\{ \frac{\partial \bar{u}\bar{c}}{\partial x} + \frac{\partial \overline{u'c'}}{\partial x} + \frac{\partial \bar{v}\bar{c}}{\partial y} + \frac{\partial \overline{v'c'}}{\partial y} \right\} dx\, dy \right] dz$

Assumption 3:

vertical transport $\overline{w'c'}(h)$ <- $\int_0^h \left[\frac{1}{4L^2} \int_{-L}^{+L} \int_{-L}^{+L} \left\{ \frac{\partial \bar{w}\bar{c}}{\partial z} + \frac{\partial \overline{w'c'}}{\partial z} \right\} dx\, dy \right] dz$

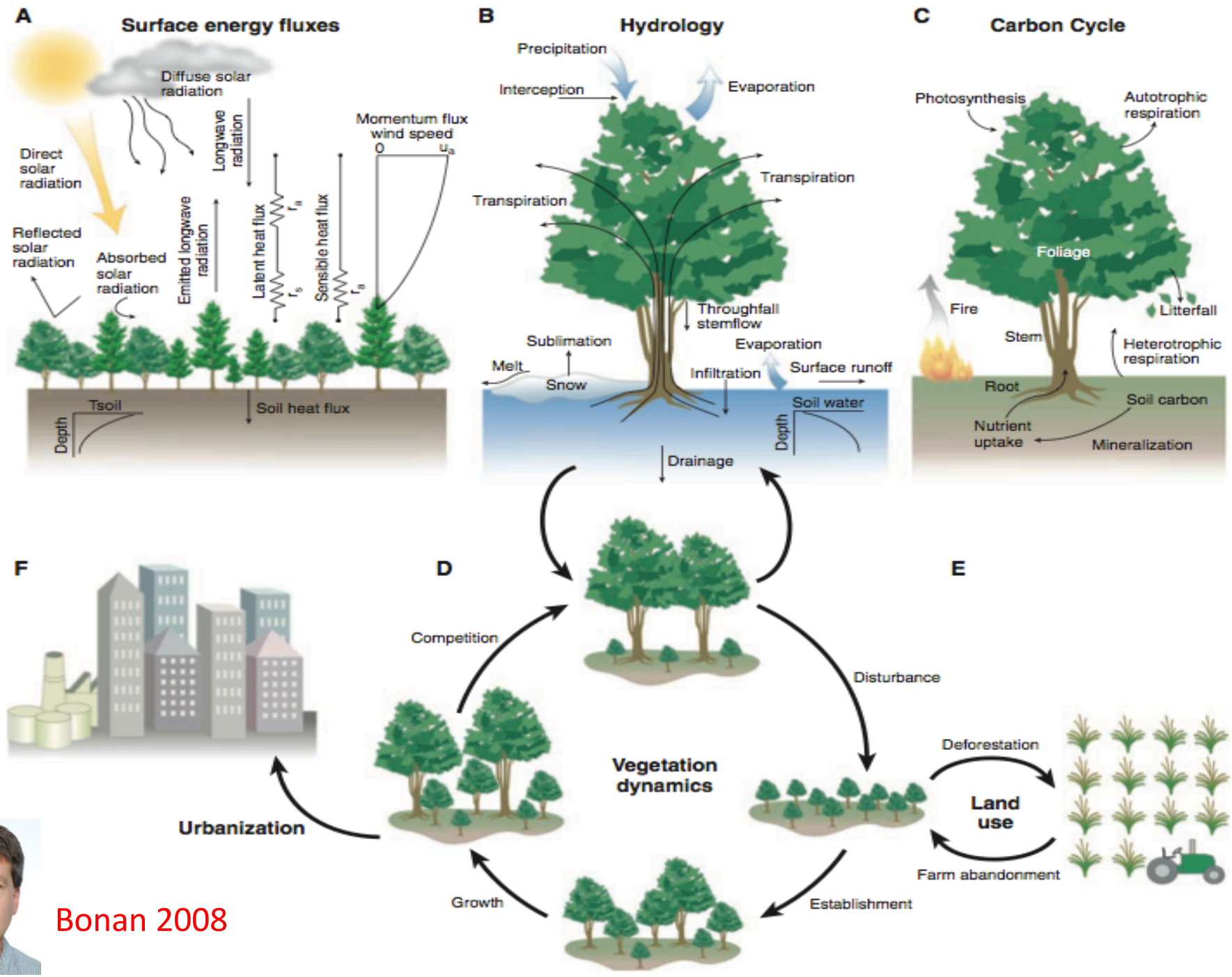
Coutesy S. Metzger, NEON

Time Line of Carbon, Water & Energy Flux Data

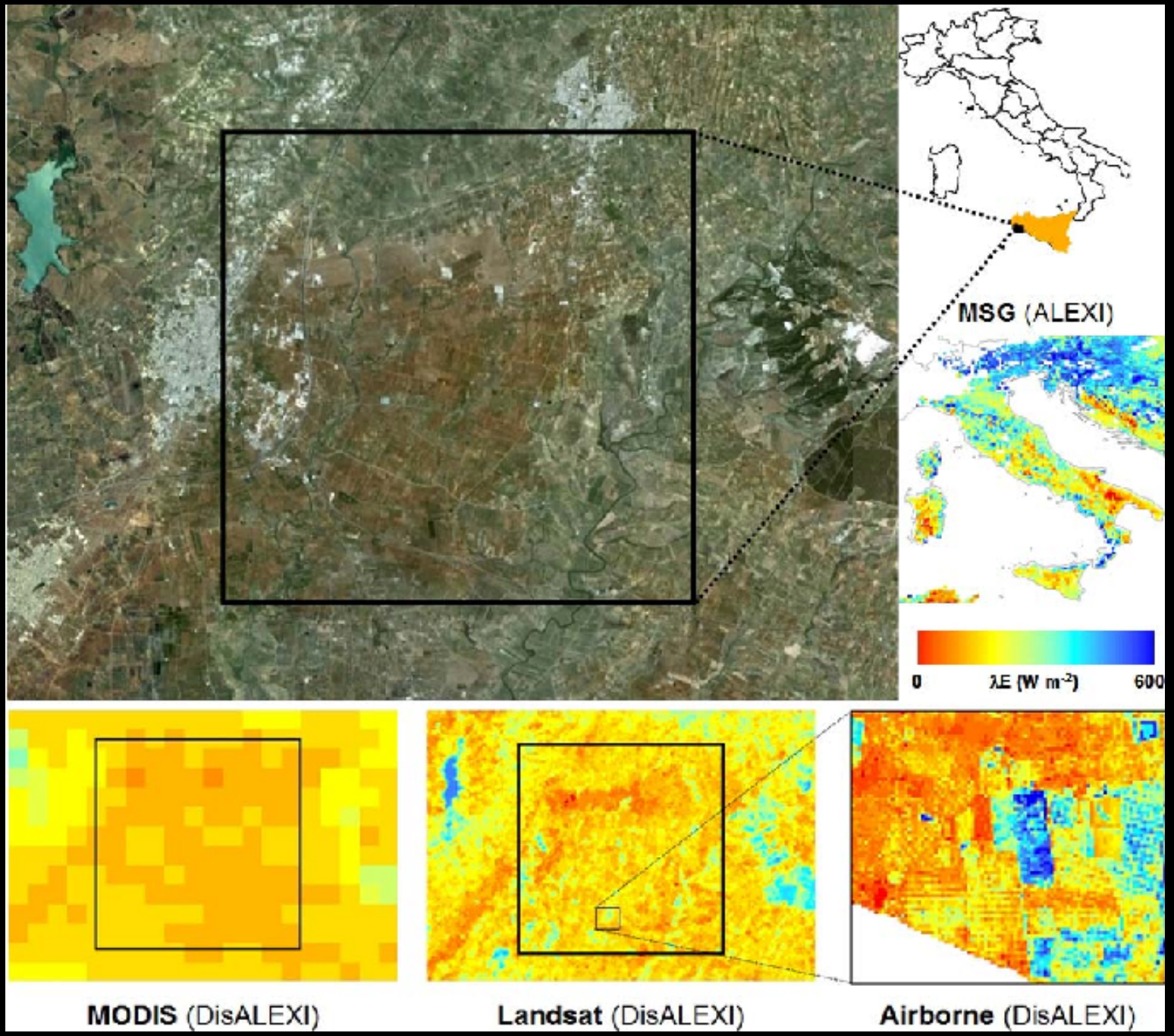


Courtesy of D. Baldocchi

Forests in Flux

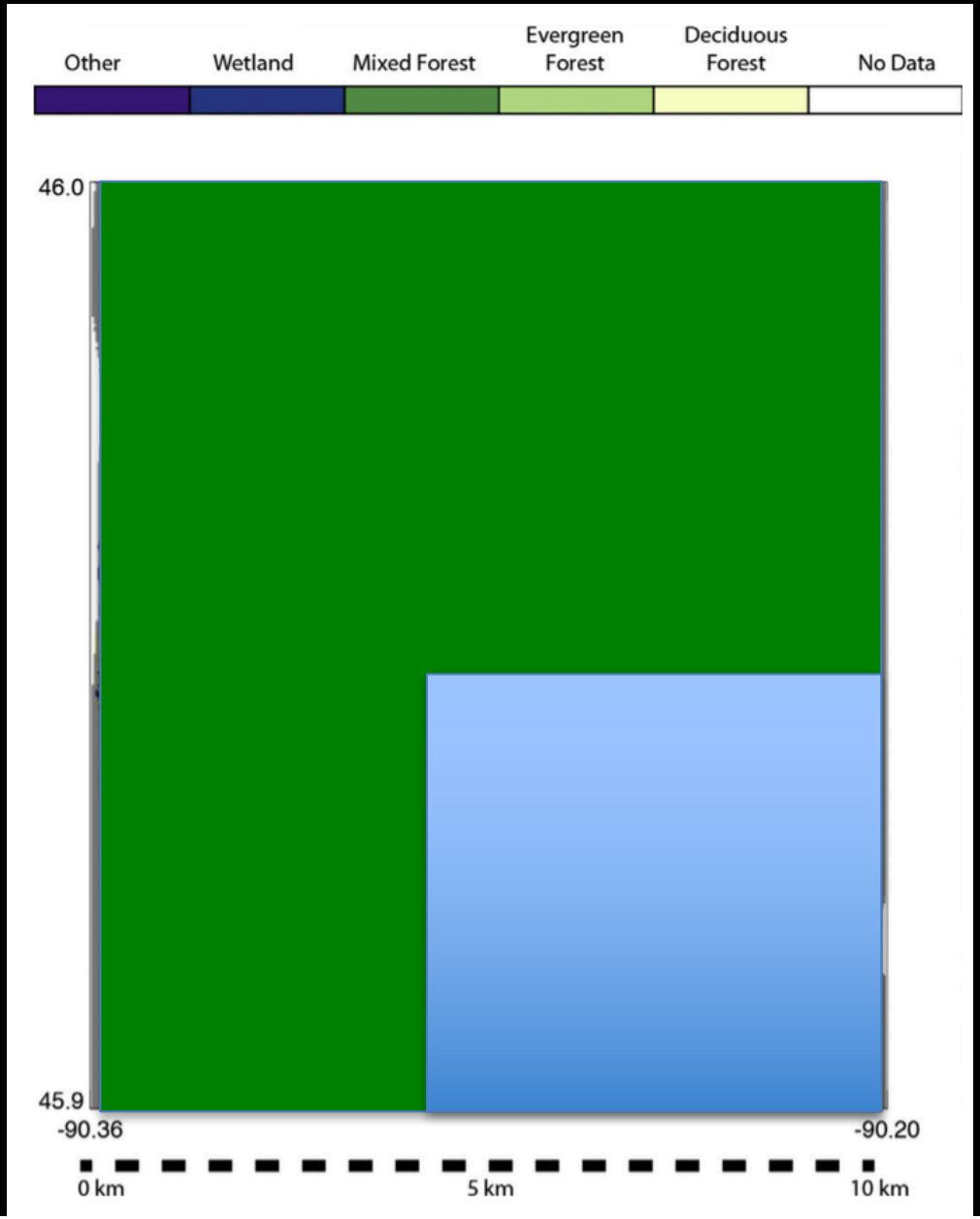


Bonan 2008



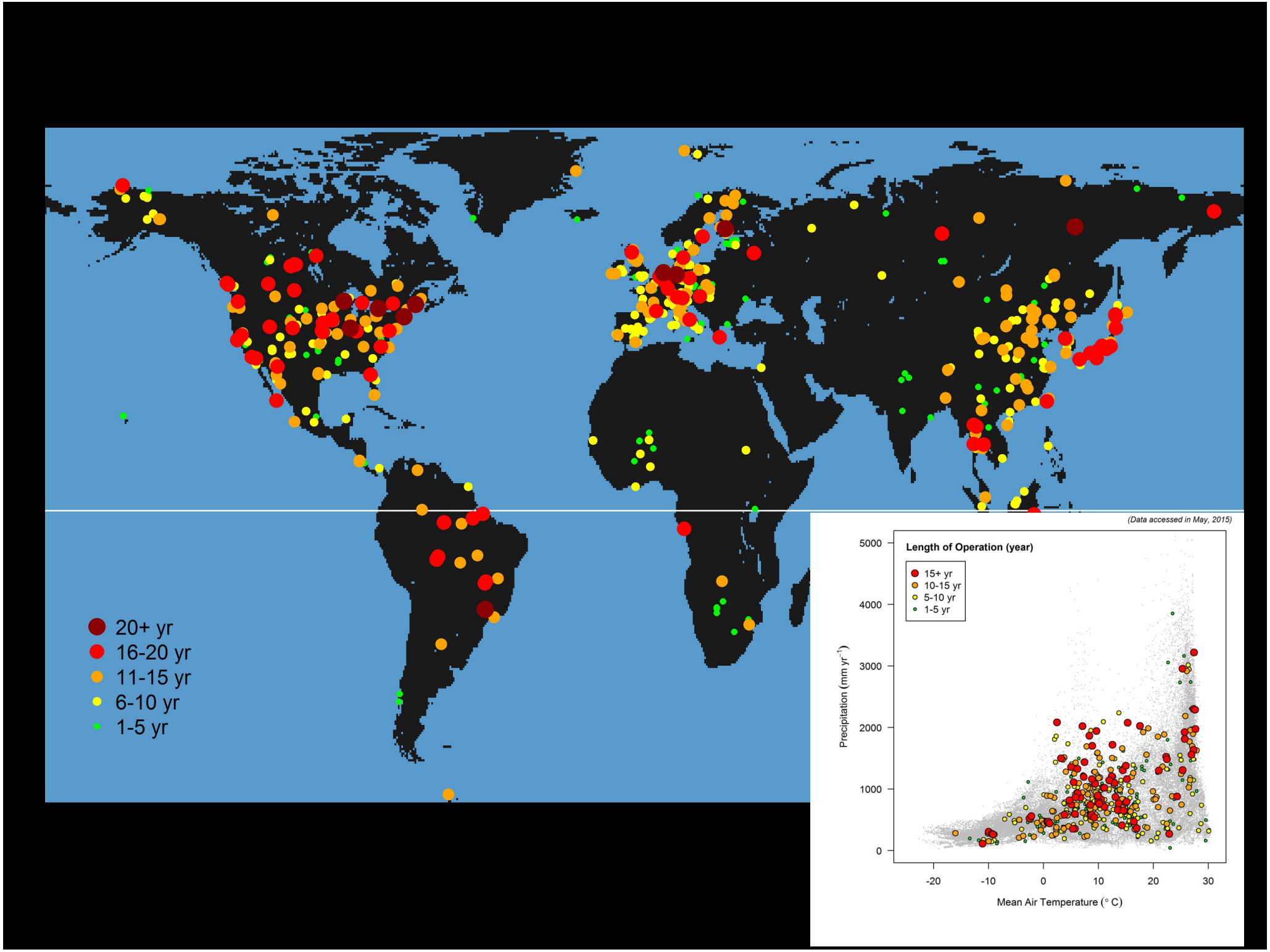
Martha Anderson, Hydrology and Earth System Sciences, 2011

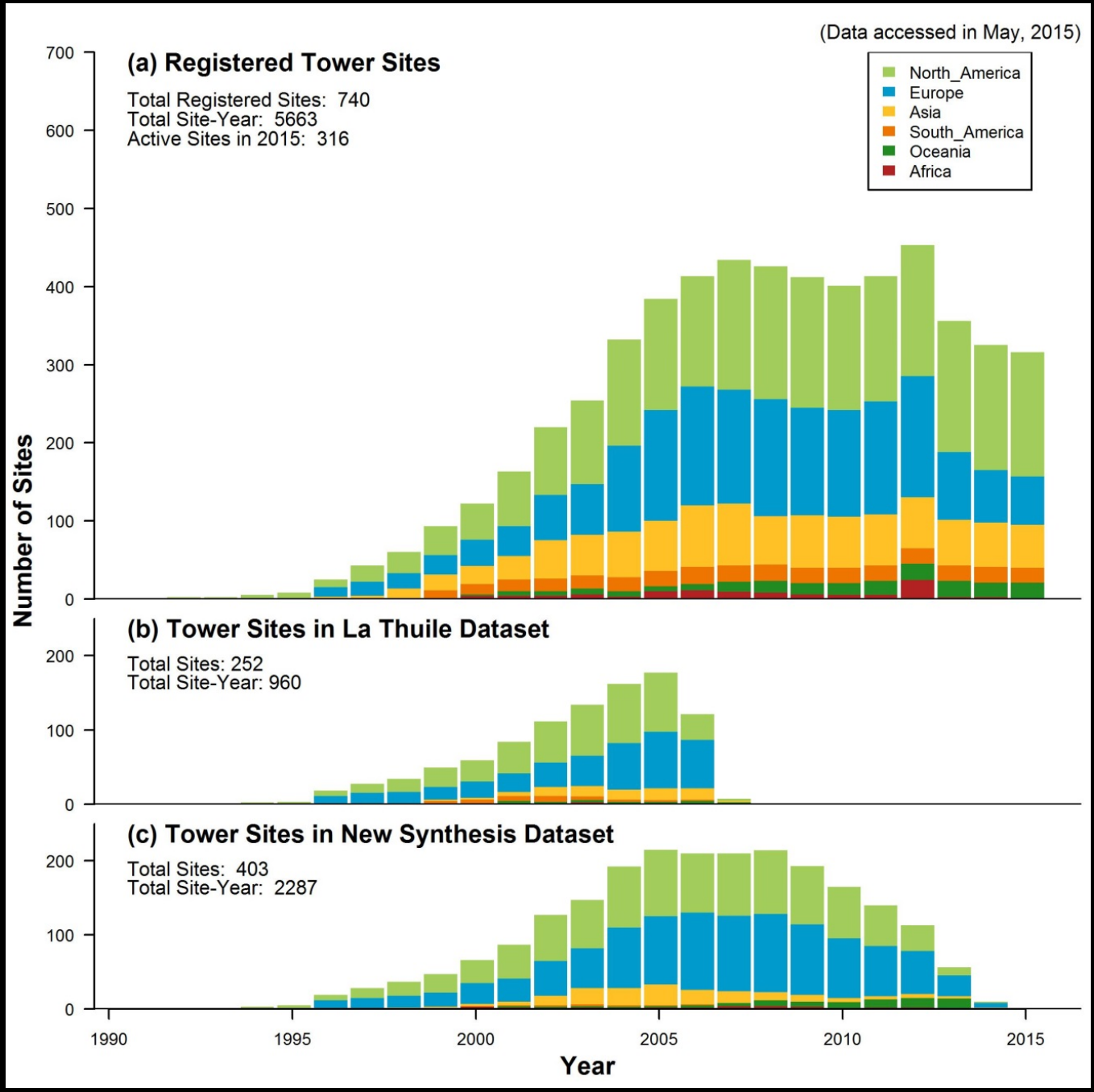
Earth system models see green slime



Desai et al., 2015, AFM

ACT II: Enter Fluxnet


20+ yr
16-20 yr
11-15 yr
6-10 yr
1-5 yr
(Data accessed in May, 2015)
Length of Operation (year)
15+ yr
10-15 yr
5-10 yr
1-5 yr
Precipitation (mm yr⁻¹)
5000
4000
3000
2000
1000
0
-20
-10
0
10
20
30
Mean Air Temperature (° C)


(Data accessed in May, 2015)
(a) Registered Tower Sites
Total Registered Sites: 740
Total Site-Year: 5663
Active Sites in 2015: 316
North_America
Europe
Asia
South_America
Oceania
Africa
Number of Sites
(b) Tower Sites in La Thuile Dataset
Total Sites: 252
Total Site-Year: 960
(c) Tower Sites in New Synthesis Dataset
Total Sites: 403
Total Site-Year: 2287
Year

D. Baldocchi

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116, G00J07, doi:10.1029/2010JG001566, 2011

Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance,

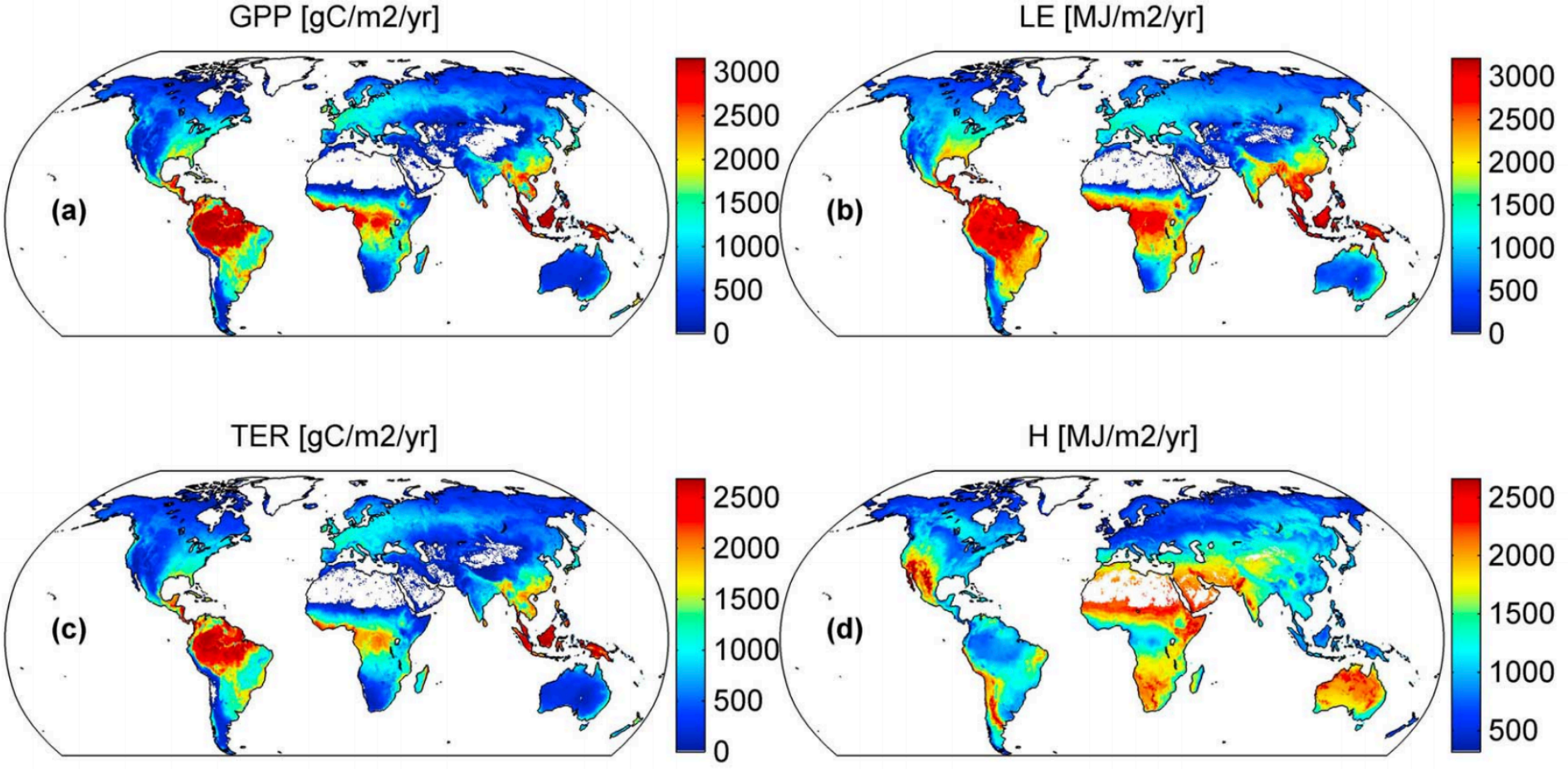


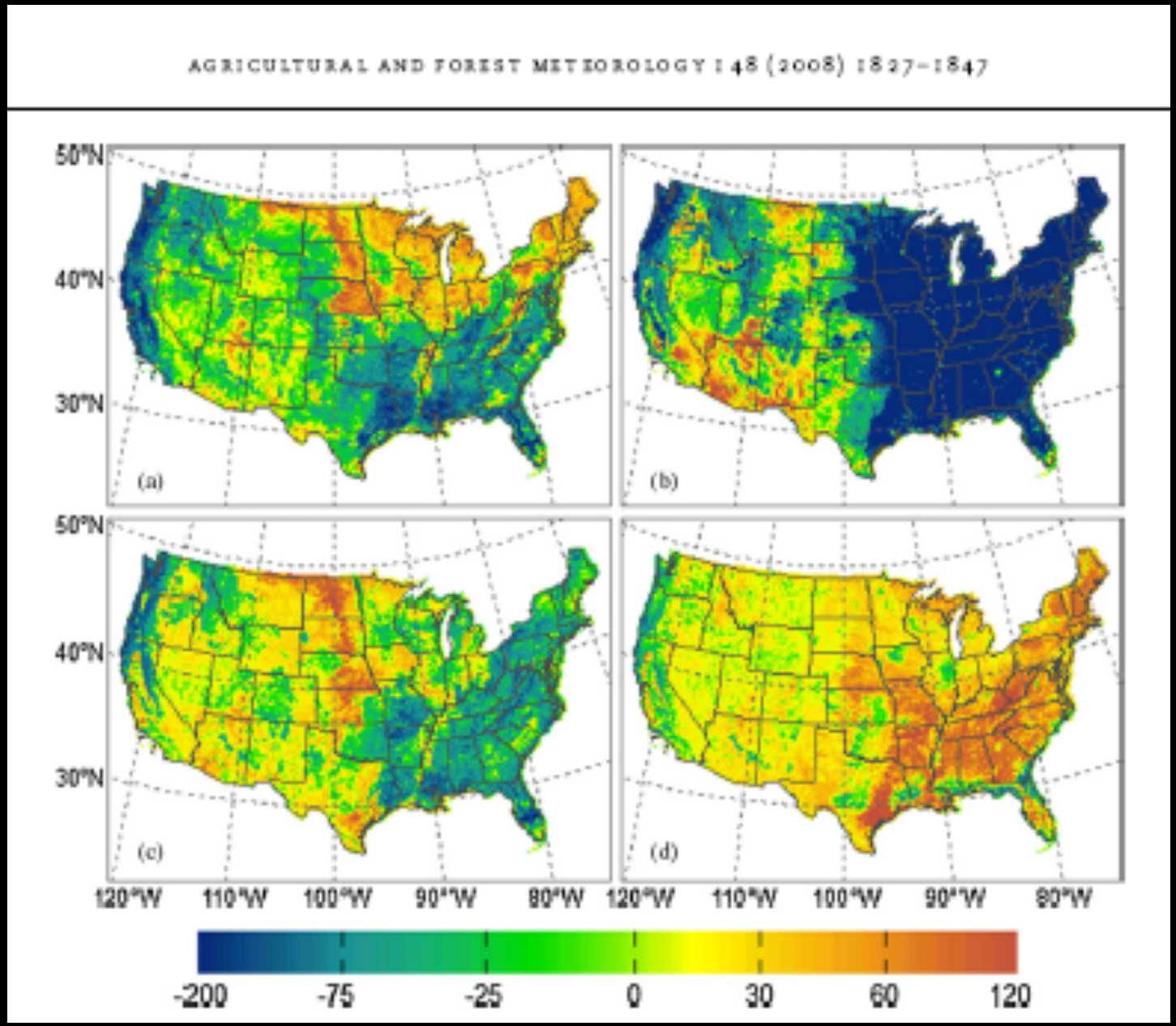
Figure 3. Mean annual (1982–2008) (a) GPP, (b) LE, (c) TER, and (d) H derived from global empirical upscaling of FLUXNET data.

spring

summer

autumn

winter



Xiao et al., 2008

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2016-36, 2016
Manuscript under review for journal Earth Syst. Sci. Data
Published: 23 August 2016

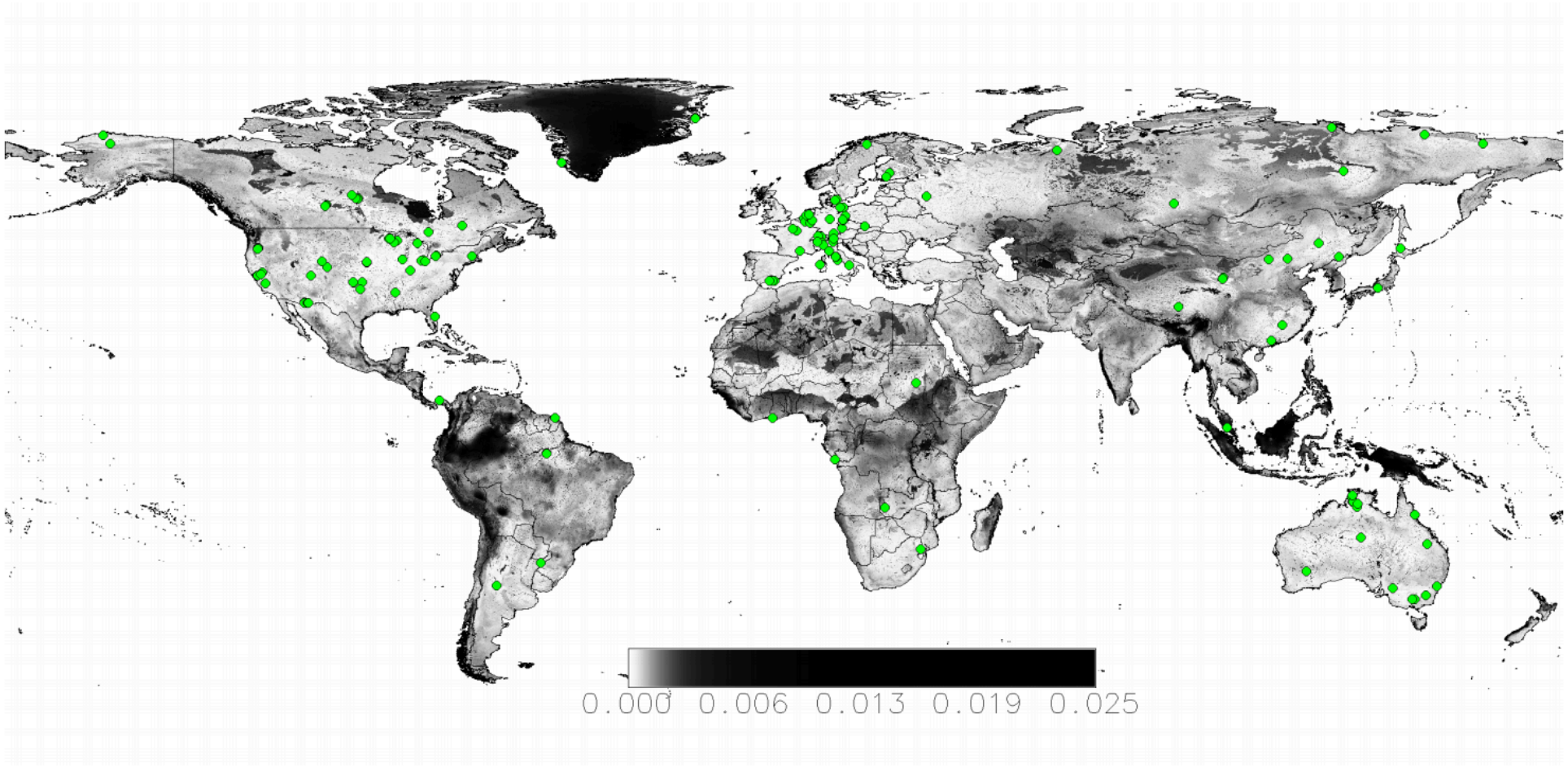


Figure 4. Network representativeness for all of the FLUXNET2015 sites (164 sites).

Journal of Geophysical Research: Biogeosciences

RESEARCH ARTICLE

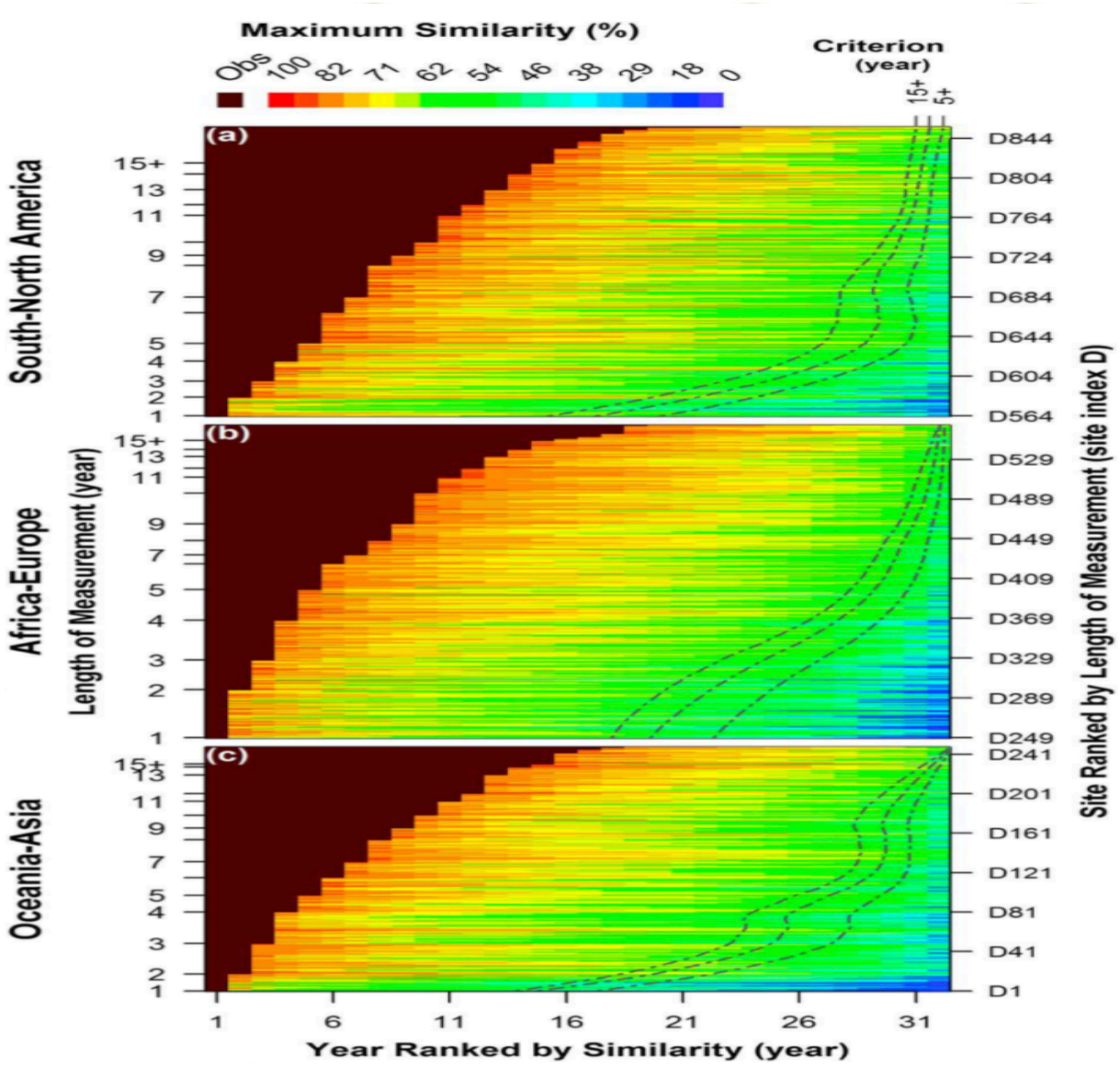
10.1002/2016JG003576

Fluxes all of the time? A primer on the temporal representativeness of FLUXNET

Wolf[3], and

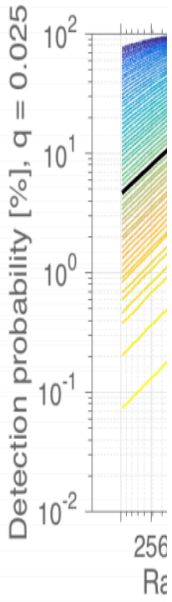
Key Points:

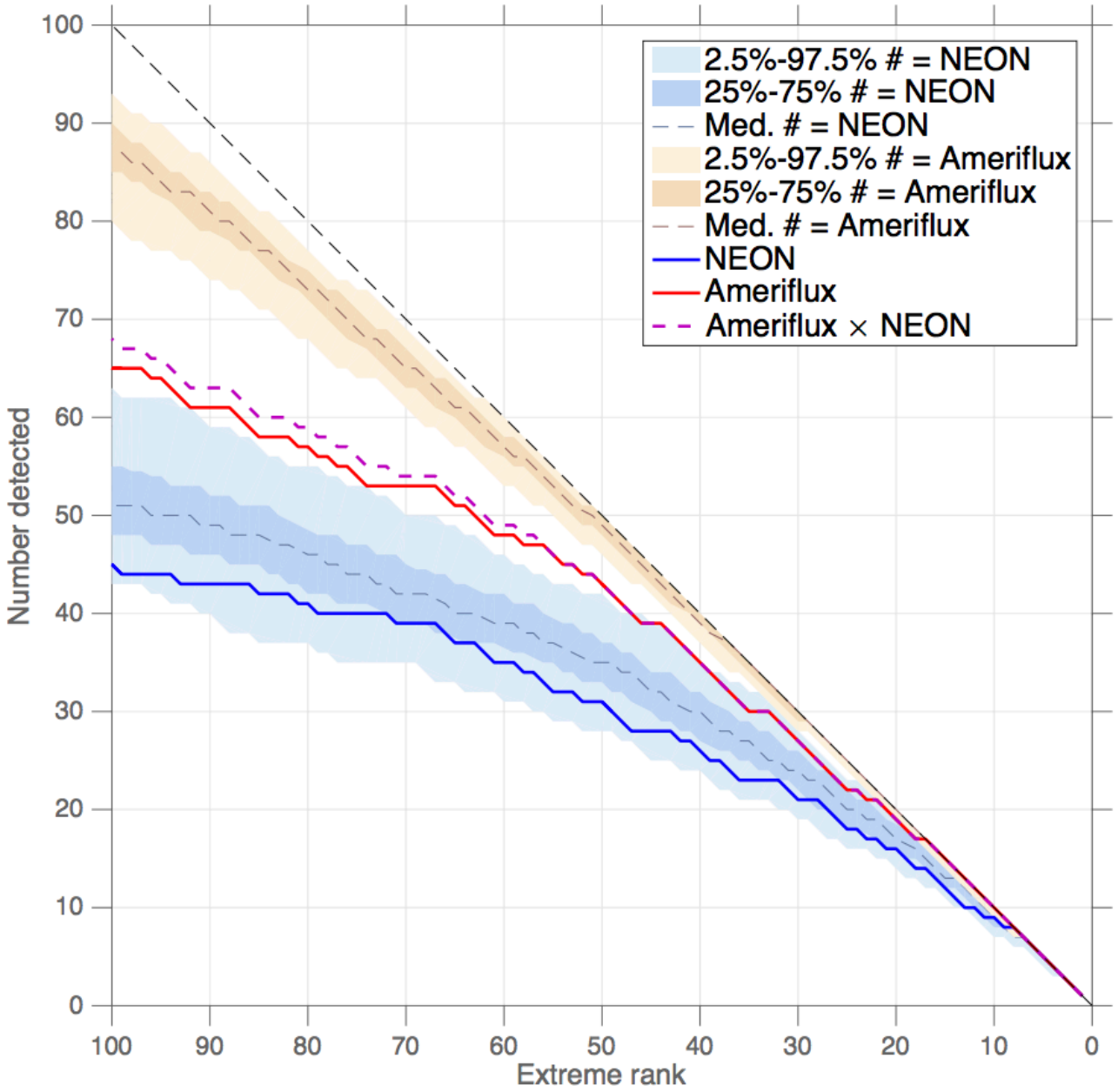
- FLUXNET is unevenly re
  across sites in terms of

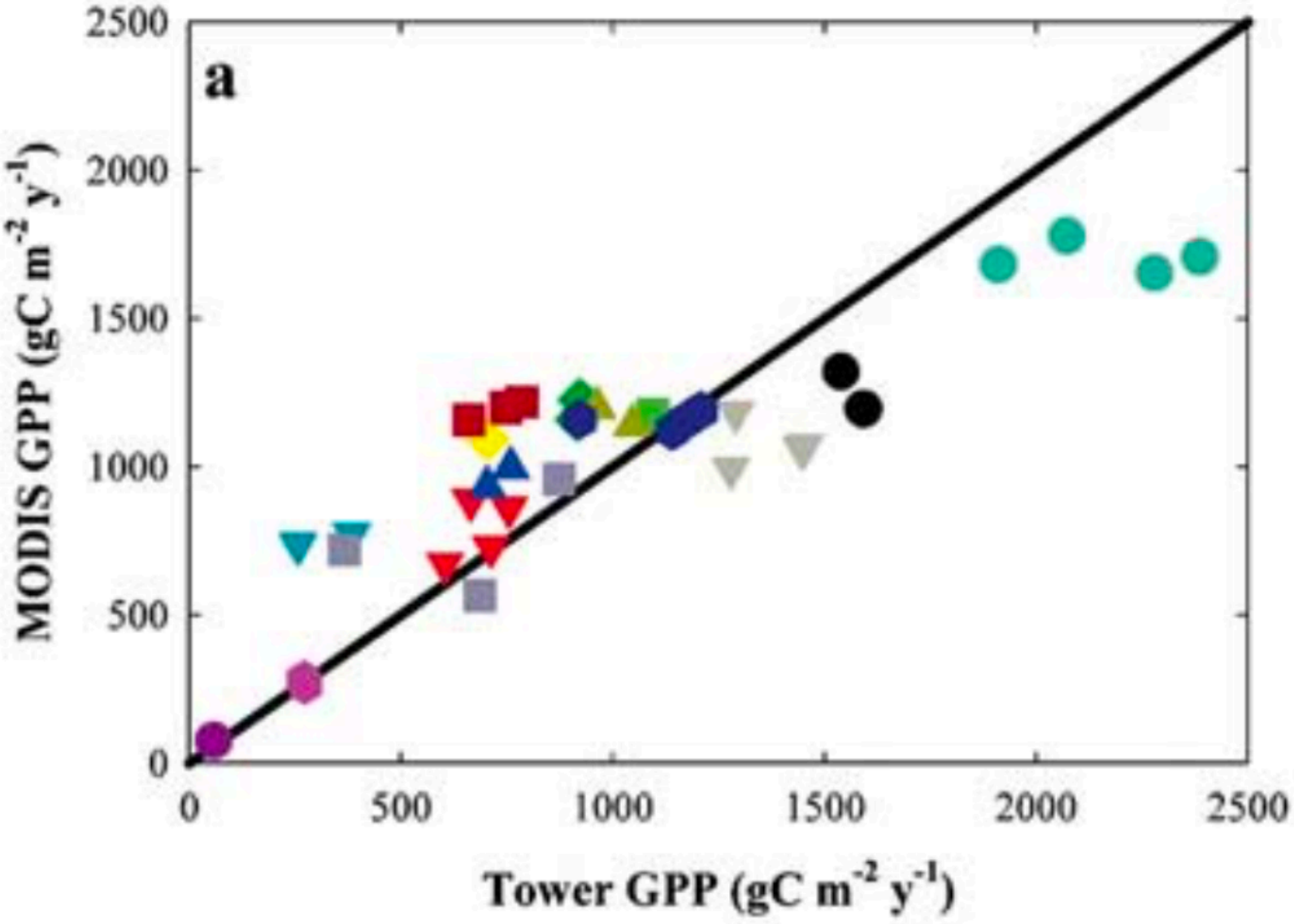


Detec
monit

Miguel I
Stefan M
nski[7],
er[4]

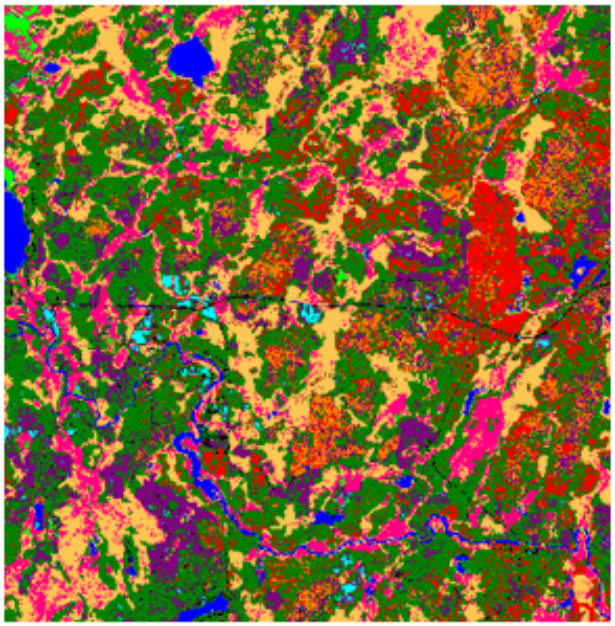
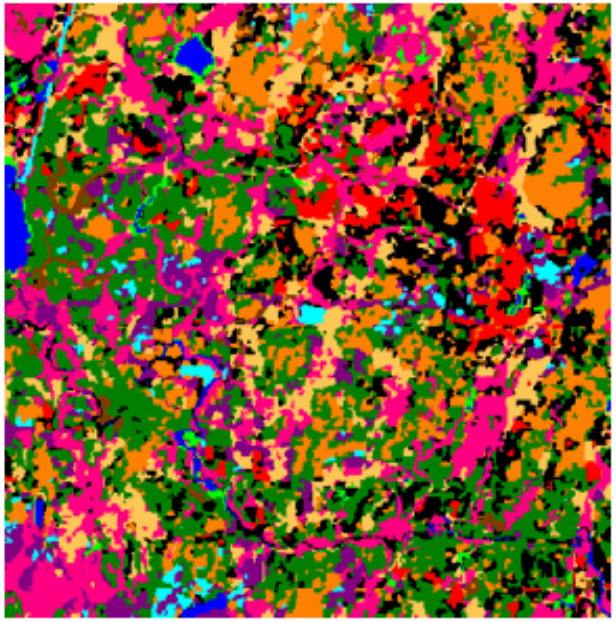
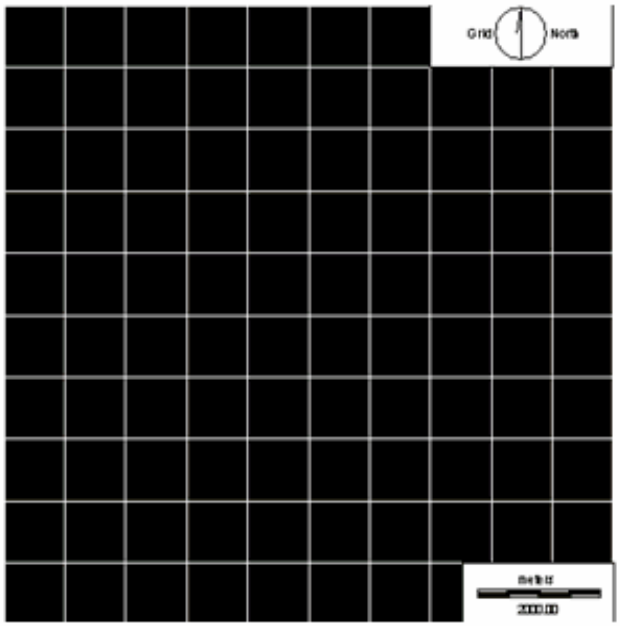


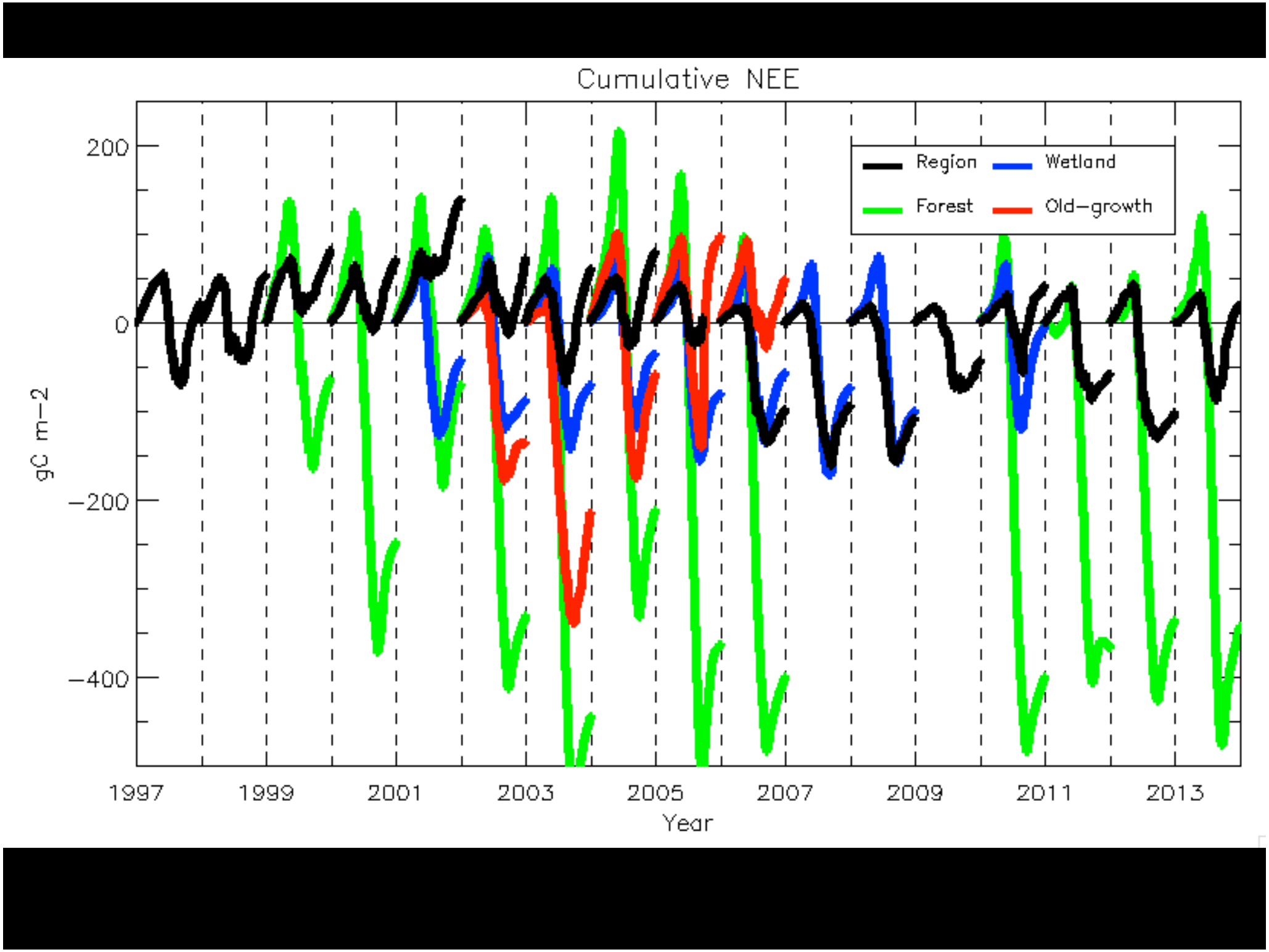




Heinsch et al., 2006

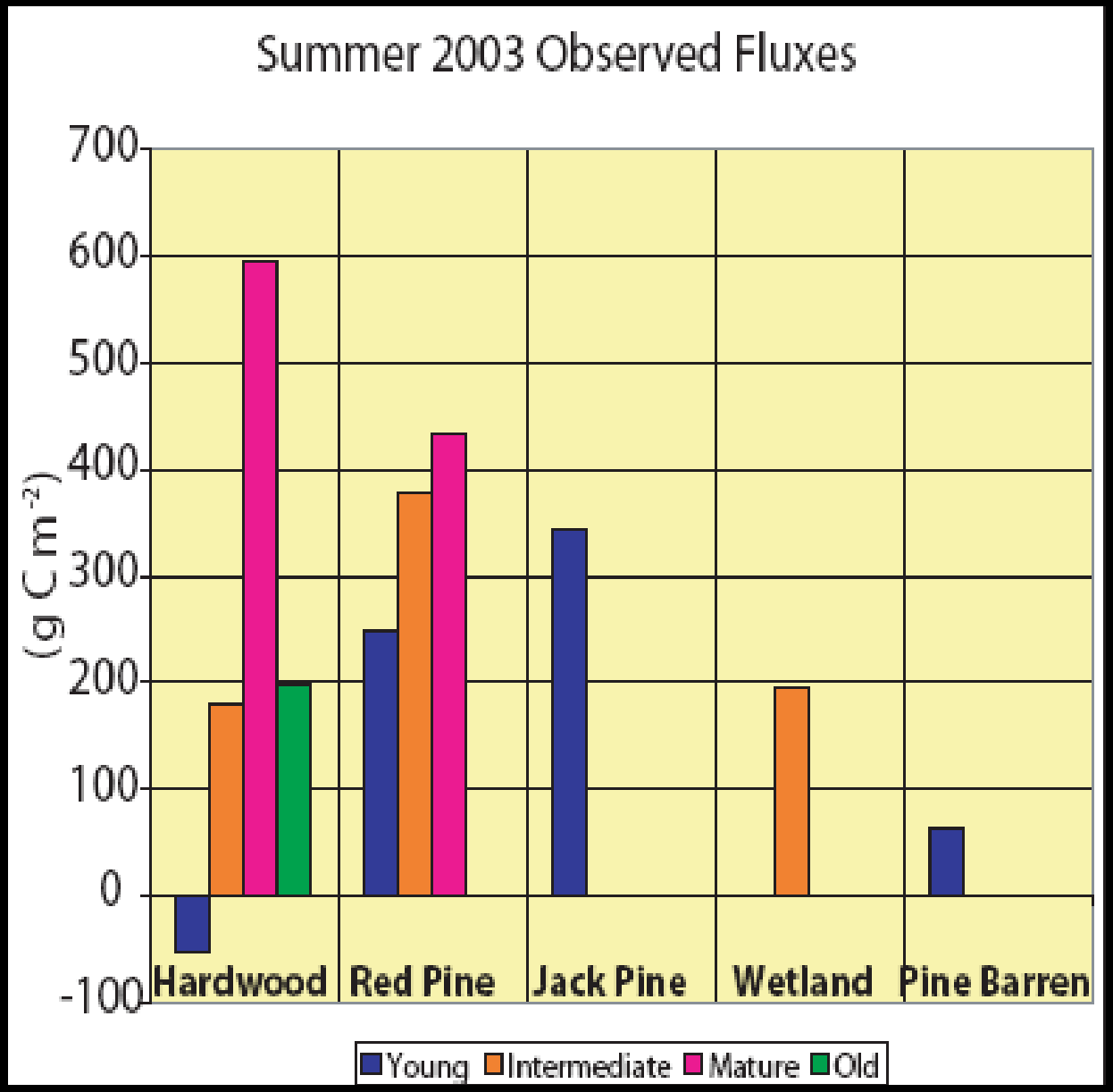
Complex Regions: 1+1≠2

a) IKONOS.	b) WISCLAND.	c) MODIS-UMD and IGBP.
		
— Mixed Forest 13.3% Upland Conifer 34.8% Aspen-Birch 5.7% Upland Hardwood 12.0% Upland Opening/Shrub 0.9% Grassland 17.8% Lowland Conifer 0.7% Lowland Deciduous 10.6% Lowland Shrub 0.6% Wet Meadow 2.6% Open Water 1.0% Road	7.1% Mixed Forest 13.0% Upland Conifer 25.3% Aspen-Birch 14.6% Upland Hardwood 6.8% Upland Opening/Shrub 1.8% Grassland 10.7% Lowland Conifer 1.9% Lowland Deciduous 16.3% Lowland Shrub 1.0% Wet Meadow 1.6% Open Water — Road	100% Mixed Forest

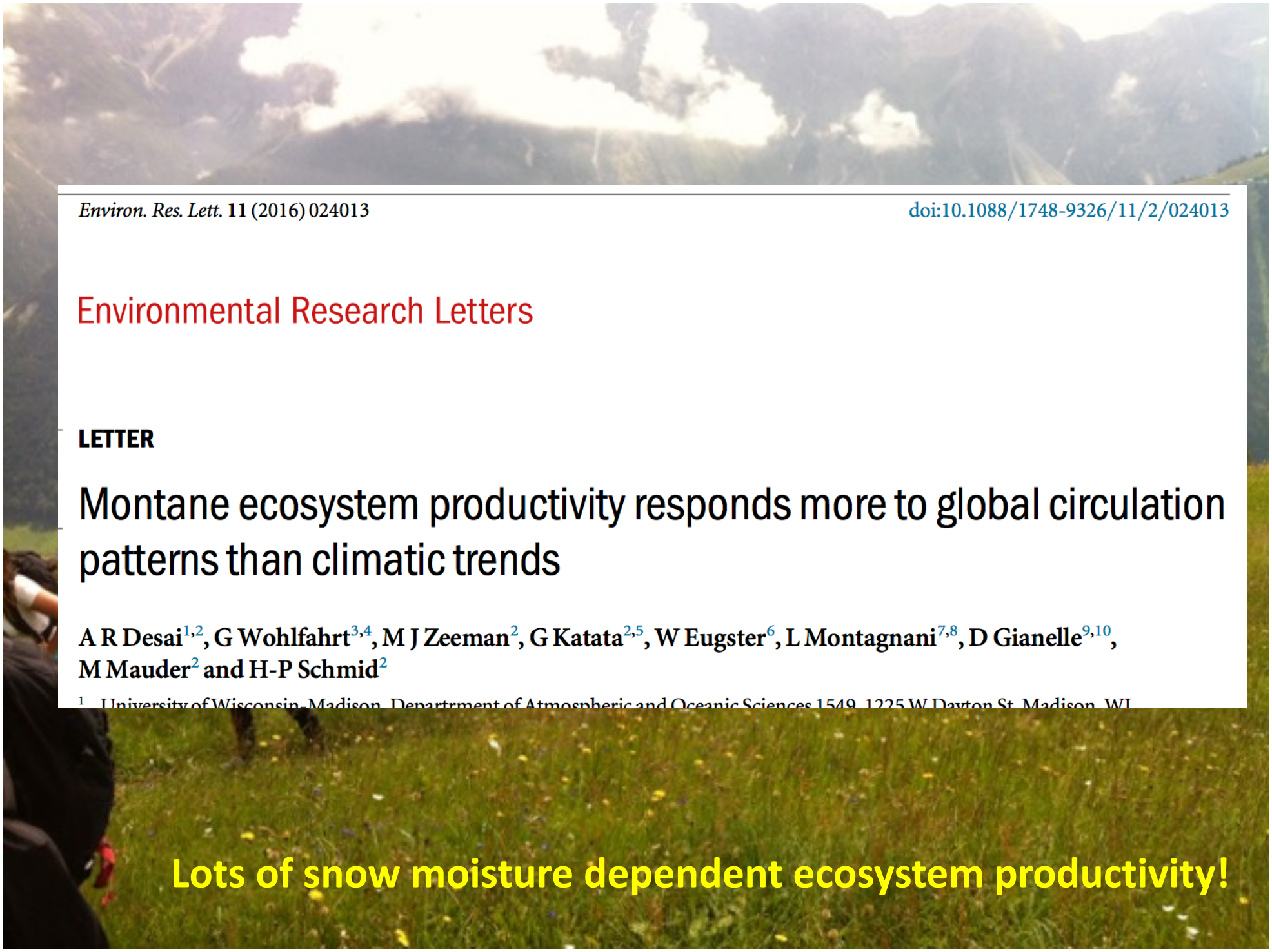

Cumulative NEE
Region
Wetland
Forest
Old−growth
200
0
−200
−400
gC m−2
1997
1999
2001
2003
2005
2007
2009
2011
2013
Year

Too many towers!

- NEP (=-NEE)
- Stand age matters
- Ecosystem type matters
- Upscaling performed with these data in Desai et al, 2008




What’s happening under the snow?



Environ. Res. Lett. **11** (2016) 024013 doi:10.1088/1748-9326/11/2/024013

Environmental Research Letters

LETTER

Montane ecosystem productivity responds more to global circulation patterns than climatic trends

A R Desai[1,2], G Wohlfahrt[3,4], M J Zeeman[2], G Katata[2,5], W Eugster[6], L Montagnani[7,8], D Gianelle[9,10], M Mauder[2] and H-P Schmid[2]

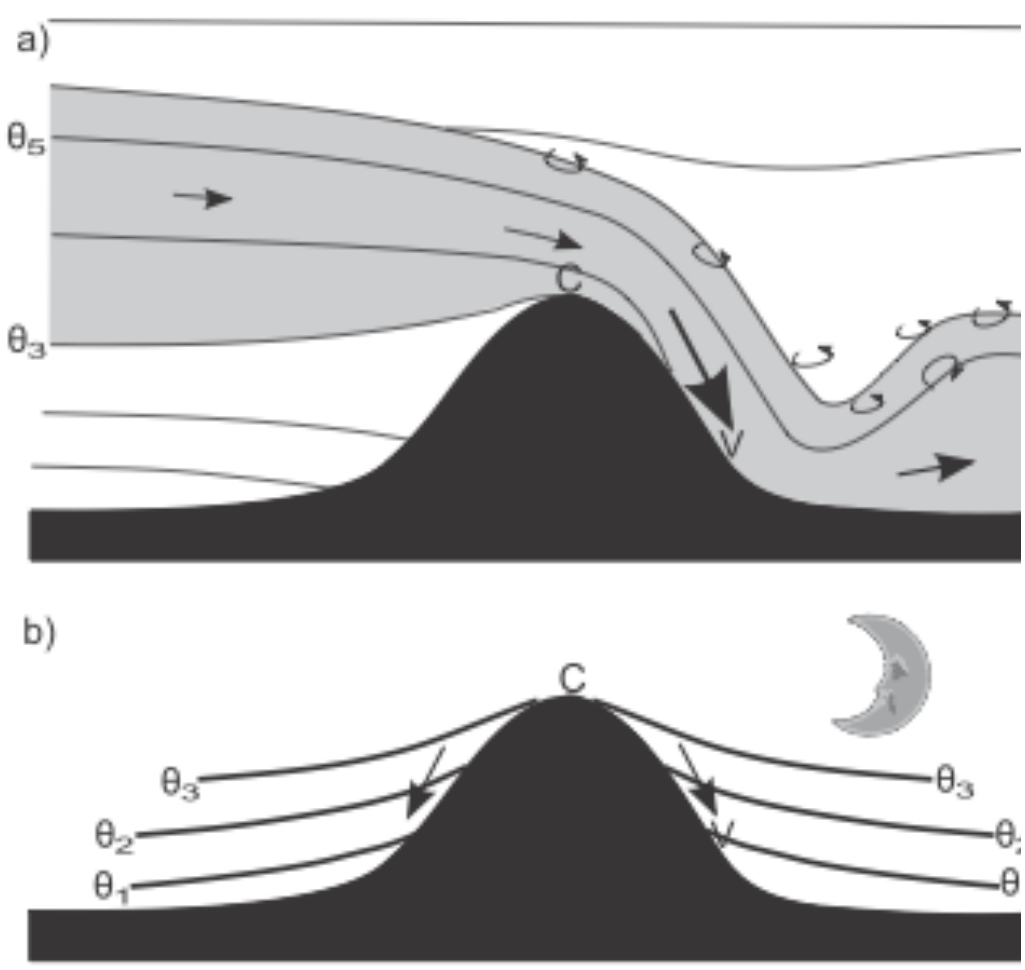
[1] University of Wisconsin-Madison, Department of Atmospheric and Oceanic Sciences 1549, 1225 W Dayton St, Madison, WI

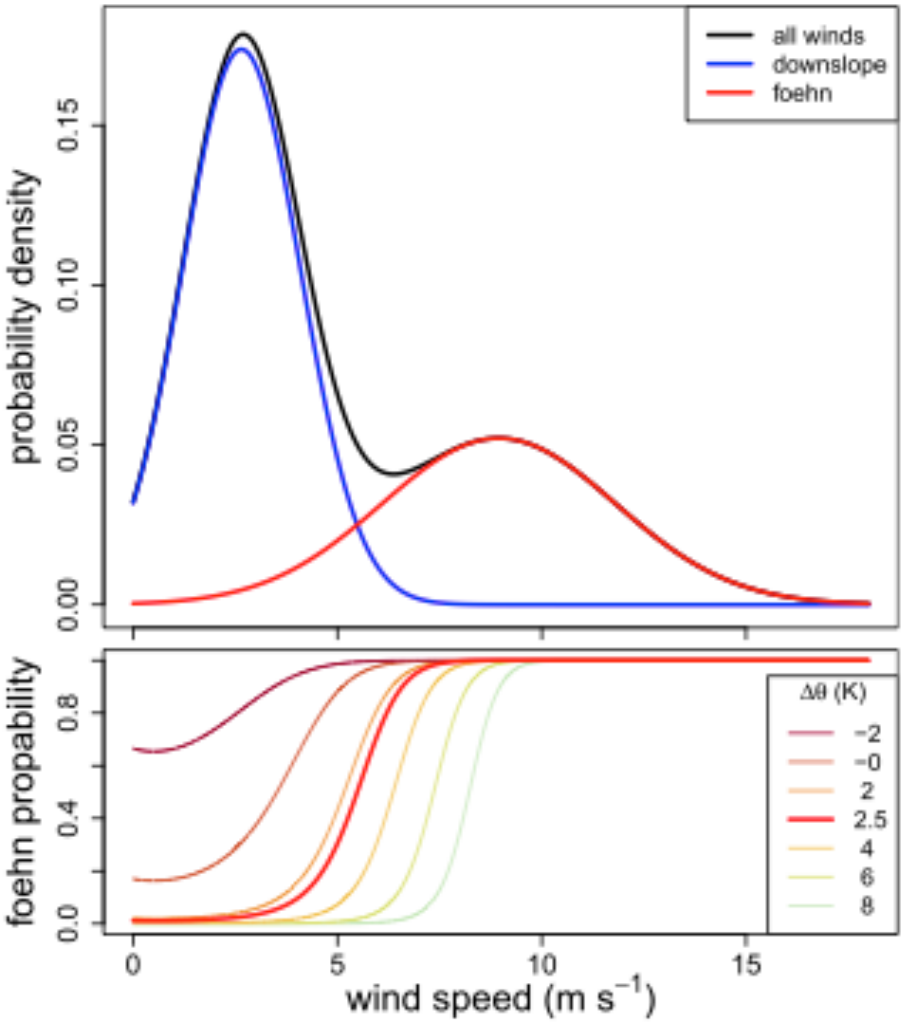
Lots of snow moisture dependent ecosystem productivity!

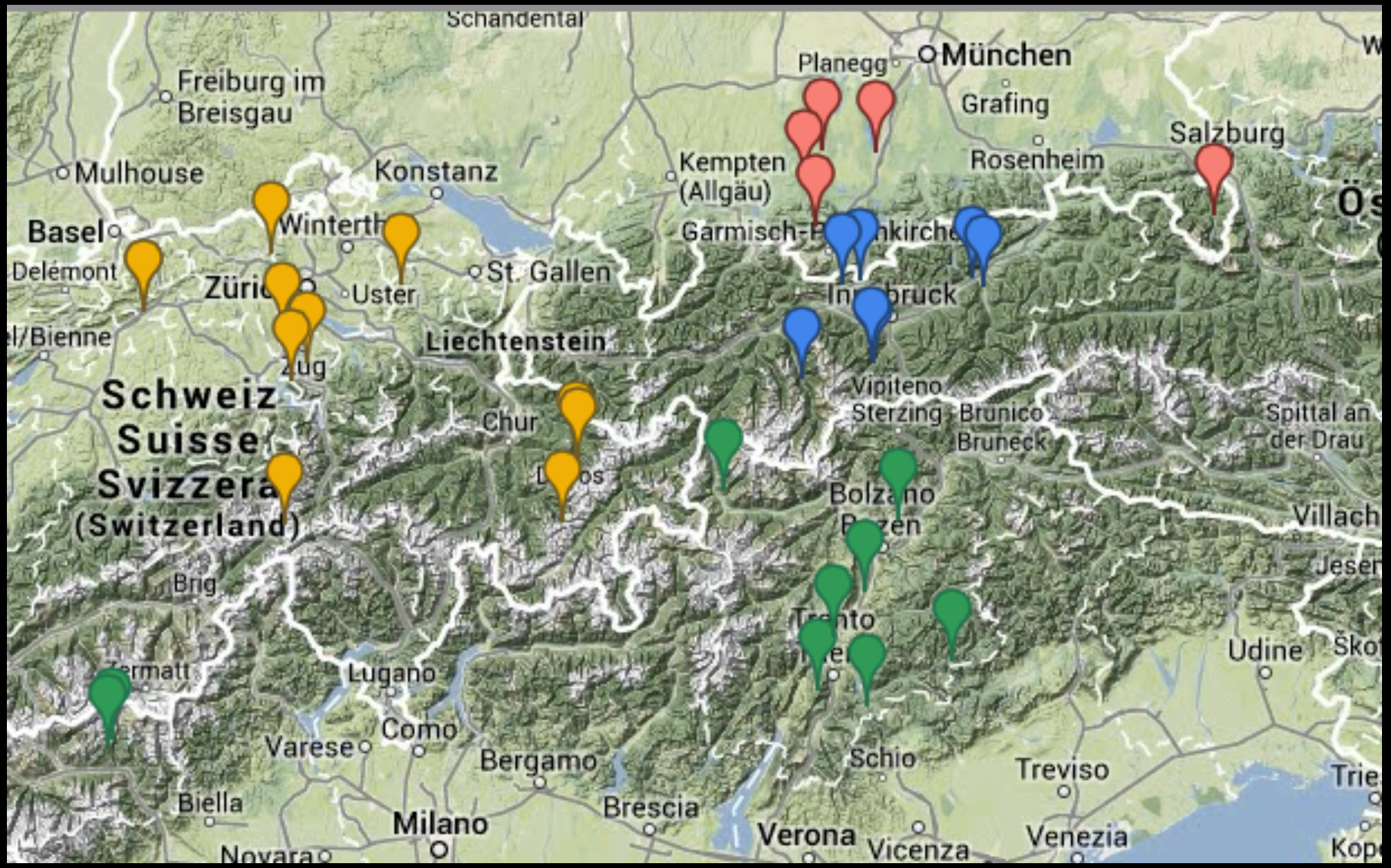
The Föhn eats snow!

Automatic and Probabilistic Foehn Diagnosis with a Statistical Mixture Model

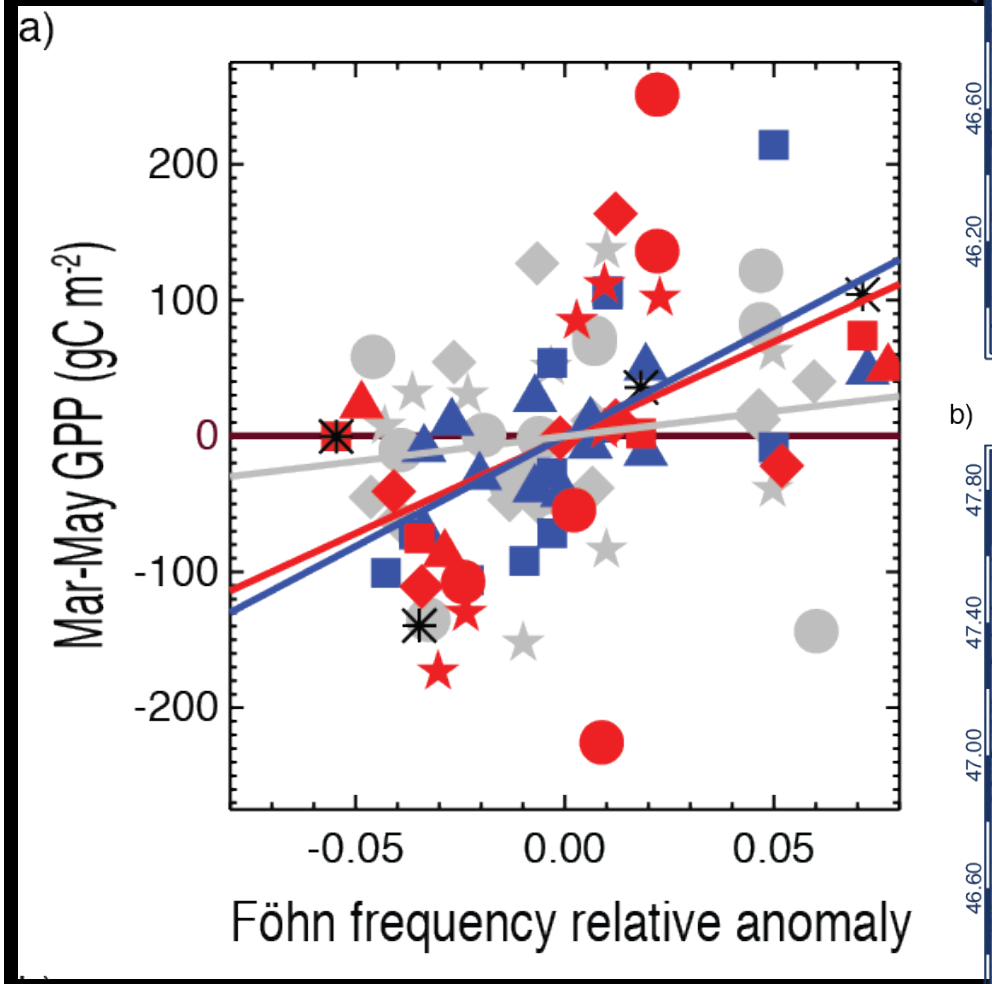
DAVID PLAVCAN AND GEORG J. MAYR
Institute of Meteorology and Geophysics, University of Innsbruck, Innsbruck, Austria
ACHIM ZEILEIS
Department of Statistics, Faculty of Economics and Statistics, University of Innsbruck, Innsbruck, Austria

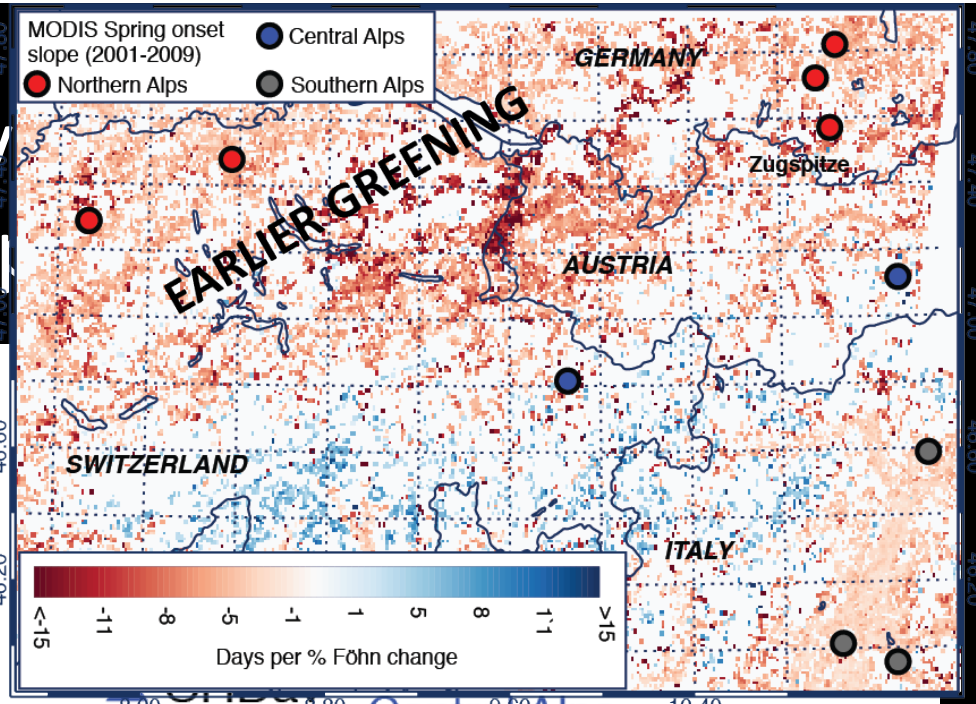





Schandental
Freiburg im Breisgau
Planegg
München
Grafing
Salzburg
Mulhouse
Konstanz
Kempten (Allgäu)
Rosenheim
Basel
Winterth
Garmisch-P
nkirche
Delémont
Züric
St. Gallen
Uster
Inn bruck
Liechtenstein
Schweiz
Suisse
Svizzera
(Switzerland)
Chur
Vipiteno
Sterzing
Brunico
Bruneck
Spittal an der Drau
Bolzano
Villach
Brig
Udine
Lugano
Como
Varese
Bergamo
Schio
Treviso
Biella
Milano
Brescia
Verona
Vicenza
Venezia

Föhn drives produtivity
feedback to s



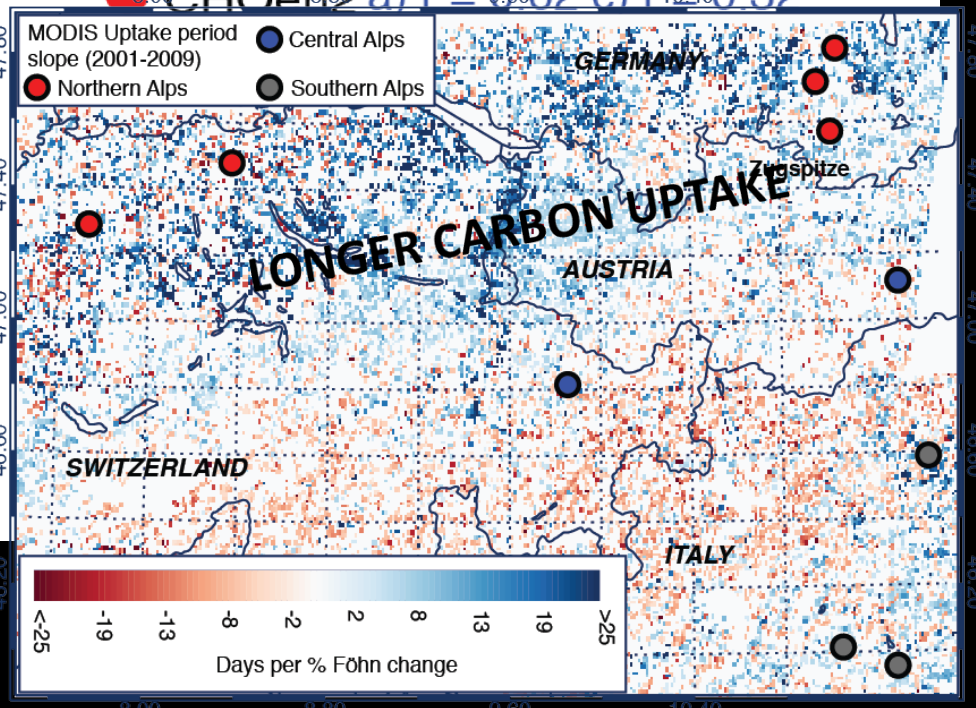


ATNeu

Central Alps

b)

CHOen2 a) r = 0.62 c) r = 0.32



Park Falls/Chequamegon National Forest region, WI

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

Credit: Matt Rydzik (U Wisconsin)

Agricultural and Forest Meteorology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

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

Agricultural and Forest Meteorology 232 (2017) 10–22

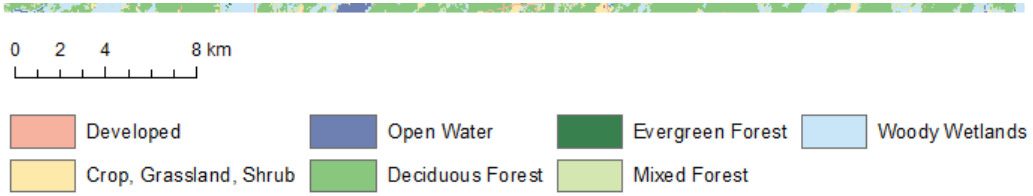
Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

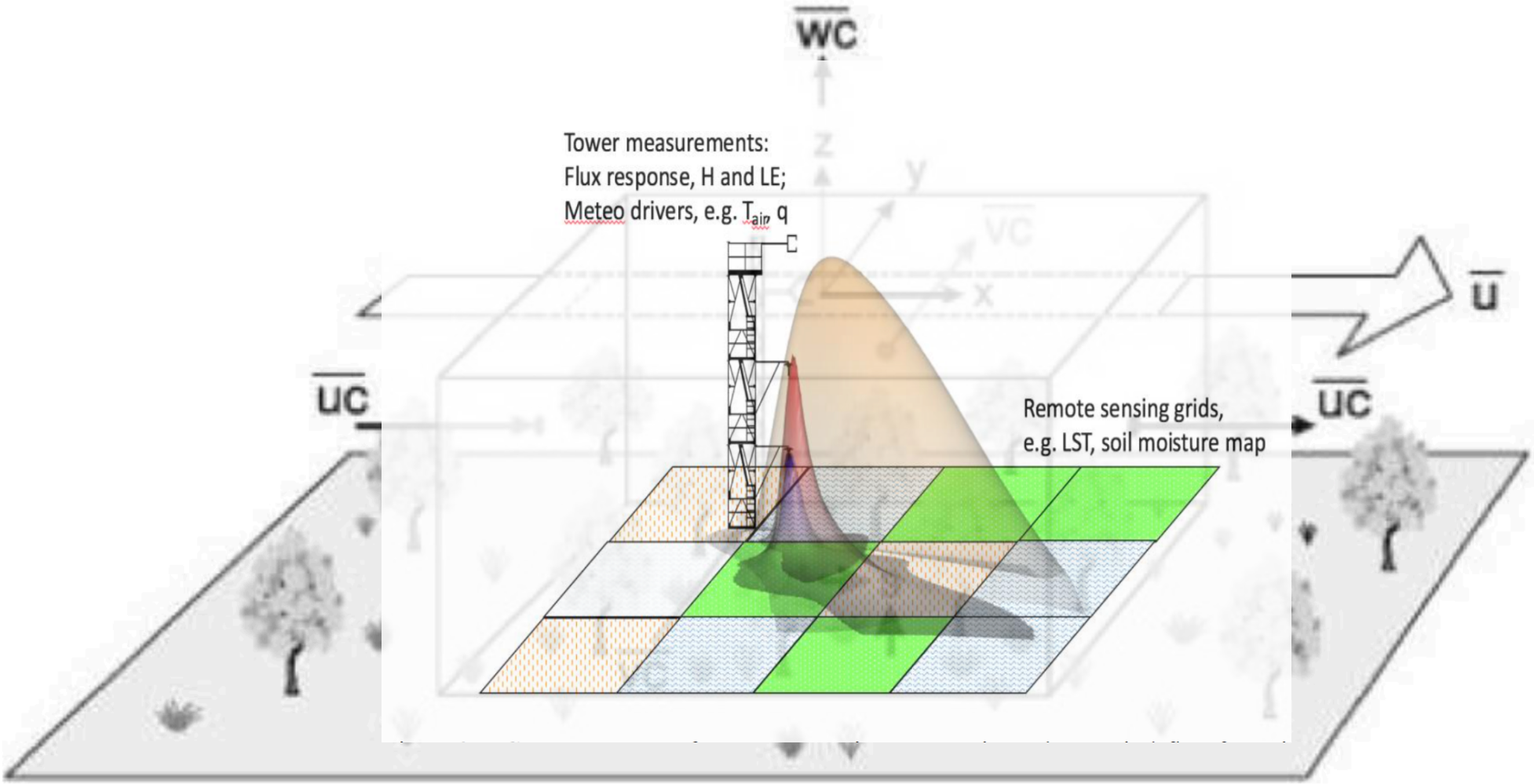
journal homepage: www.elsevier.com/locate/agrformet

Upscaling tower-observed turbulent exchange at fine spatio-temporal resolution using environmental response functions

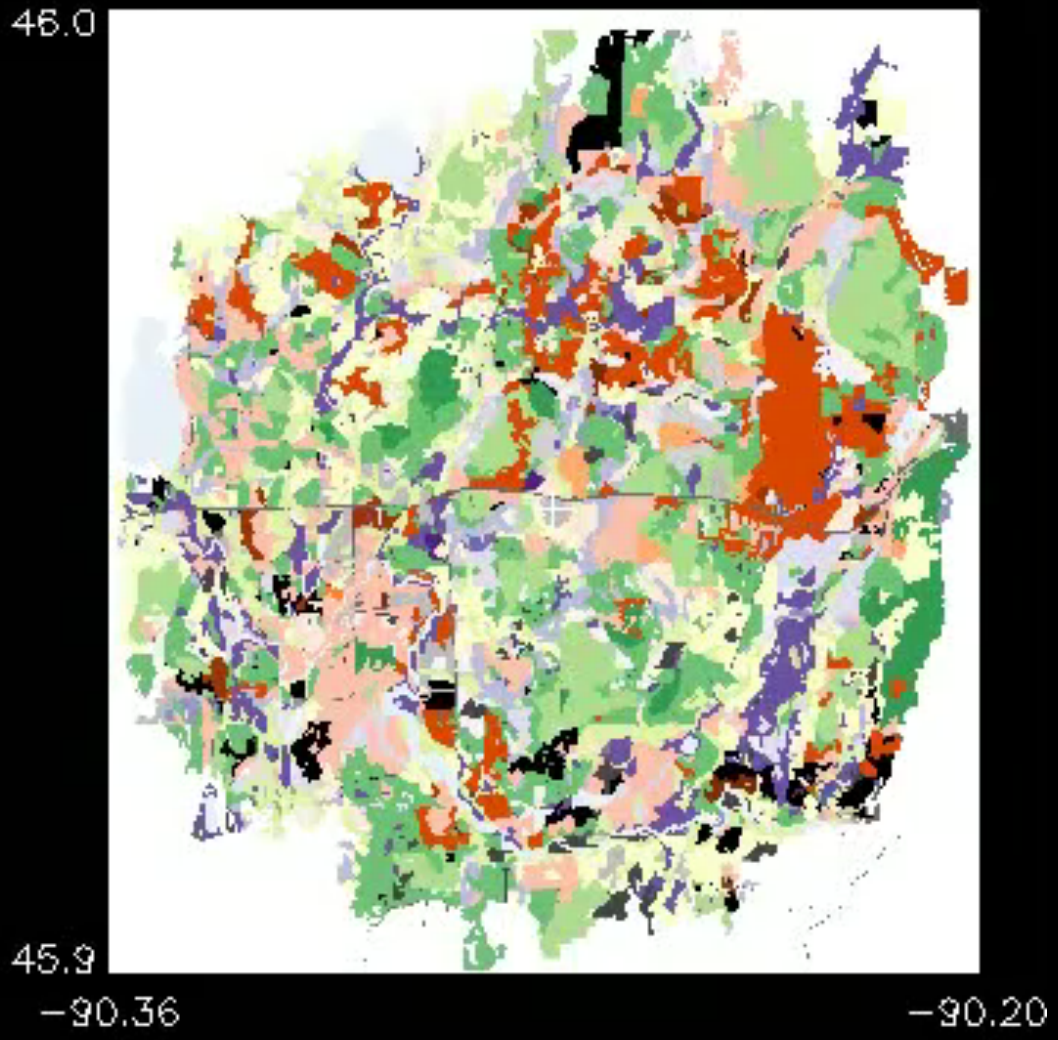
Ke Xu[a,*], Stefan Metzger[b,c], Ankur R. Desai[a]

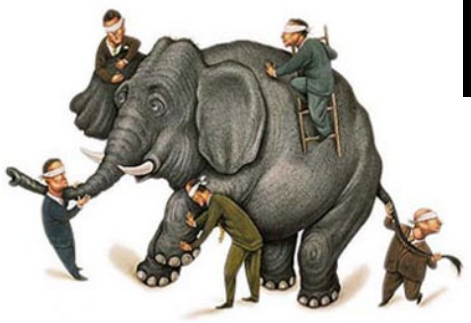


a


$\overline{wc}$
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

Flux towers see the trees for the forest…

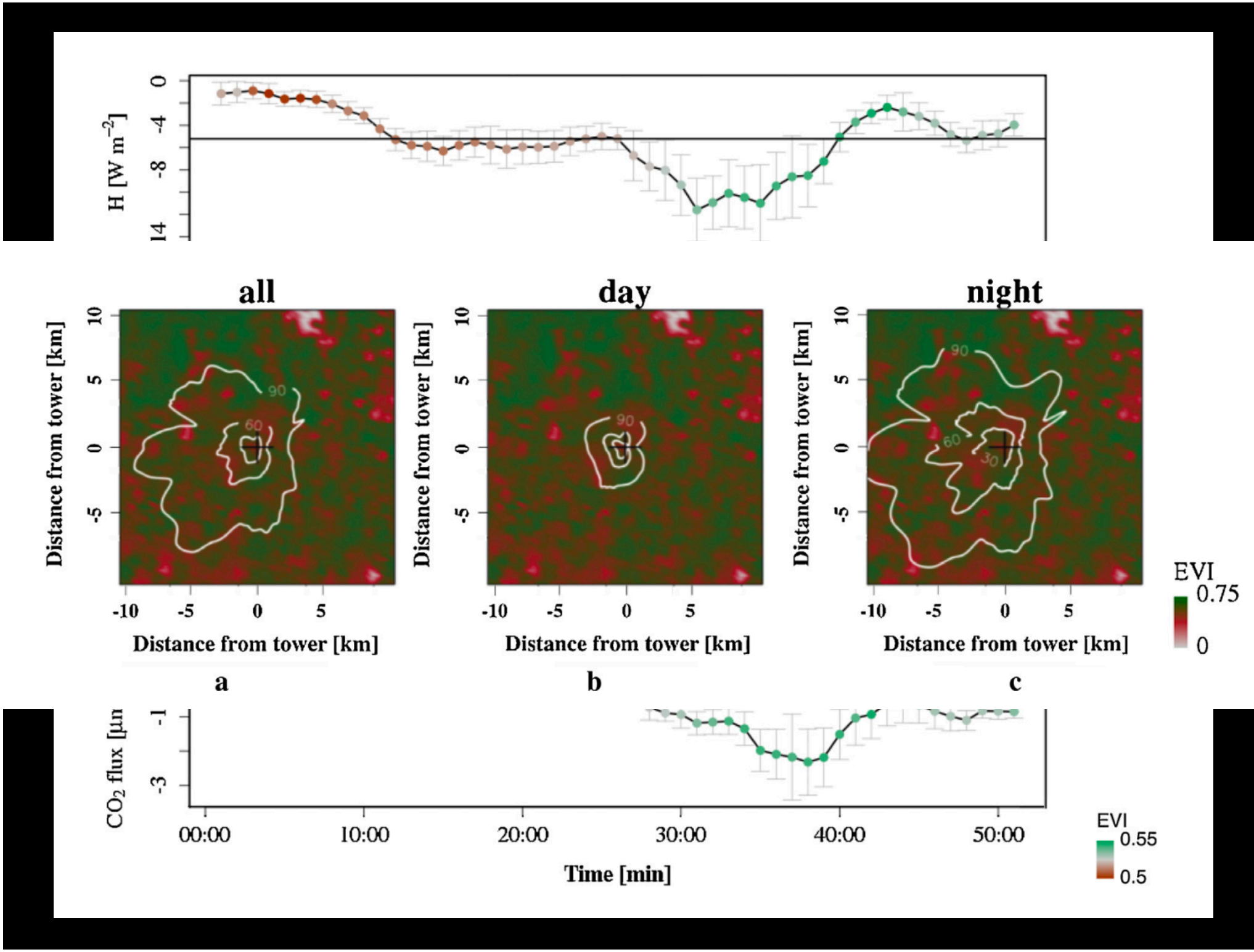




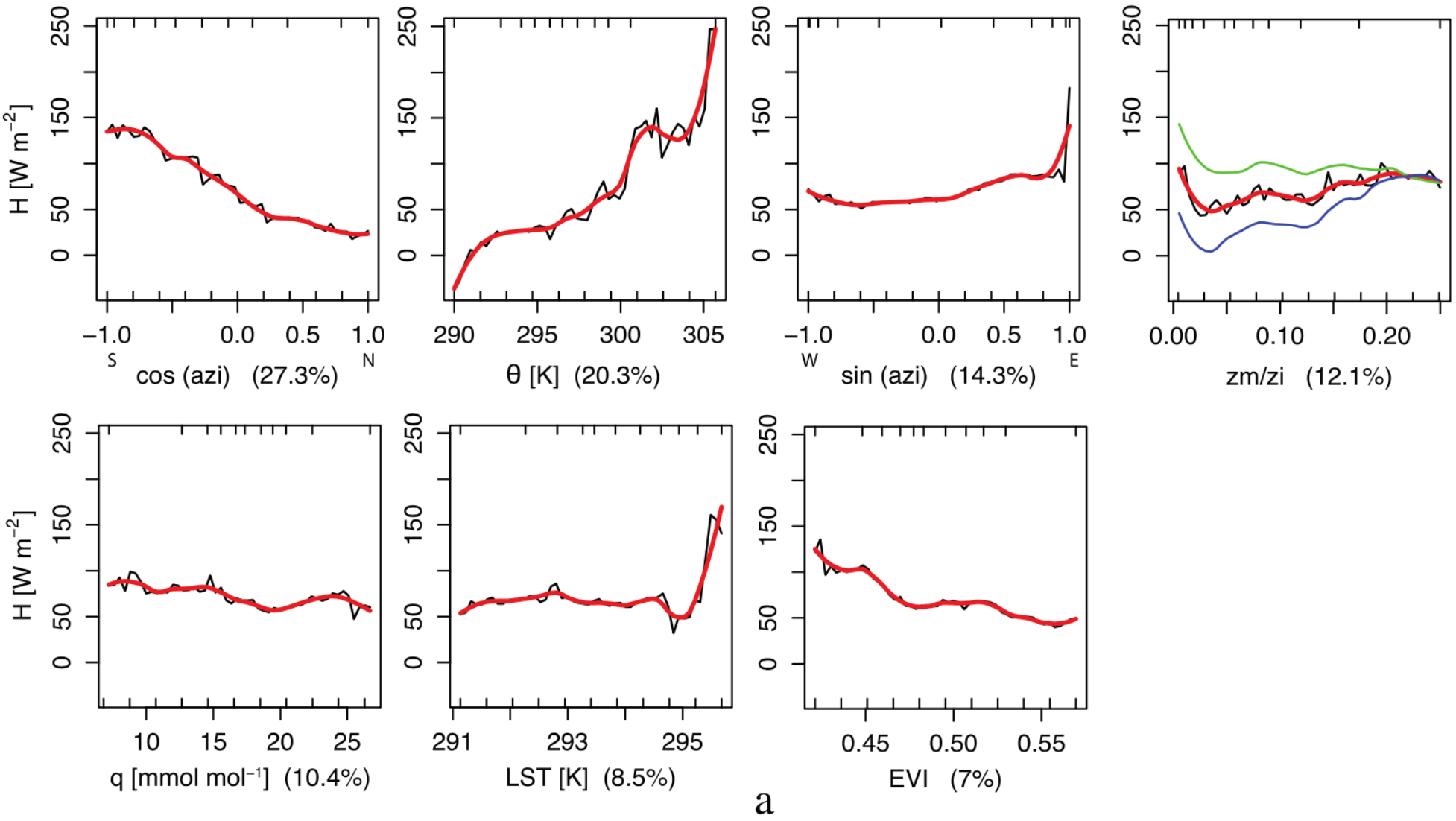
Adopted from a version by HaPE Schmid (KIT)

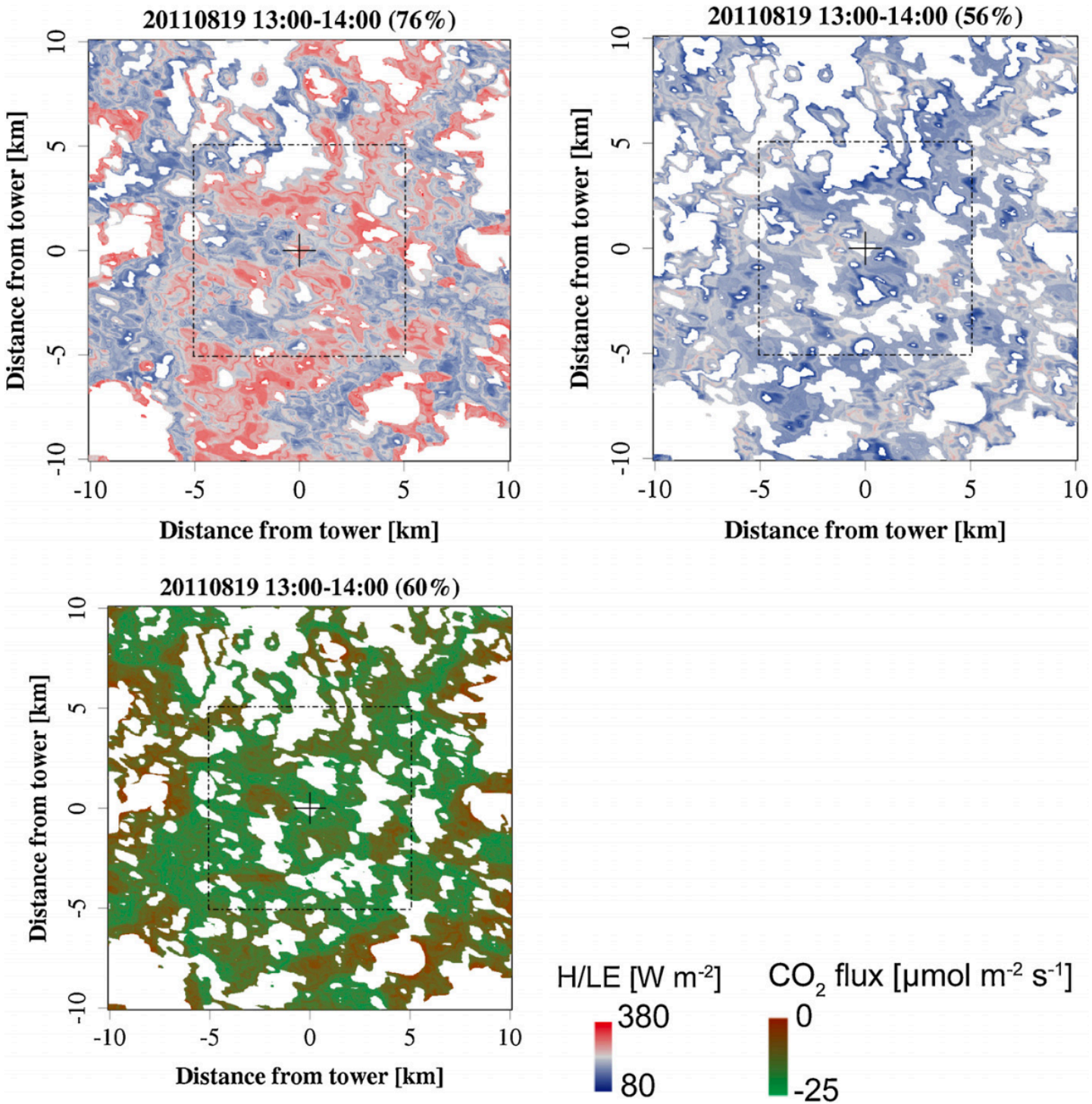
Some questions to ponder:

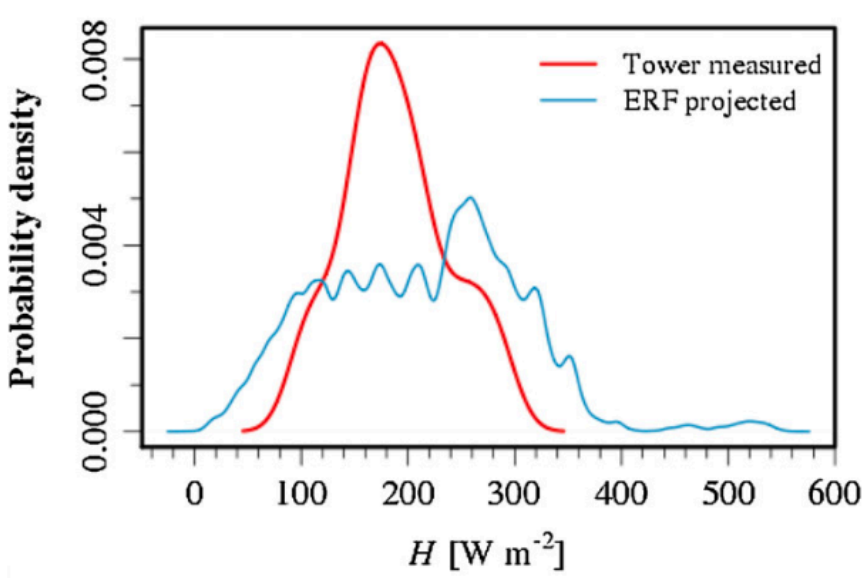
- How homogenous is homogenous enough?
  - How well does a single eddy flux tower represent a typical earth system model domain (10x10 km) mean surface energy fluxes and how does mean flux and energy balance closure vary with surface flux heterogeneity?
- How many flux towers are towers enough?
  - If you had multiple towers, how many would you need before sufficiently sampling domain mean flux? Are there smarter ways to compute the mean flux when you have multiple towers?


H [W m^{-2}]
0
-4
-8
14
all
day
night
Distance from tower [km]
10
5
0
-5
90
60
30
-10
-5
0
5
Distance from tower [km]
EVI
0.75
0
a
b
c
CO_2 flux [µn
-1
-3
00:00
10:00
20:00
30:00
40:00
50:00
Time [min]
EVI
0.55
0.5

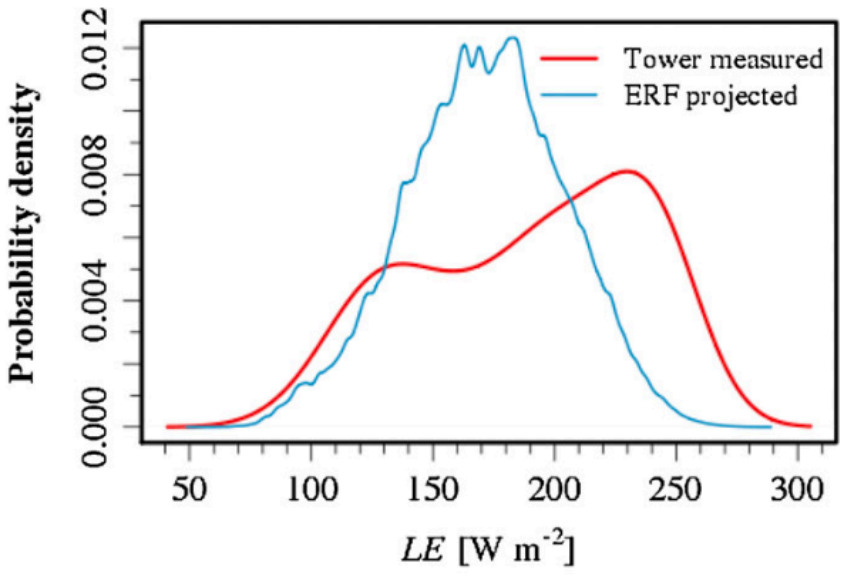
The Environmental Response Function method (Metzger et al 2013, Xu et al., 2017)



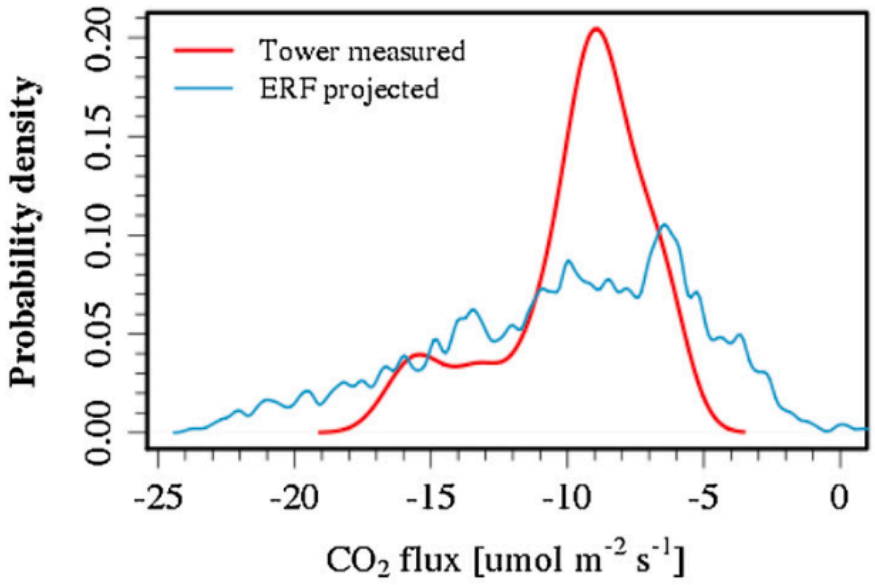

20110819 13:00-14:00 (76%)
20110819 13:00-14:00 (56%)
20110819 13:00-14:00 (60%)
Distance from tower [km]
Distance from tower [km]
-10
-5
0
5
10
H/LE [W m-2]
380
80
CO2 flux [µmol m-2 s-1]
0
-25


Probability density
0.000
0.004
0.008
Tower measured
ERF projected
0
100
200
300
400
500
600
H [W m-2]

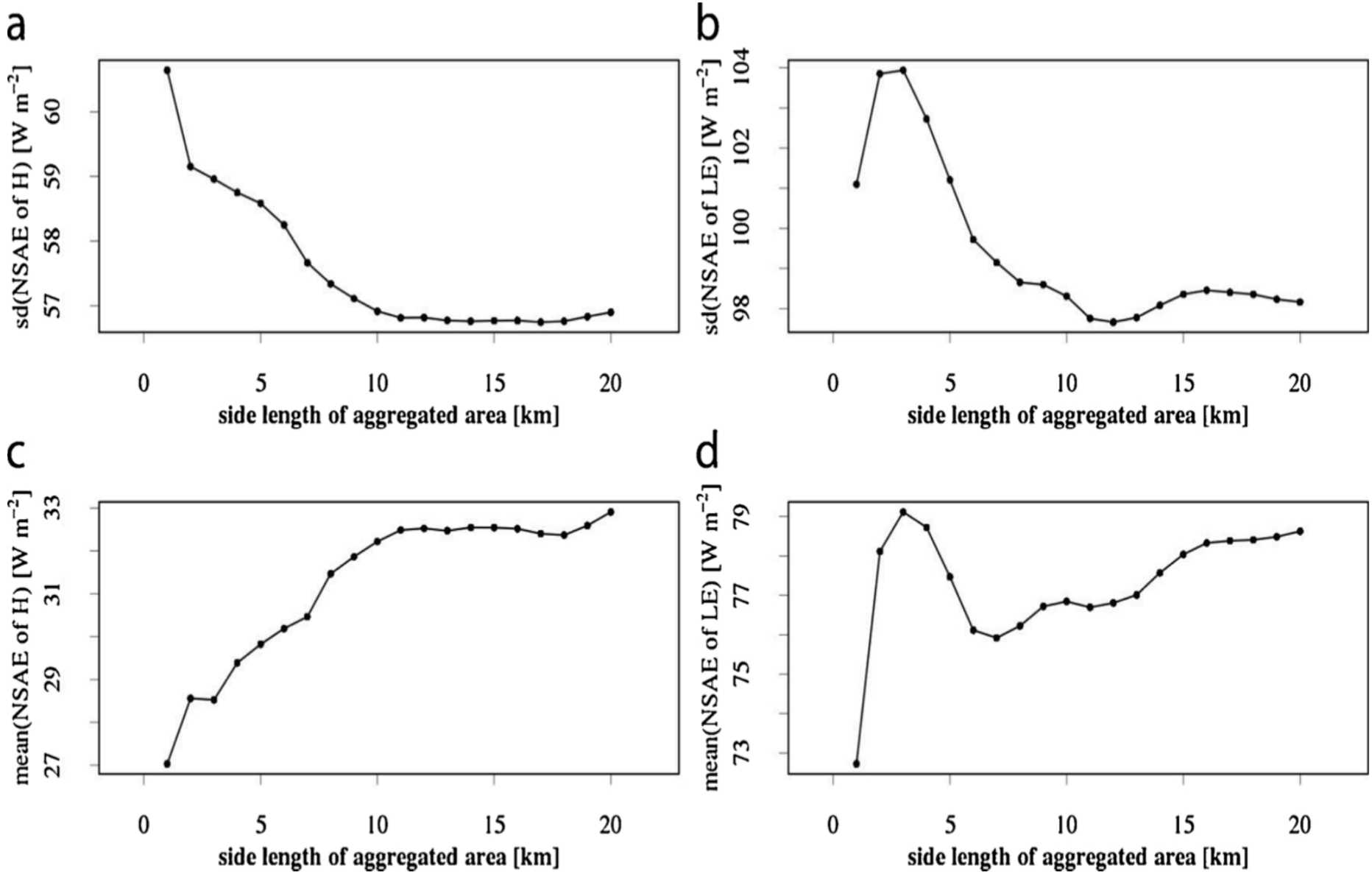
(a)

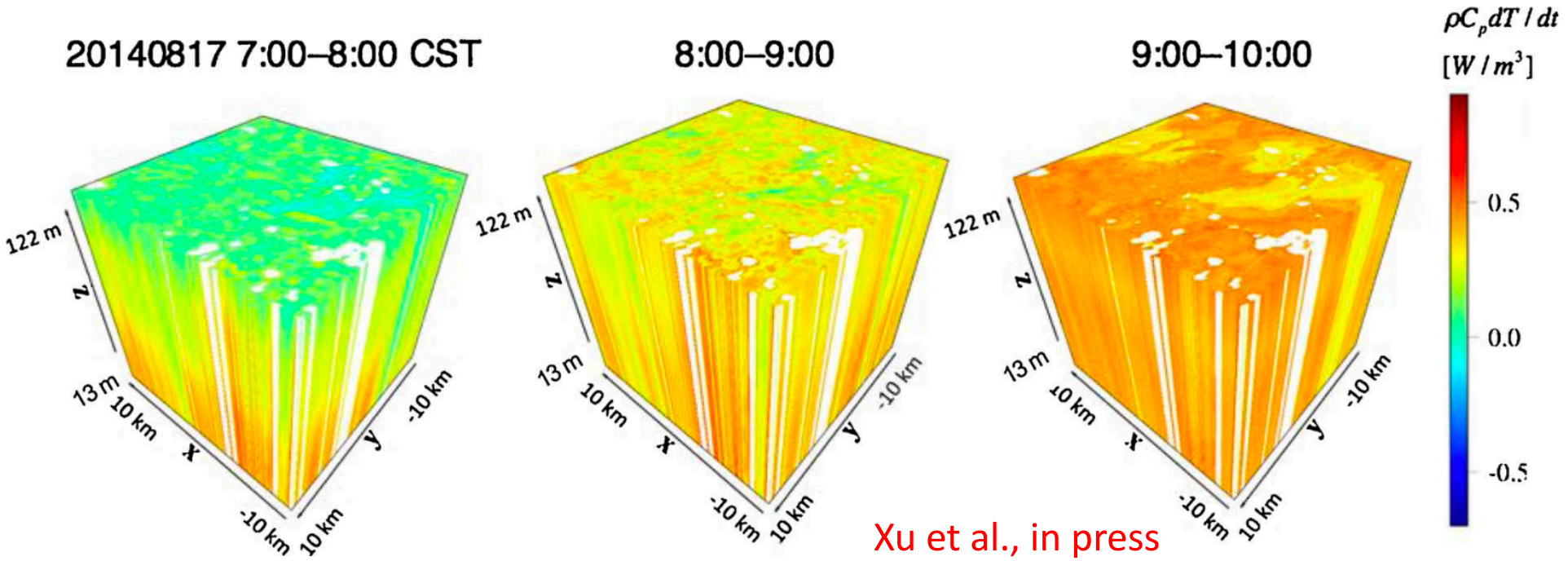

Probability density
0.000
0.004
0.008
0.012
Tower measured
ERF projected
50
100
150
200
250
300
LE [W m-2]

(b)

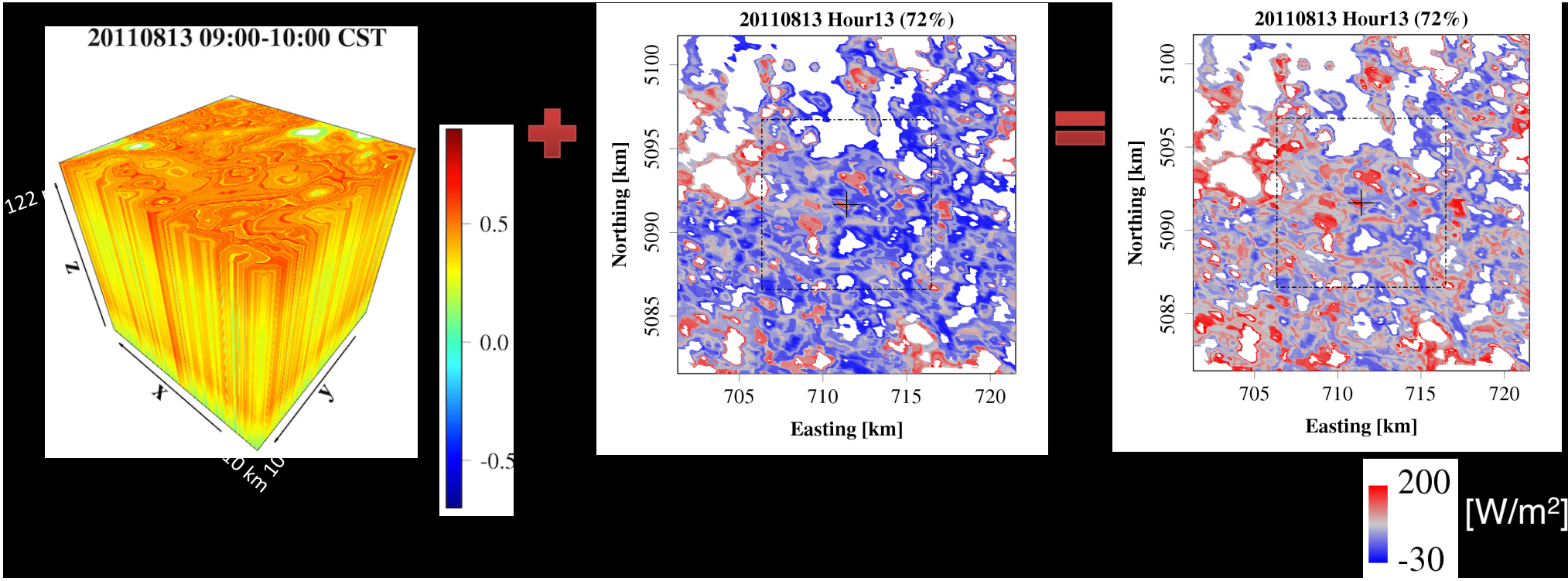

Probability density
0.00
0.05
0.10
0.15
0.20
Tower measured
ERF projected
-25
-20
-15
-10
-5
0
CO2 flux [umol m-2 s-1]

(c)


a
sd(NSAE of H) [W m^{-2}]
57
58
59
60
0
5
10
15
20
side length of aggregated area [km]
b
sd(NSAE of LE) [W m^{-2}]
98
100
102
104
0
5
10
15
20
side length of aggregated area [km]
c
mean(NSAE of H) [W m^{-2}]
27
29
31
33
0
5
10
15
20
side length of aggregated area [km]
d
mean(NSAE of LE) [W m^{-2}]
73
75
77
79
0
5
10
15
20
side length of aggregated area [km]

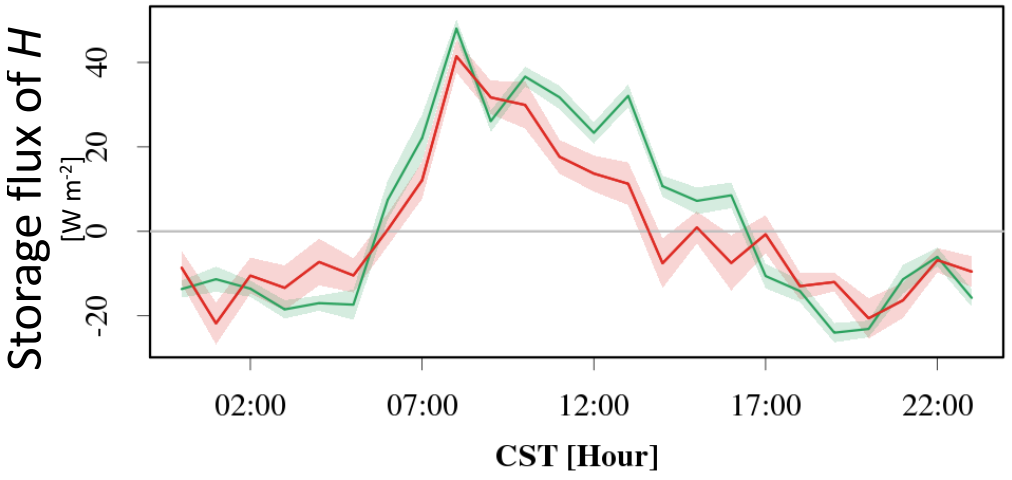


Xu et al., in press

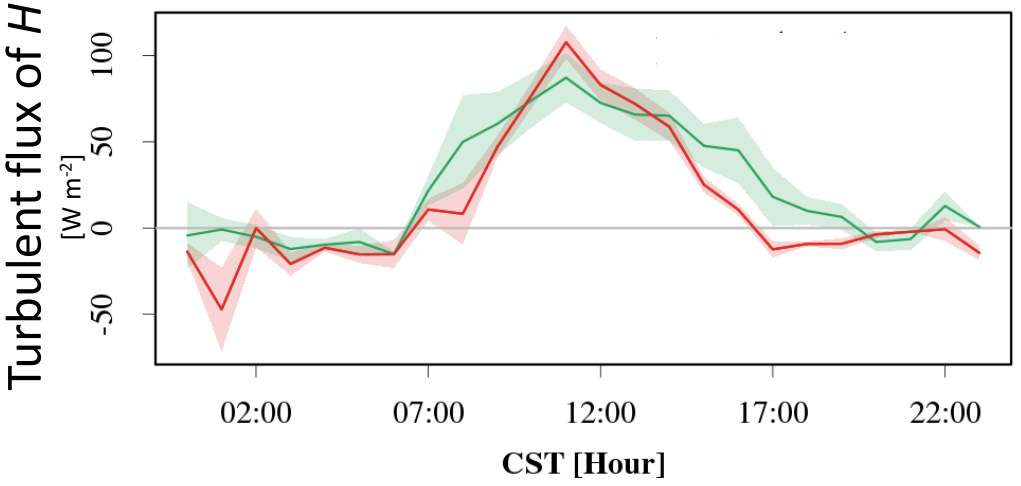


Does rectified surface atmosphere exchange help ?

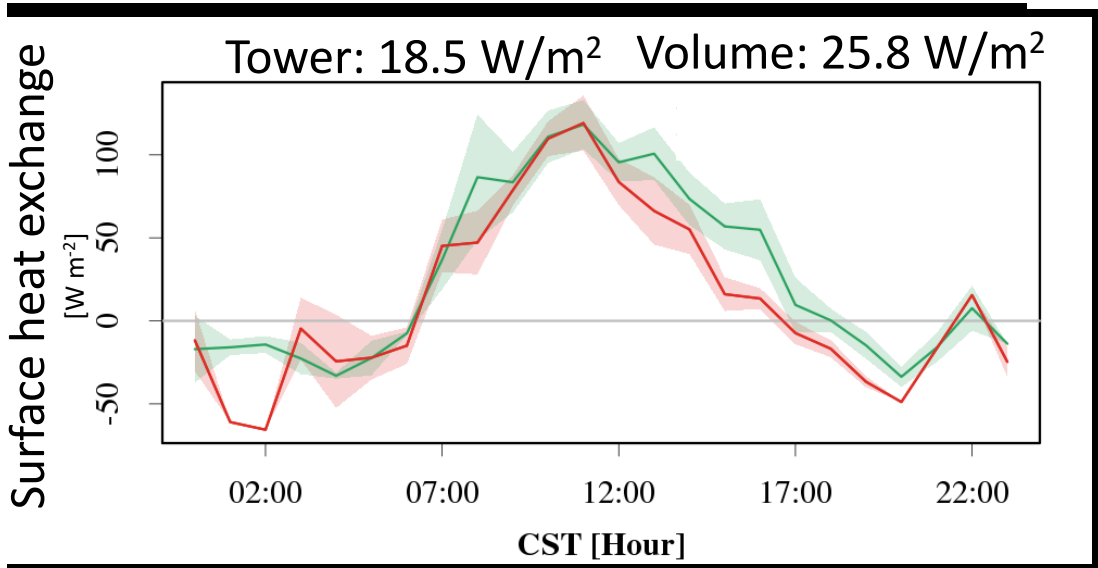
Tower: -0.3 W/m² Volume: 2.4 W/m²



Tower: 19.4 W/m² Volume: 24.1 W/m²



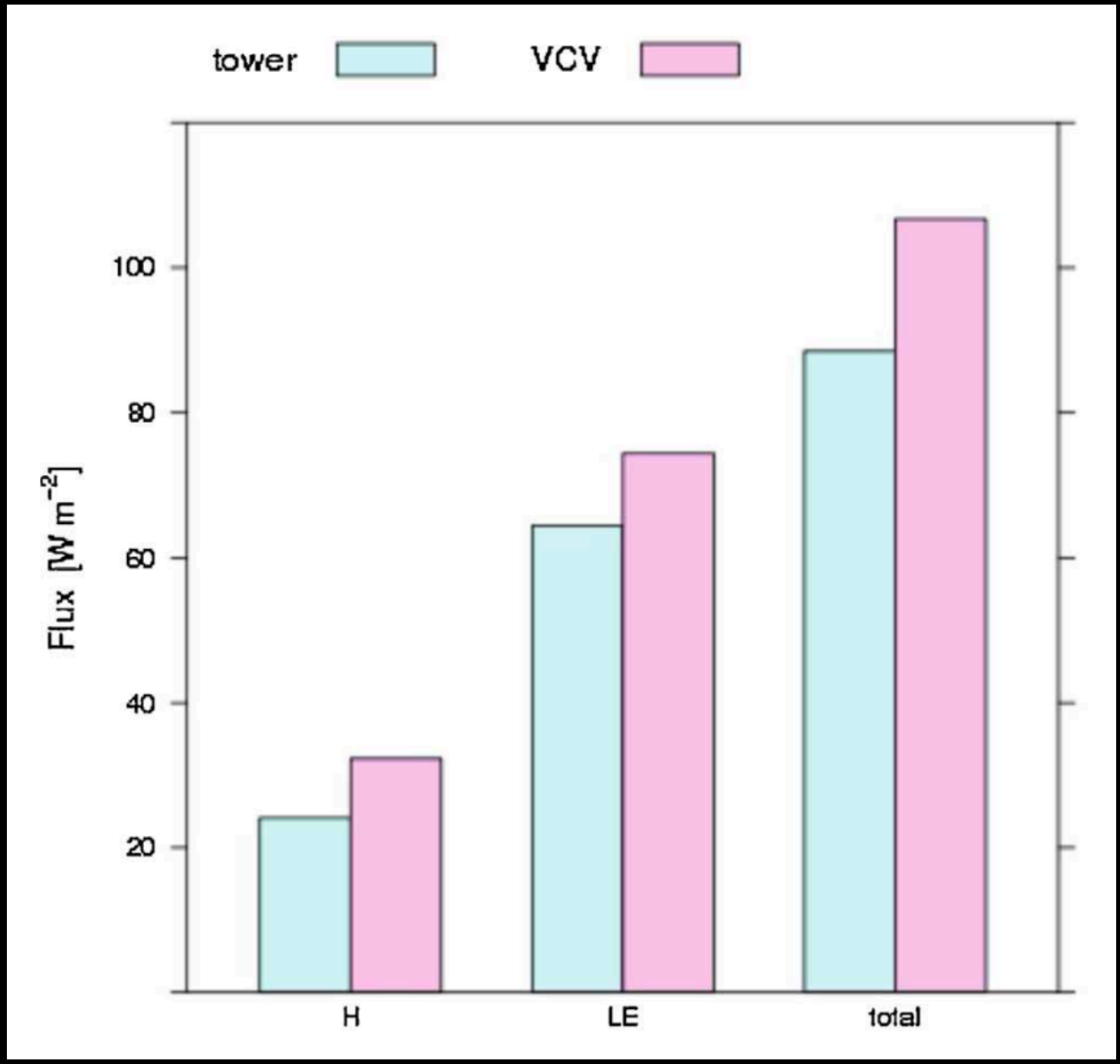
Tower: 18.5 W/m² Volume: 25.8 W/m²



Solves that day-night bias in footprint, but…
volume-rectified energy flux is + 7.3 W/m²
Why?

tower-observed

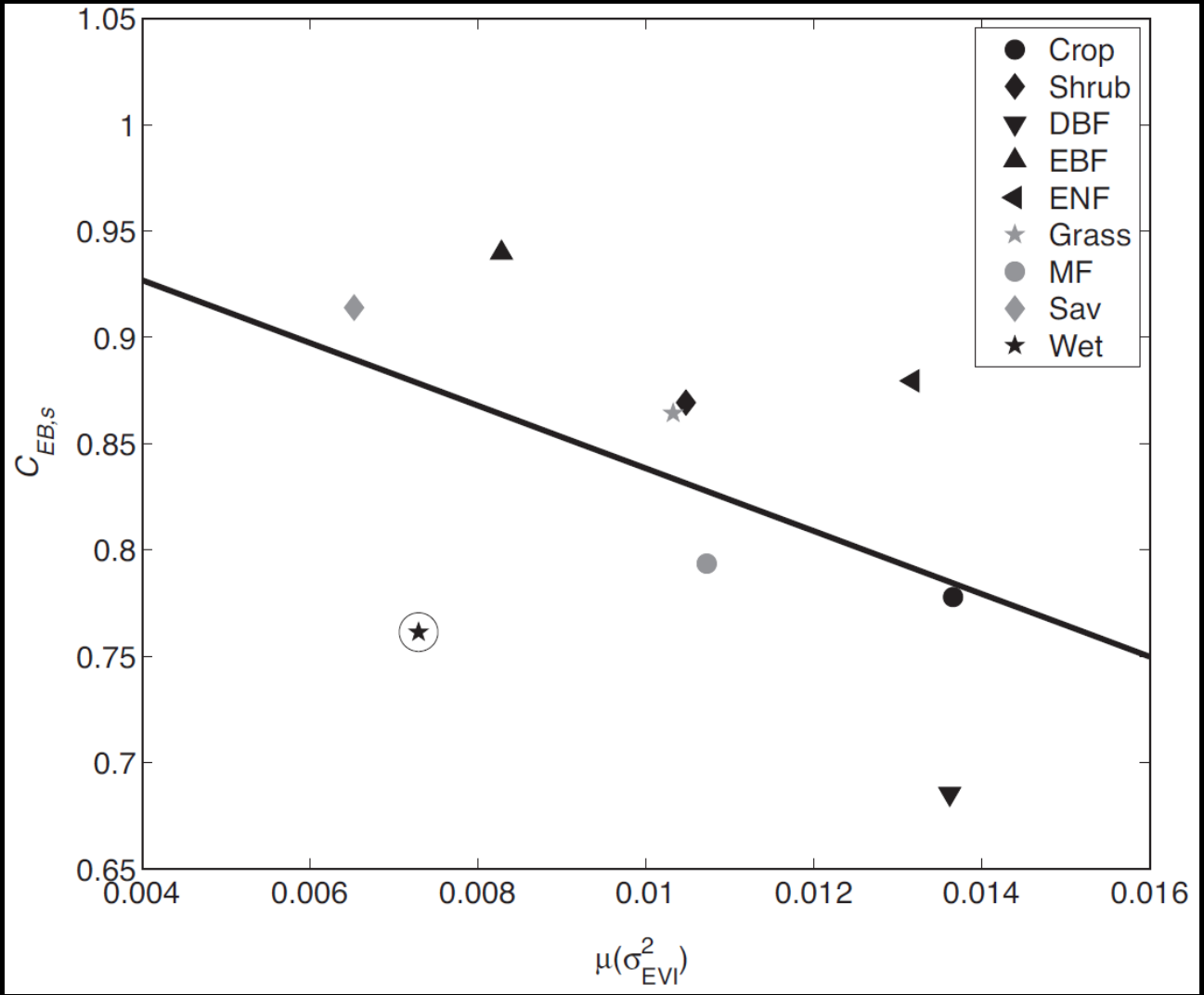
volume-rectified


tower
VCV
Flux [W m^{-2}]
100
80
60
40
20
H
LE
total

Heterogeneous sites have worse energy balance closure (EBC)

EBC=
H+Le

Rnet-G



Greenness spatial variance

Stoy et al., 2013, AFM

Landscape variance potentially drives stationary eddies

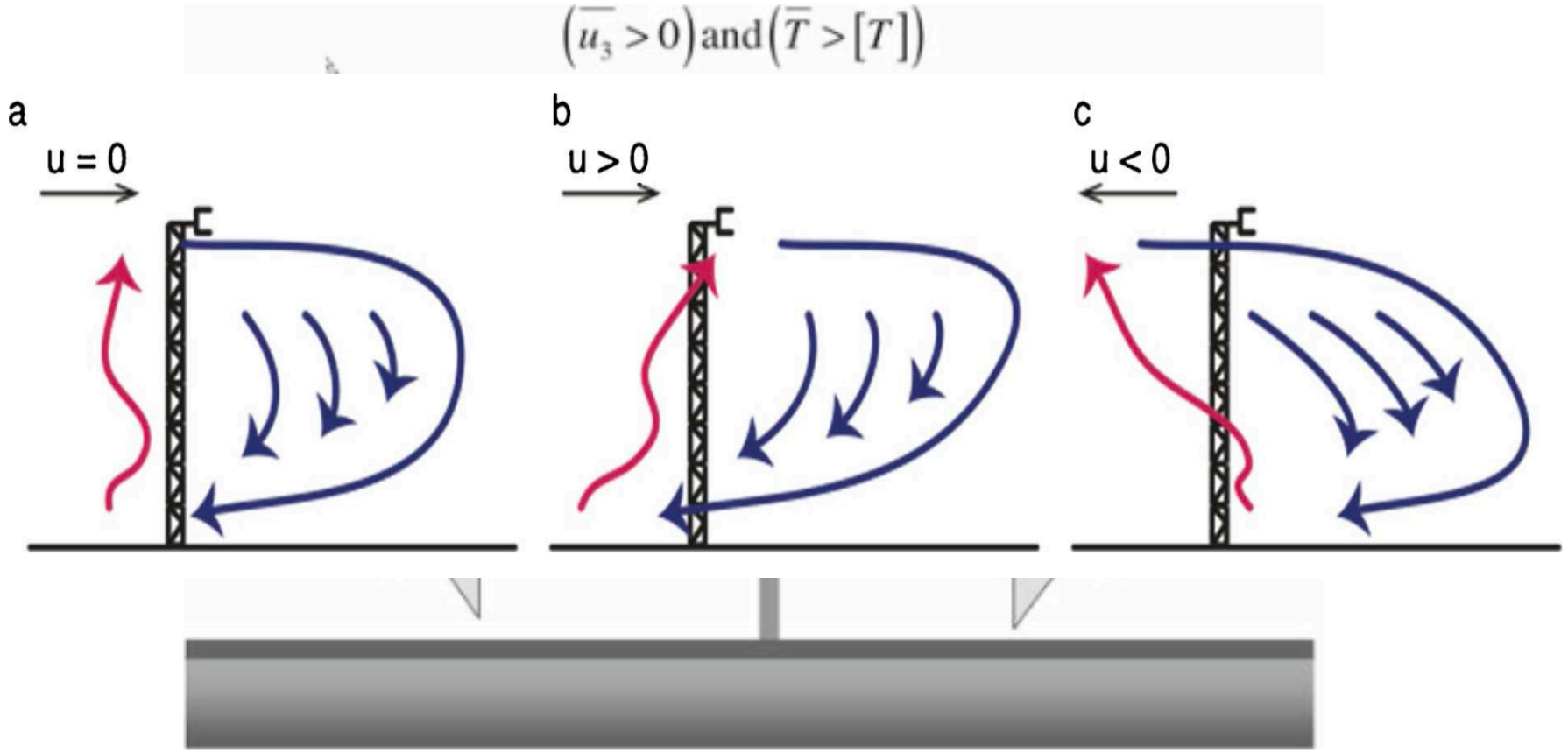
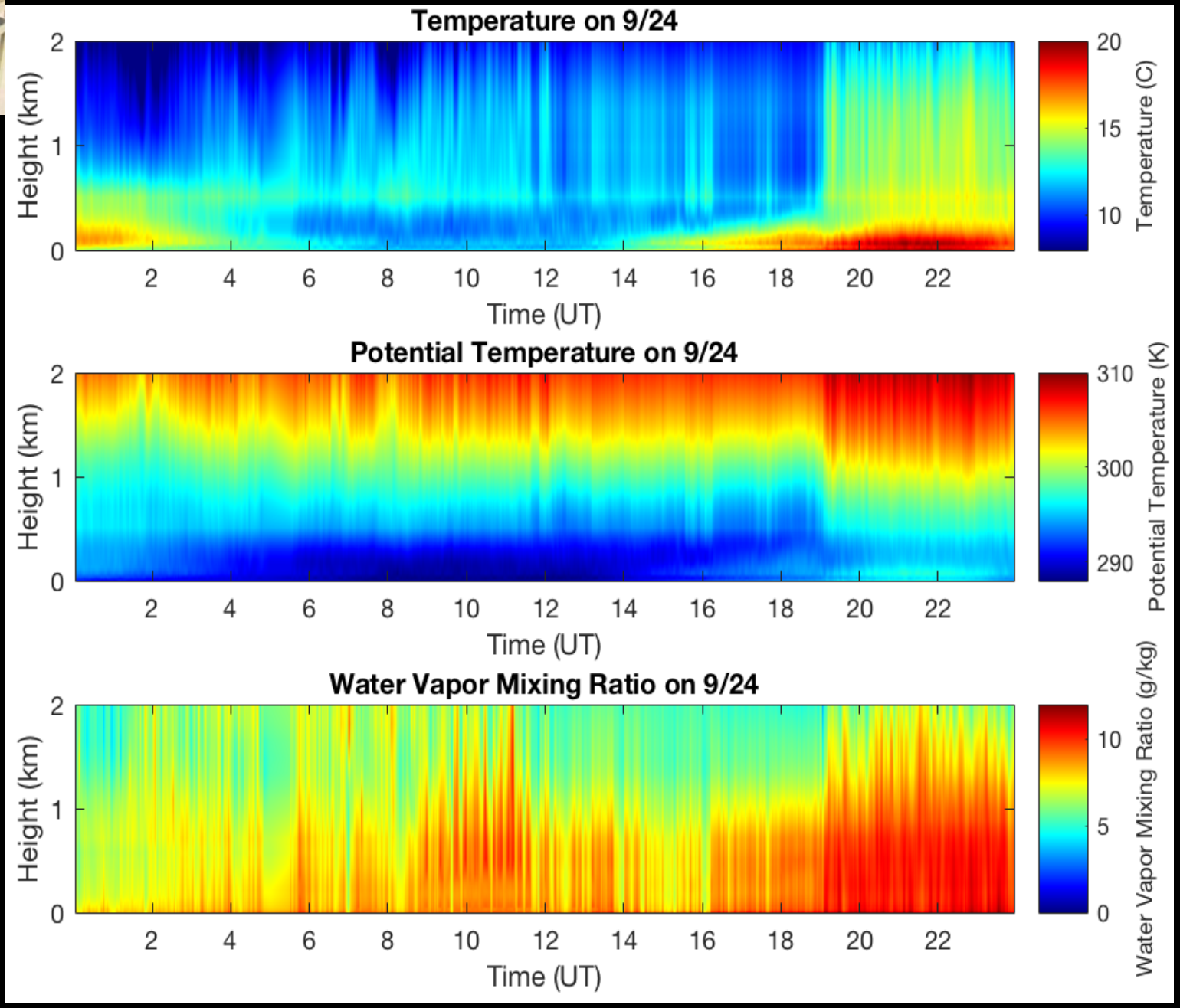


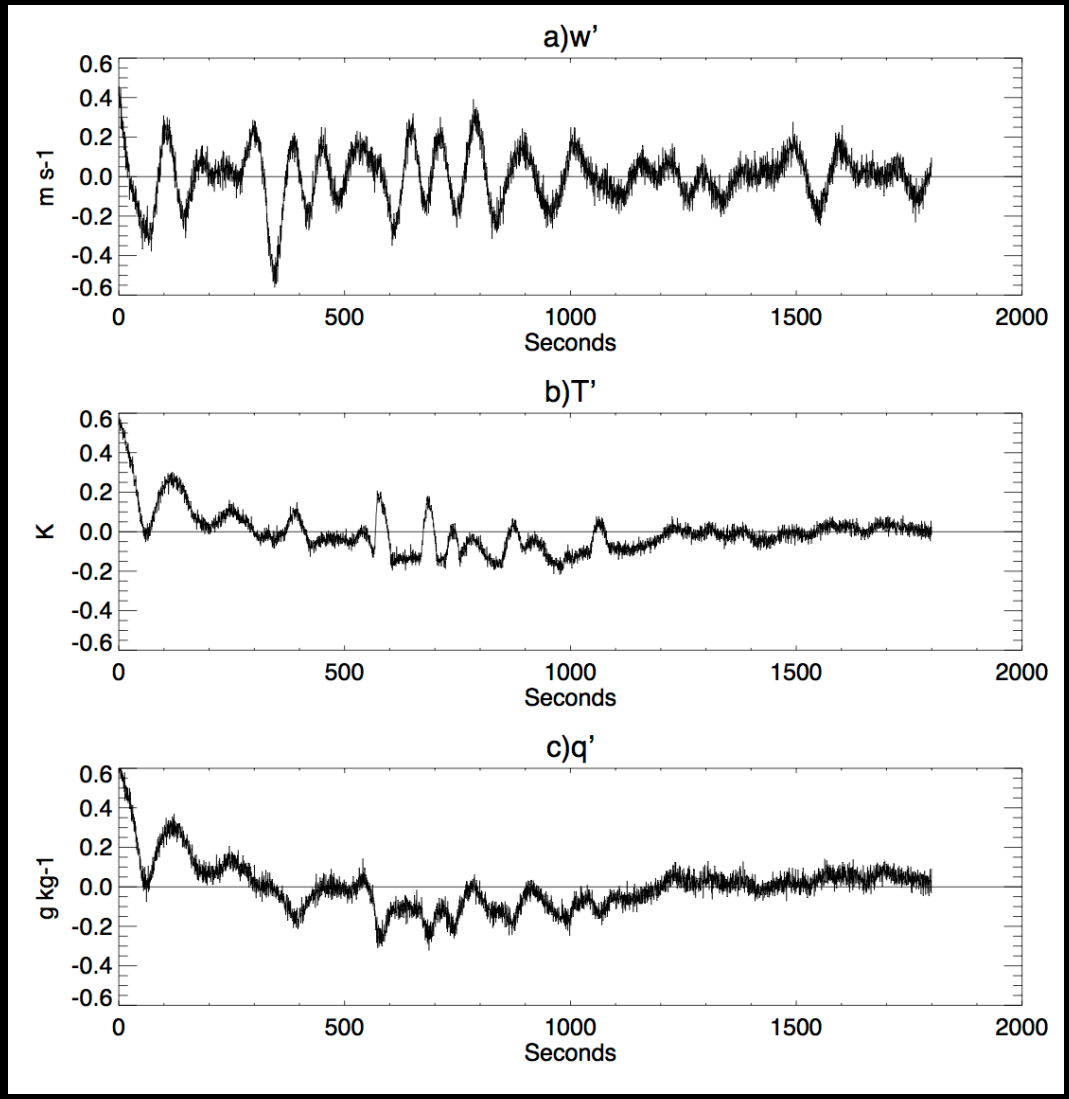
Fig. 1 Schematic showing how quasi-stationary eddies cause an underestimation of the total sensible heat flux H when using the temporal EC method to calculate H_t. The single-point sonic measurement in the centre is not able to resolve quasi-stationary eddies

Mauder et al., 2008, BLM

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

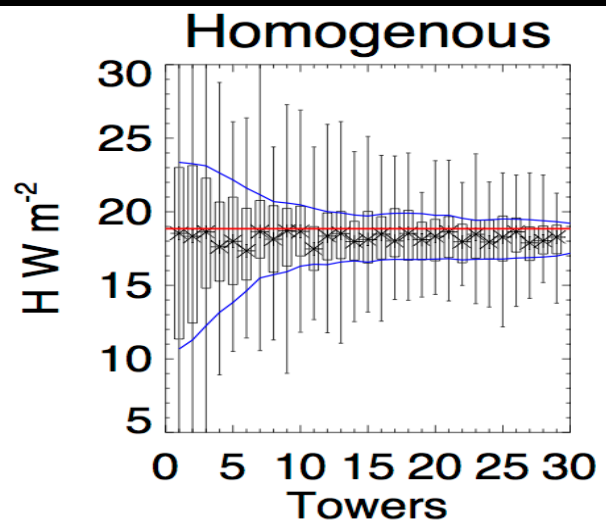


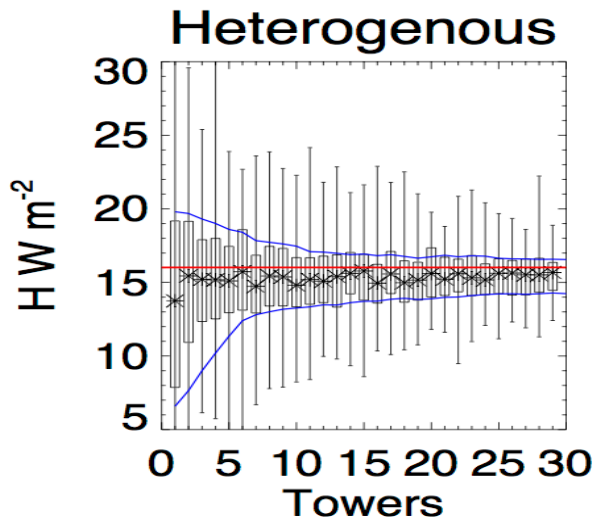
Let's test it: sample Large Eddy Simulation (LES) like a flux tower in both homogenous and heterogeneous domains, and see if accounting for mesoscale "flux" helps



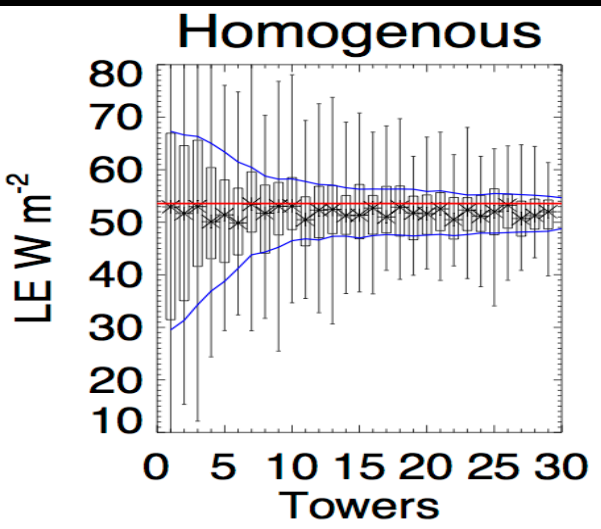
In both cases, a single random tower could vary by ~60% of mean domain flux, and heterogeneous simulation more consistently low biased

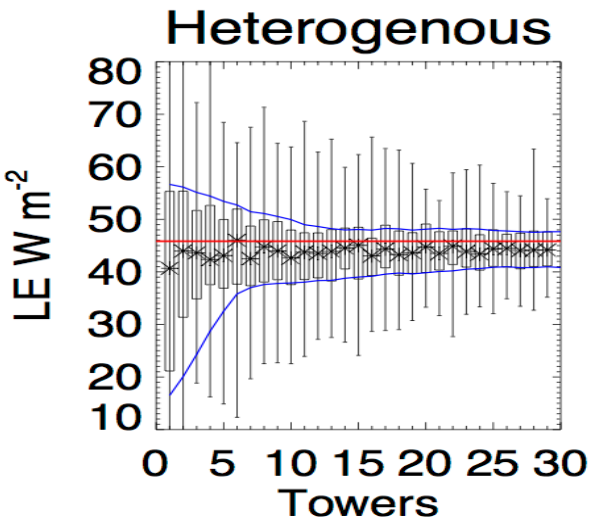
SENSIBLE HEAT (H)

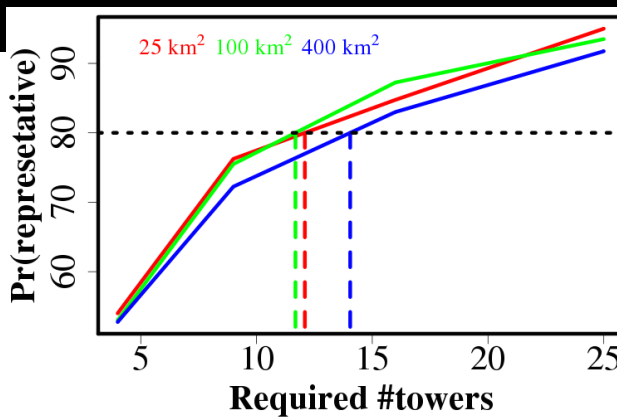




LATENT HEAT (LE)







Interestingly, convergence on domain mean flux (<10% error) with multiple towers in LES happens around ~10 towers, about sample as number of towers needed to sample land cover variance in actual domain

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

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

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

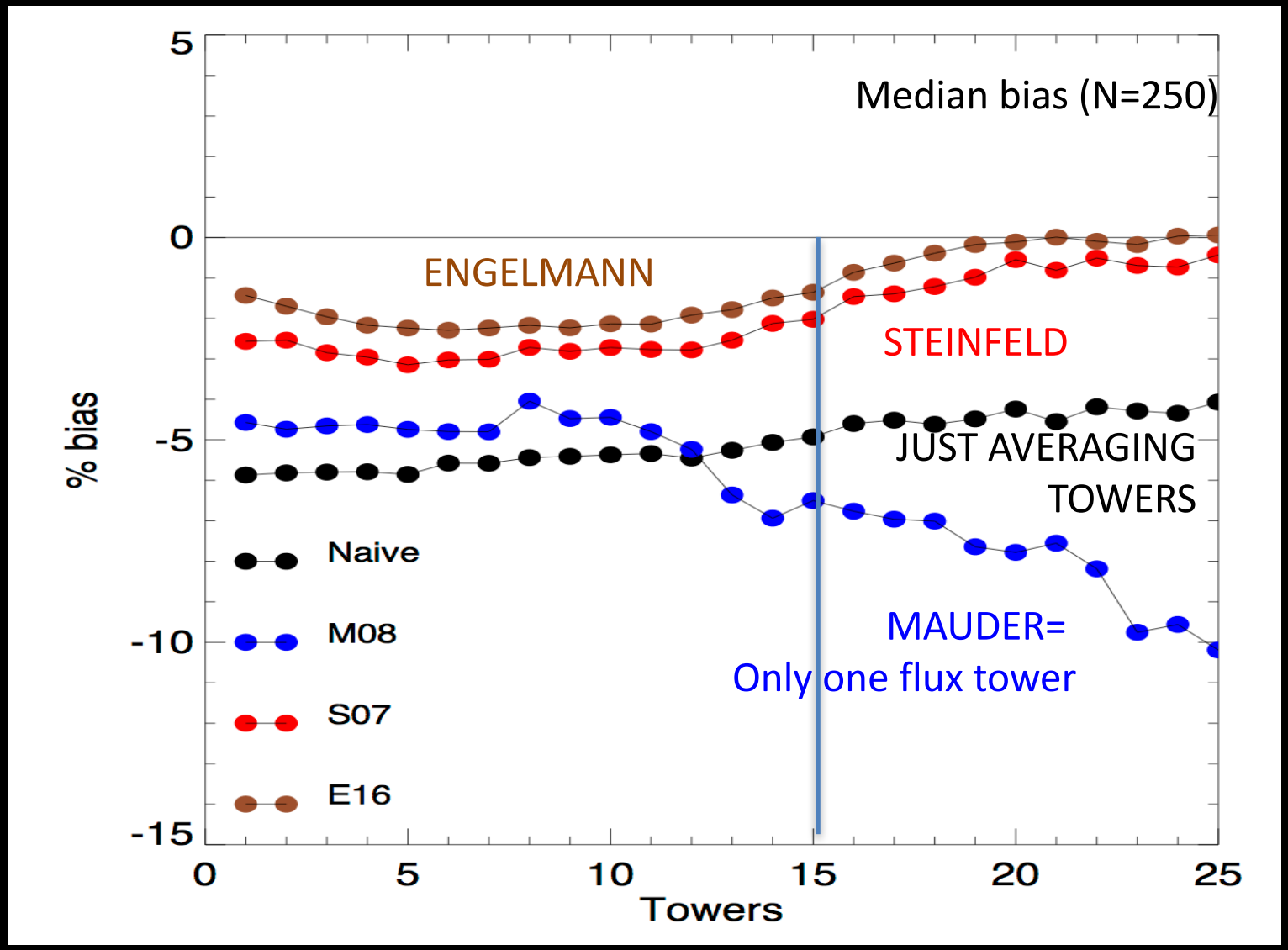
ORIGINAL PAPER

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

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

Spatial covariance approaches do improve the flux relative to domain mean, but in different ways



Energy balance may be addressed with density of ~10-20 towers per 100 square kilometers

So globally, we only need 70 million towers?

Don’t we have enough flux towers already?

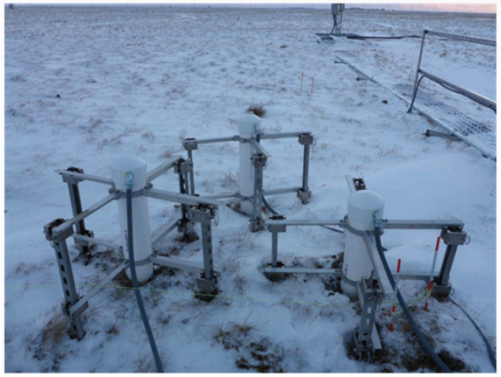
- NO
- There are critical regions that are undersampled
- Satellites and models miss a lot of details
- But we can probably use the towers we have better, and resolve critical biases that limit flux tower usability such as energy balance closure
- A variety of research efforts are underway to do just that

ACT III: A New Era, with Neon Glow

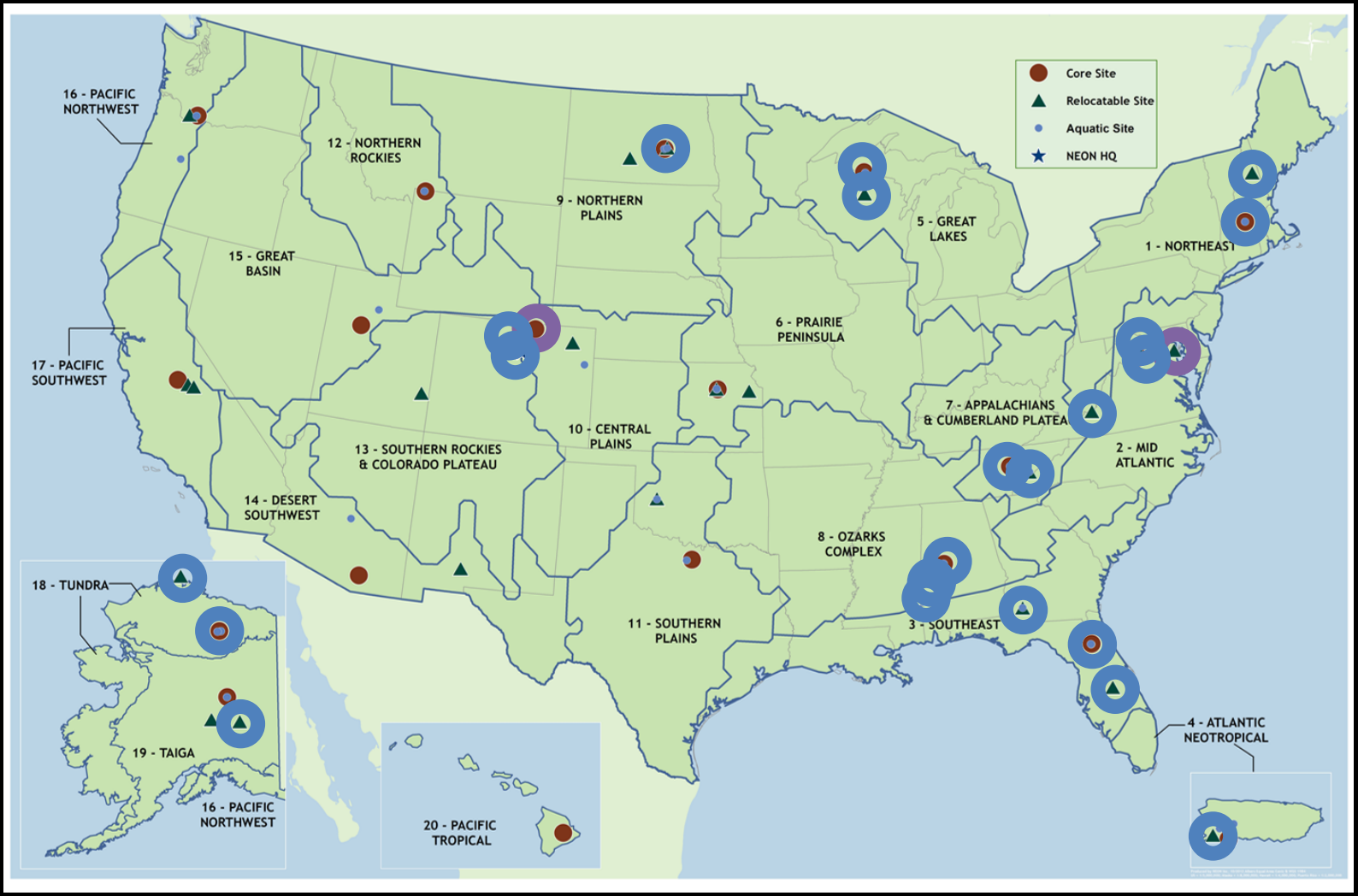
National Ecological Observatory Network

boots on the ground: flux tower sites

D18: Barrow Environmental Observatory - BARR



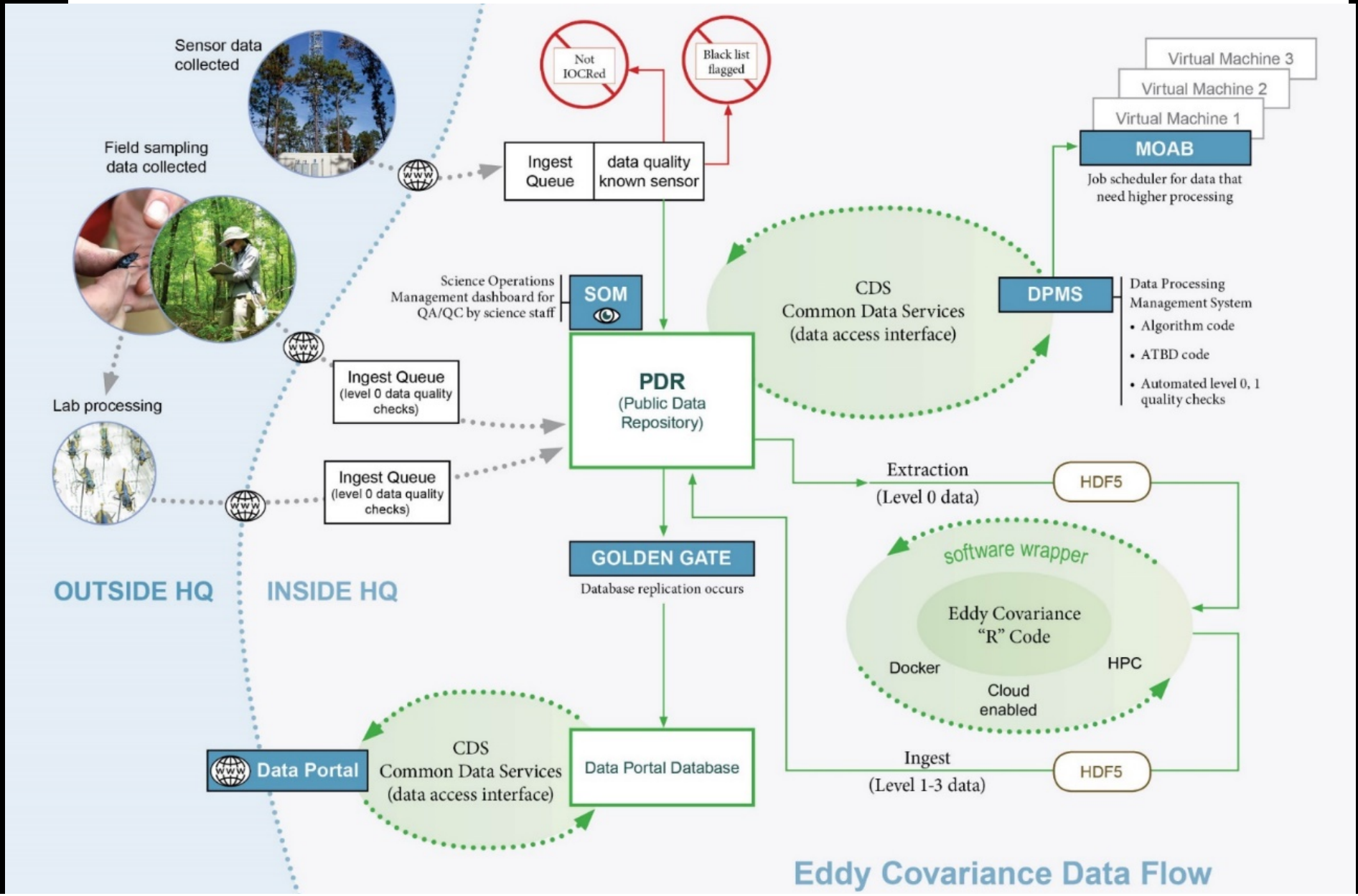
eddy-covariance data products: sites and schedule



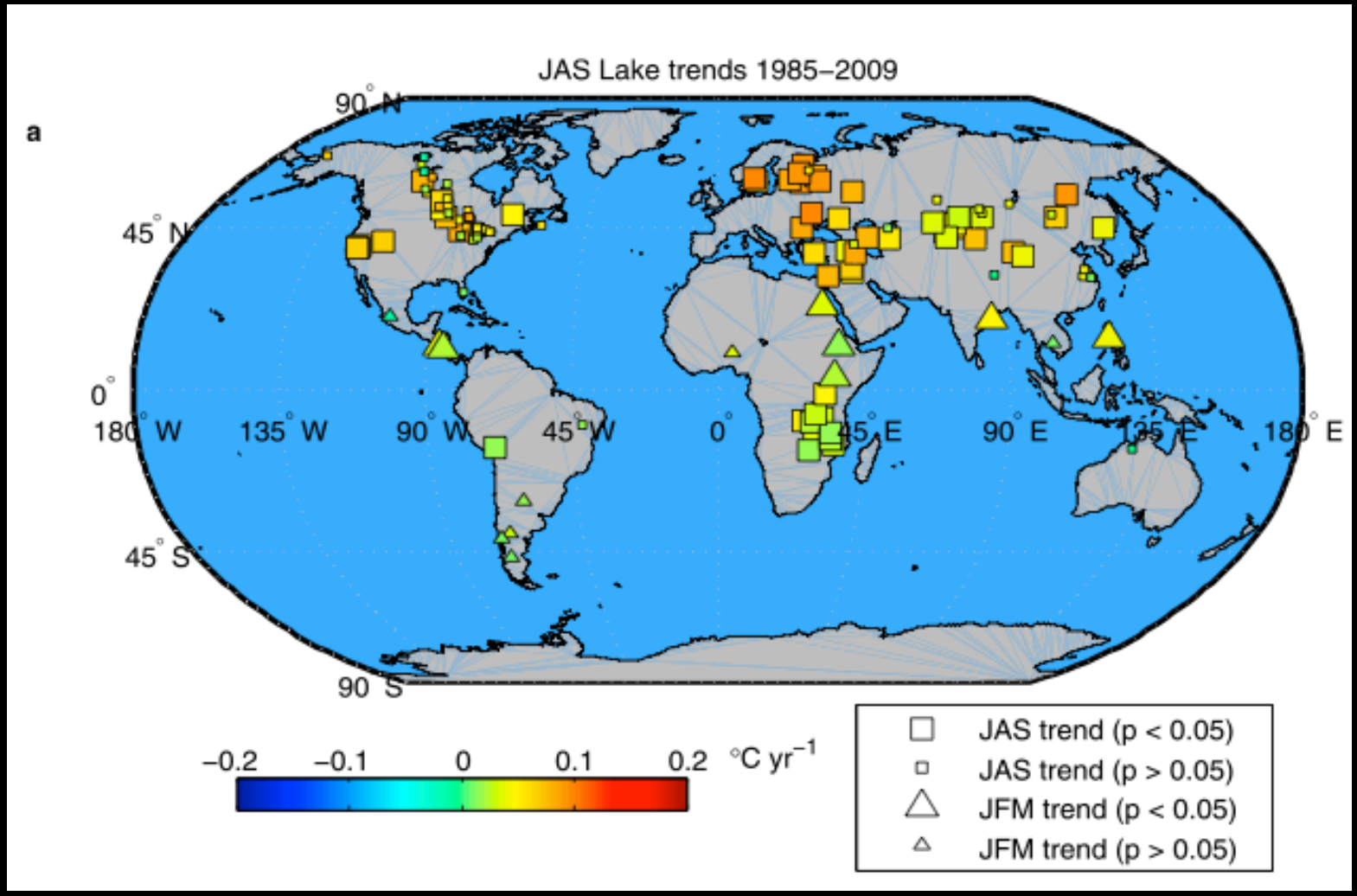
- initially: 2 sites
- +6 months: 25 sites
- +12 months: all 47 sites
- provisional data until first versioning (mid-2019)

Geosci. Model Dev., 10, 1–18, 2017
https://doi.org/10.5194/gmd-10-1-2017

Geoscientific Model Development
Open Access
EGU



Globally, lakes are warming faster than the atmosphere



Schneider and Hook, 2010 GRL

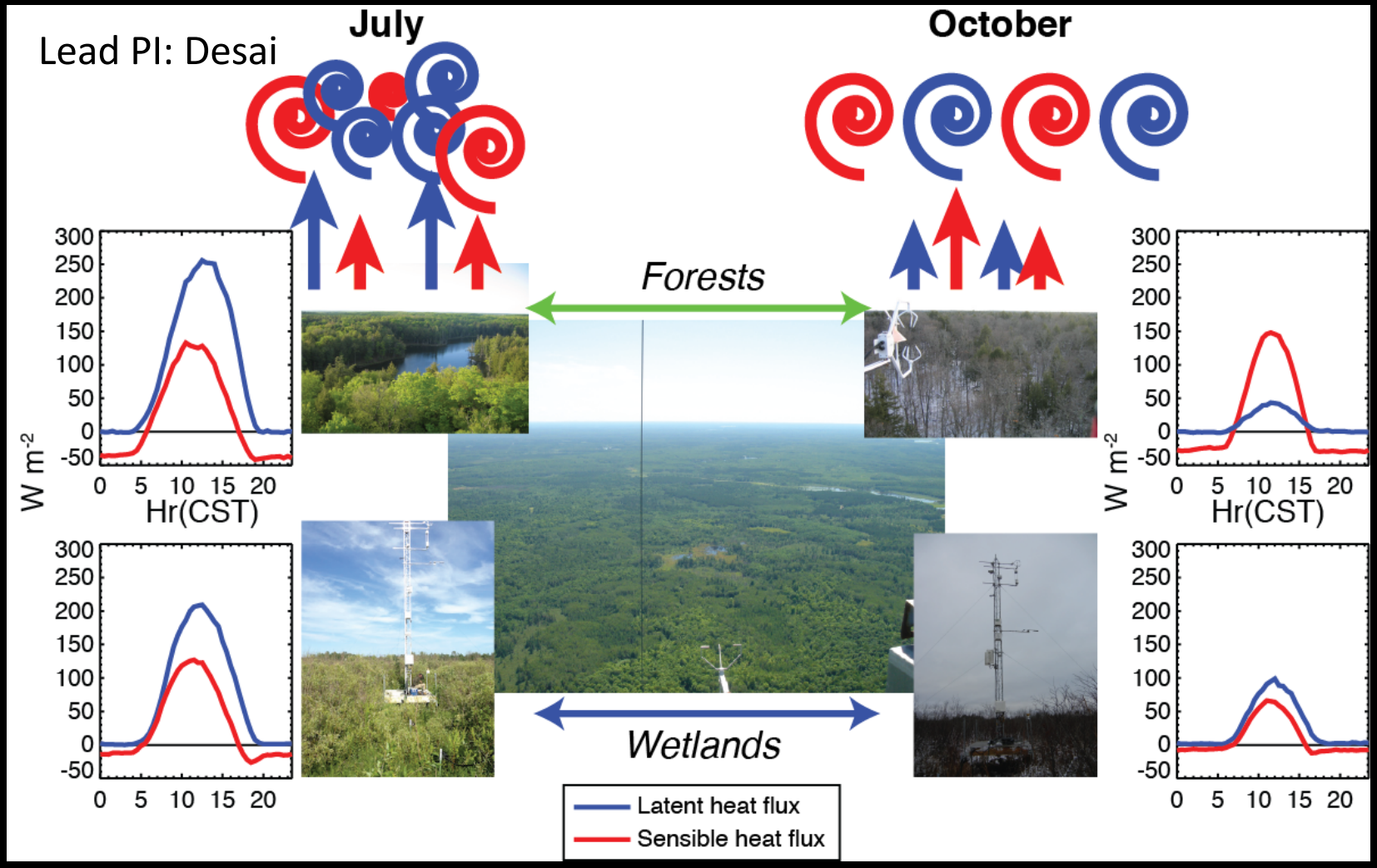
GLEON


90° N
75° N
60° N
45° N
30° N
15° N
0° N
150°
120° E
HMDL
HSVL
MDL
ESVL
ESL
EDL
FR
ESEVR
Daily Net Ecosystem Exchange [mgC m-2 d-1]
1200
900
600
300
0.0
-300
-600
May
Jun
Jul
Aug
Sep
Oct
Months

in prep

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



KPBH

- ISFS towers
- Tall tower ISS/SPARC site
- Forest Sevice Roads
- Target Domain
- Airports
- Open Water
- Developed, Open Space
- Developed, Low Intensity
- Deciduous Forest
- Evergreen Forest
- Mixed Forest
- Shrub/Scrub
- Grassland
- Pasture
- Cultivated Crops
- Woody Wetlands
- Emergent Herbaceous Wetland
- King Air flight track

THANKS!!!

Ankur Desai, desai@aos.wisc.edu, 608-520-0305, http://flux.aos.wisc.edu