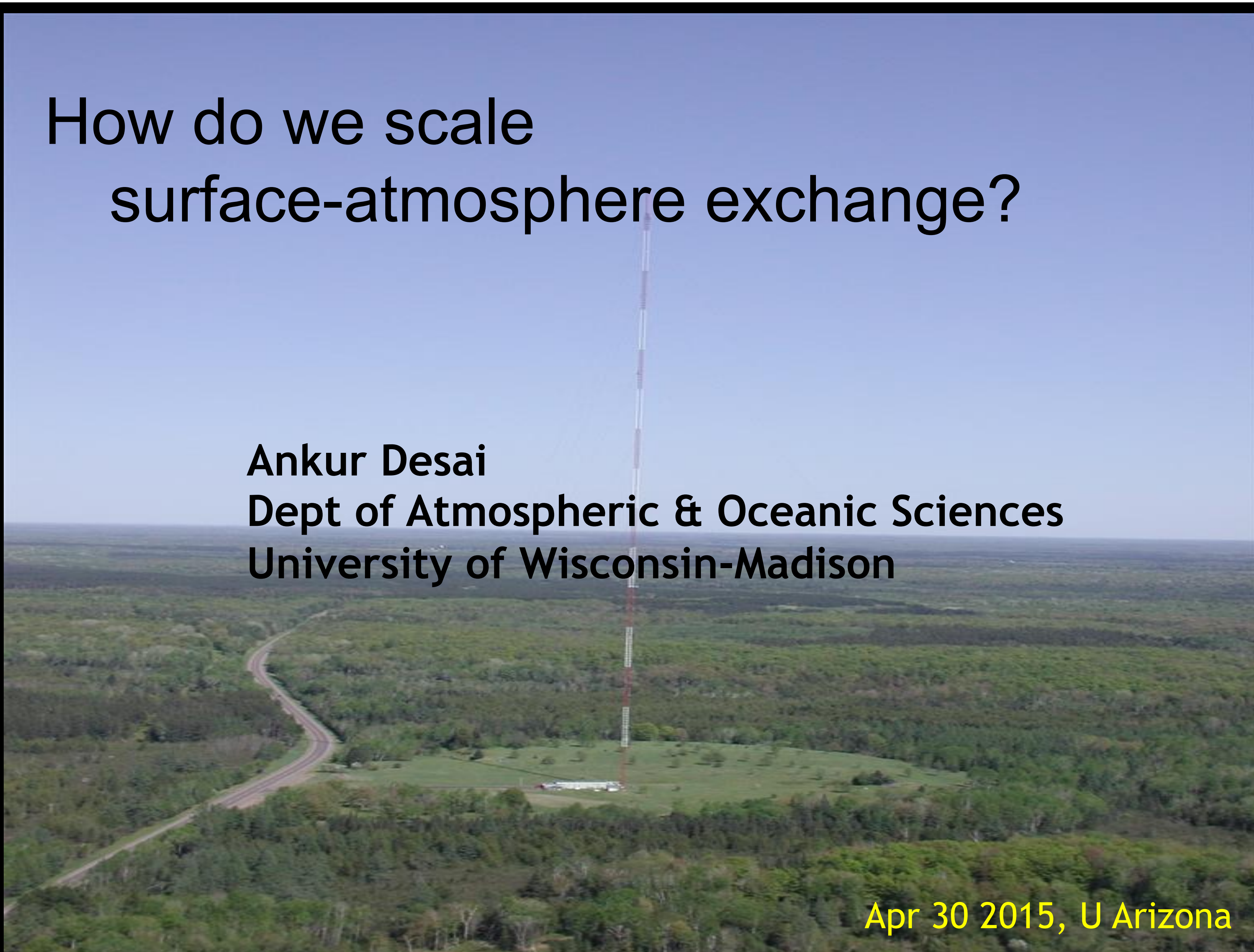
How do we scale surface-atmosphere exchange?



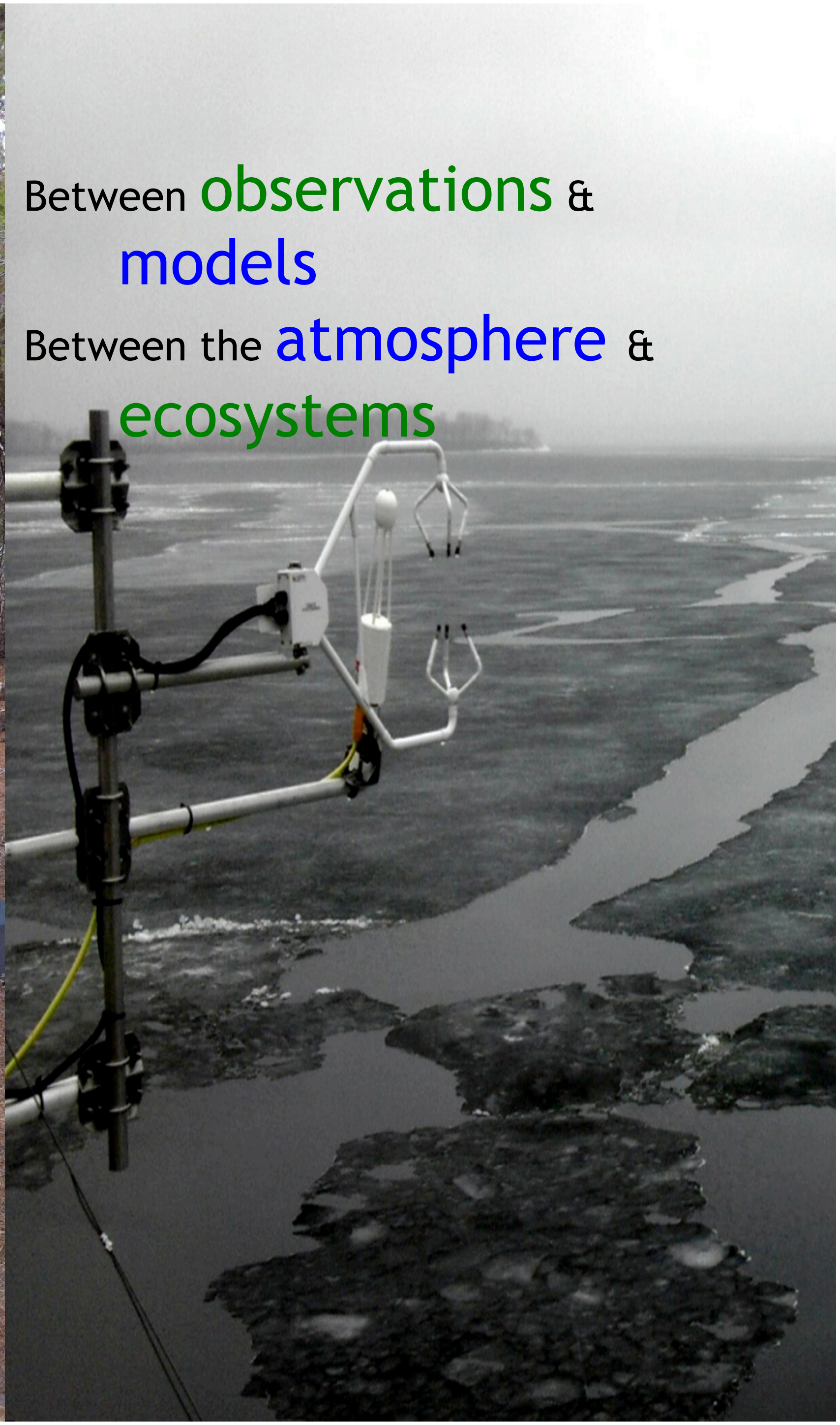
Ankur Desai
Dept of Atmospheric & Oceanic Sciences
University of Wisconsin-Madison

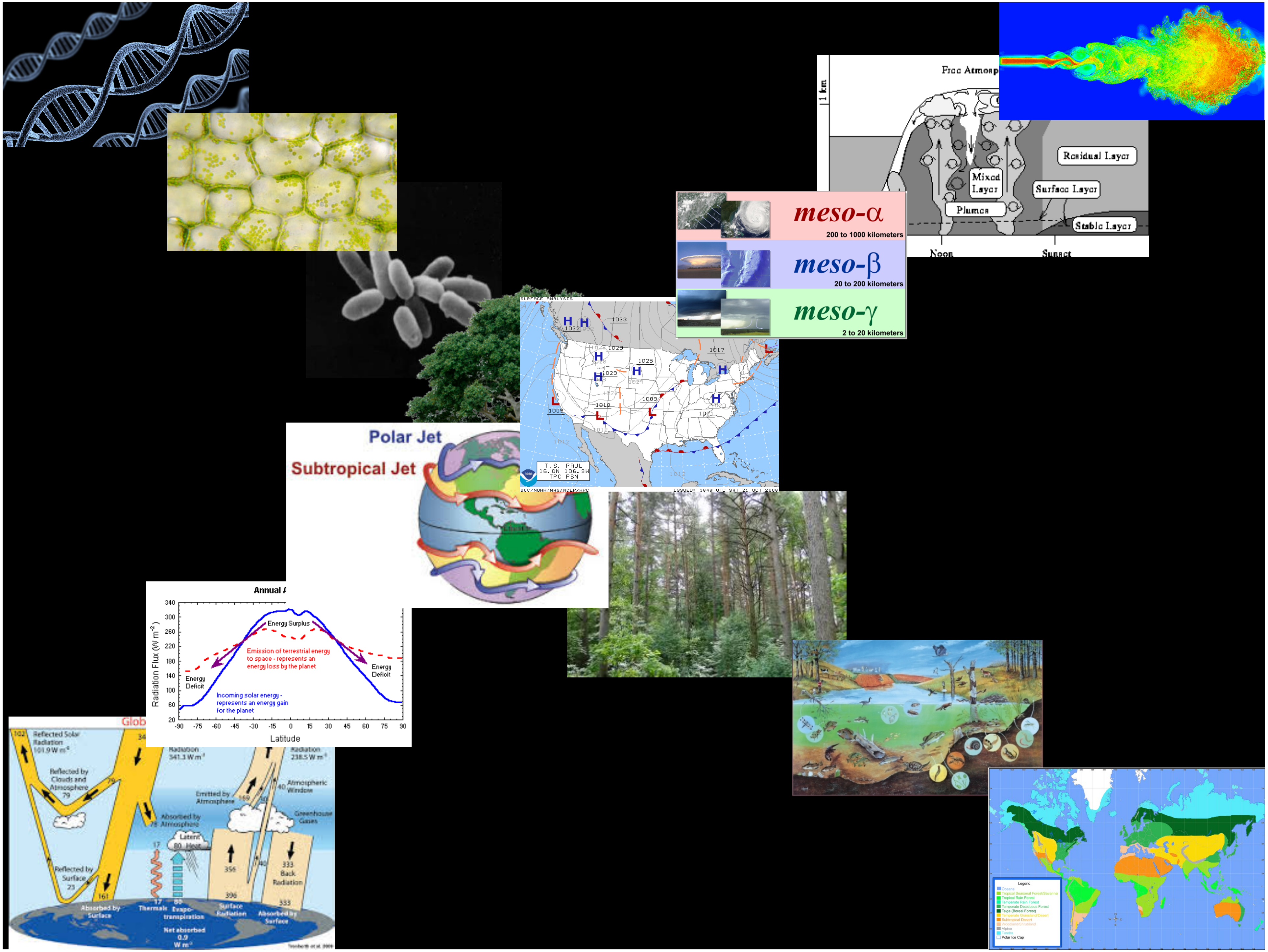
Apr 30 2015, U Arizona


Why is this so damn hard to model?

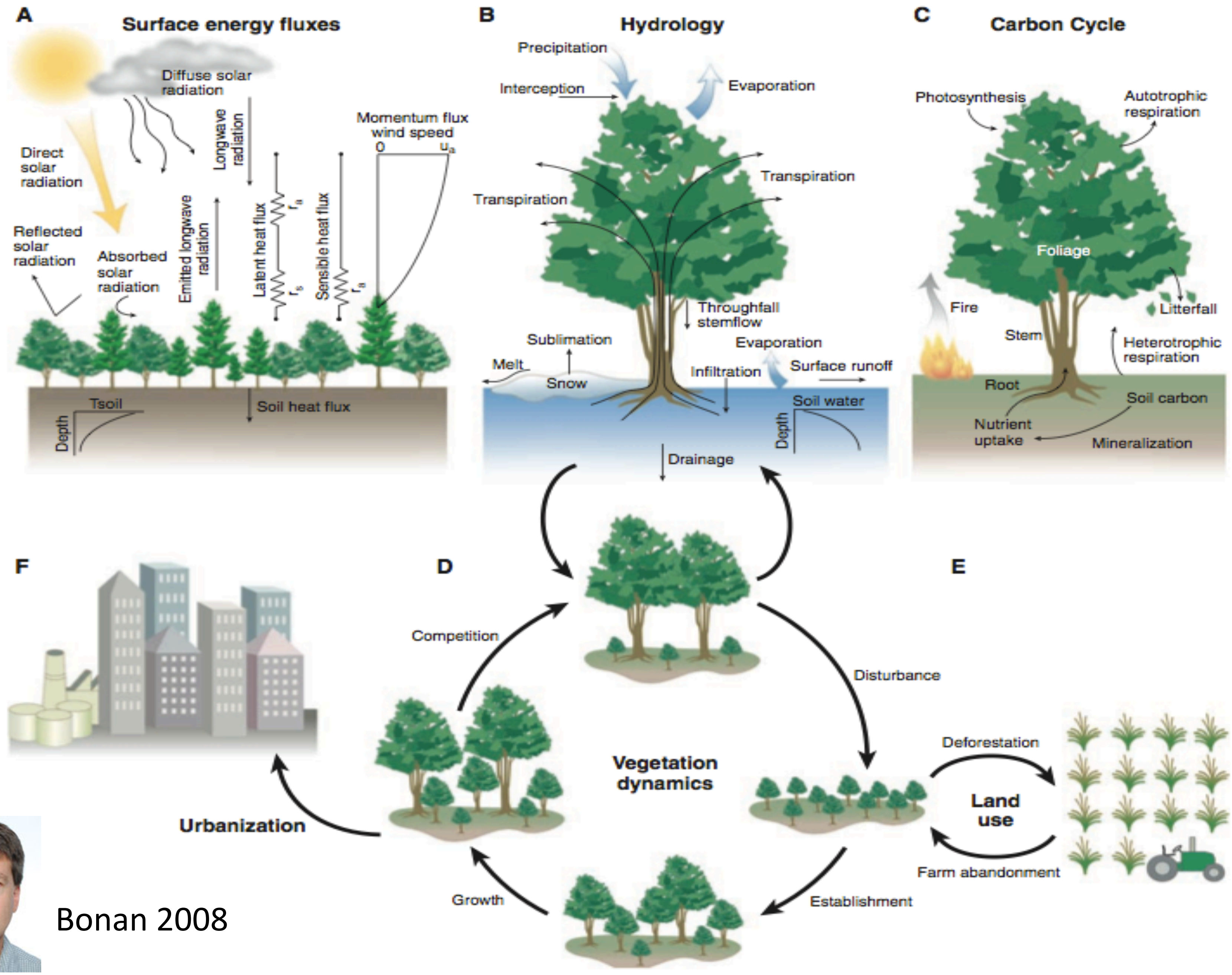

What does it have to do with scale?


We face a fundamental scale mismatch

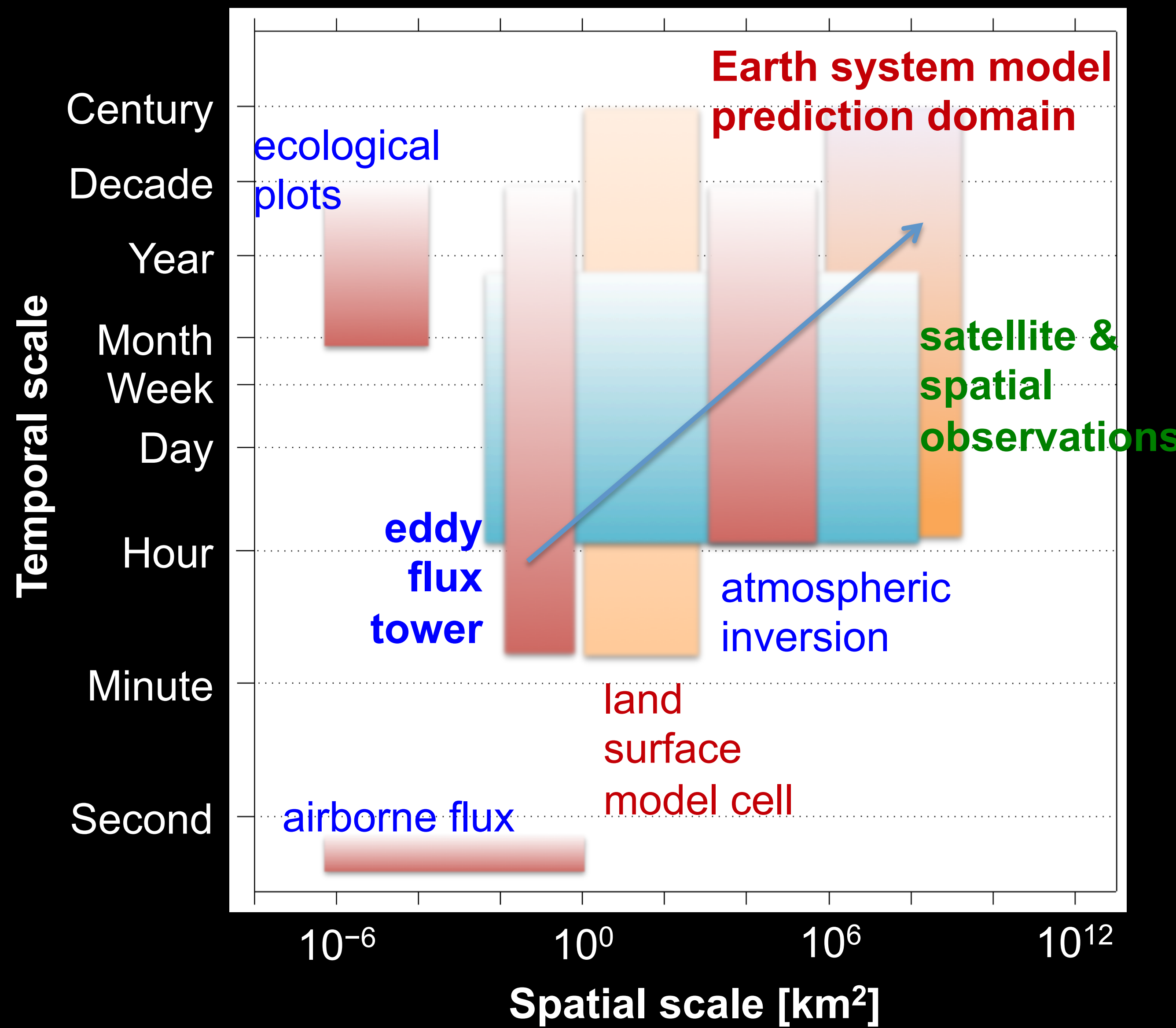

Between observations &
models
Between the atmosphere &
ecosystems


Free Atmosp
1 km
Residual Layer
Mixed Layer
Surface Layer
Plumes
Stable Layer
Noon
Sunset
meso-α
200 to 1000 kilometers
meso-β
20 to 200 kilometers
meso-γ
2 to 20 kilometers
SURFACE ANALYSIS
T.S. PAUL
Polar Jet
Subtropical Jet
Annual A
Radiation Flux (W m^{-2})
Energy Surplus
Emission of terrestrial energy to space - represents an energy loss by the planet
Energy Deficit
Energy Deficit
Incoming solar energy - represents an energy gain for the planet
Latitude
Glob
Reflected Solar Radiation 101.9 W m^{-2}
Reflected by Clouds and Atmosphere 79
Reflected by Surface 23
Absorbed by Surface
Emitted by Atmosphere
Atmospheric Window
Greenhouse Gases
Absorbed by Atmosphere
Latent Heat
Thermals
Evapo-transpiration
Surface Radiation
Back Radiation
Absorbed by Surface
Net absorbed 0.9 W m^{-2}

Forests in Flux



Bonan 2008

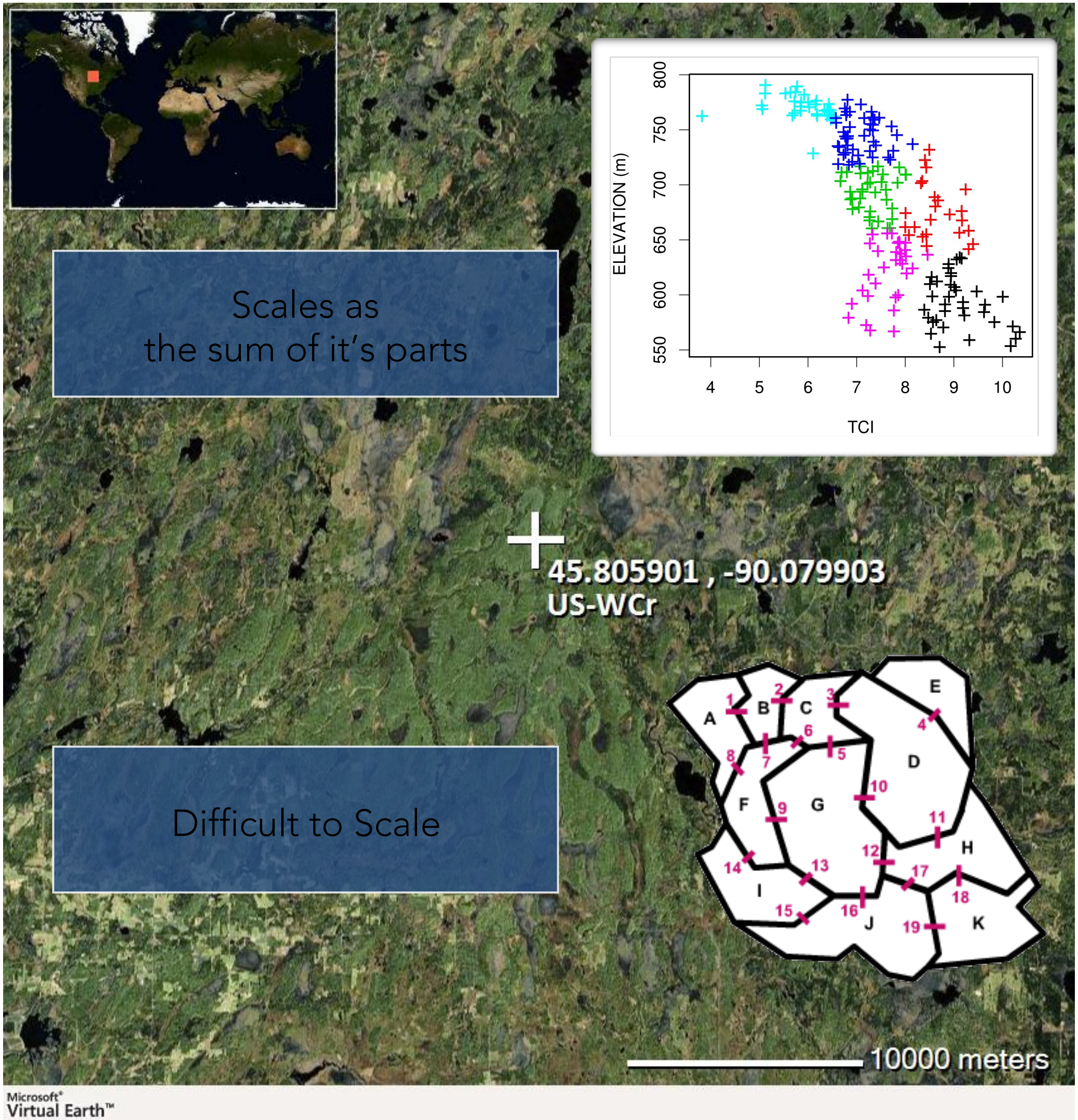


S. Metzger et al.:
Spatio-temporal rectification of tower-based EC

Global NPP 1983 version

		-180			-150			-120			-90			-60			-30			0			30			60			90			120			150		
LAT	J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
90.0	24																																				
82.2	23								0	0	0	0	0	0	0	0	0	0	0		0	0	0						0	0							
74.3	22	0		0	0			3	3	1	2	3	0	0	0	0	0	2				0	0		1	0	1	2	4	7	6	5	3	3	1	0	
66.5	21	4	1	14	23	18	16	14	7	6	5	2	5	0	2	0	0	2	0		5	17	24	14	18	19	17	20	24	23	27	28	22	18	22	19	12
58.7	20	0	0	9	8	7	18	25	20	17	4	2	8	2	0	0			1	5	17	14	27	28	28	29	25	26	28	29	29	30	30	17	8	9	3
50.9	19						6	28	34	30	22	22	27	15	2				4	23	32	33	34	36	28	31	35	36	28	34	33	34	34	20		3	
43.0	18							30	32	40	36	36	22	3					8	21	19	31	20	27	13	10	11	22	11	21	33	36	27	10			
35.2	17							14	22	39	42	31							8	14	9	4	6	20	29	23	26	10	10	31	40	23	19	13			
27.4	16							0	10	18	8	8							10	2	2	3	3	4	11	19	15	37	48	36	71	39					
19.6	15			0					1	21	28	3	7					2	5	9	7	7	2	6	2	1	9	38	25	63	26	8					
11.7	14										14	20	24	10				3	31	37	39	37	33	20	9		2	19		23	9	12	2				
3.9	13											29	72	75	24				16	20	54	74	52	26	6			4		34	23	35	6				
-3.9	12											42	94	94	82	15					29	73	38	15						22	35	22	16	51	13	1	
-11.7	11											11	79	72	54	15					7	23	22	14	4						2	4	13	17	7		
-19.6	10	1											23	32	45	24					3	36	31	12	20						1	13	25	33	16		1
-27.4	9												16	24	36						0	15	30	0	2						1	13	12	21	24		
-35.2	8	3											13	32	4							3	5									4	1	14	17		1
-43.0	7	3											23	1																					6		14
-50.9	6												19	0													0										
-58.7	5												1																								
-66.5	4												0	0						0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
-74.3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-82.2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-90.0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LAT	J	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
		-180			-150			-120			-90			-60			-30			0			30			60			90			120			150		

Fig. 2. Global distribution of NPP (× 10 gm $C/m^2/yr$) at the tracer model resolution.



Spatial
Heterogeneity

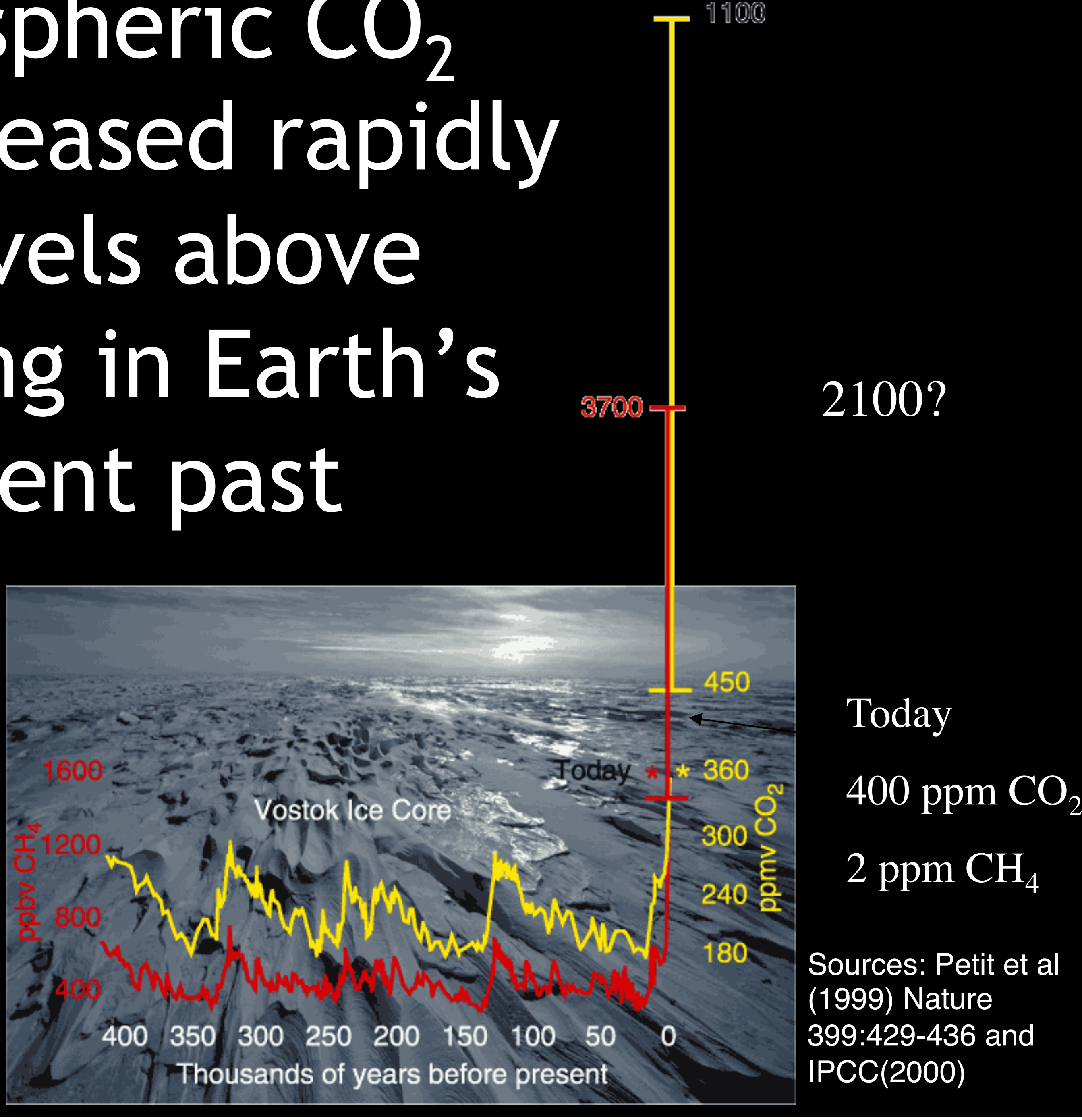
- Amount
- Frequency
  Distribution

Spatial Process

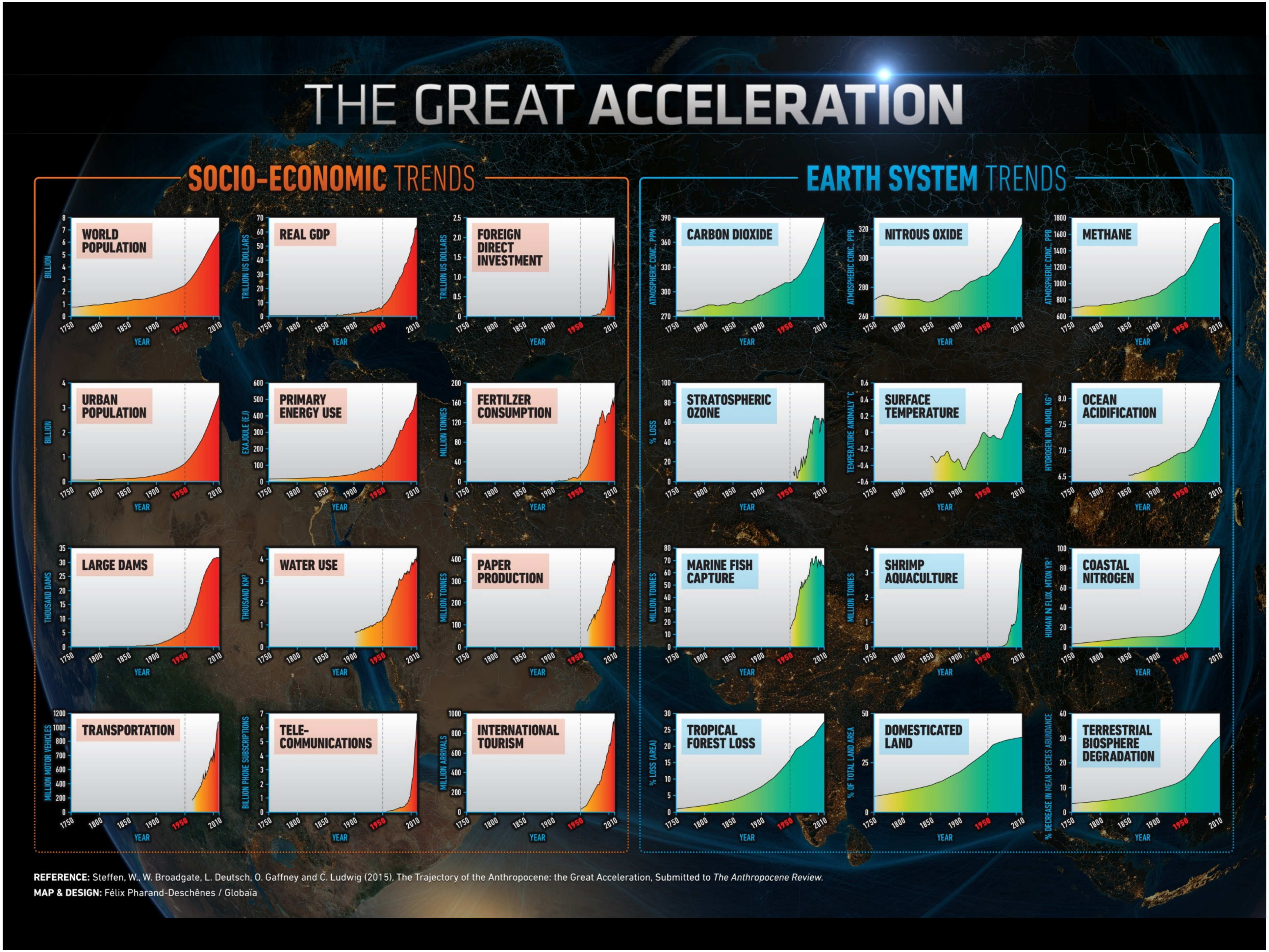
- Arrangement
- Location
- Distance

Why does it matter?

Atmospheric CO_2 has increased rapidly to levels above anything in Earth's recent past



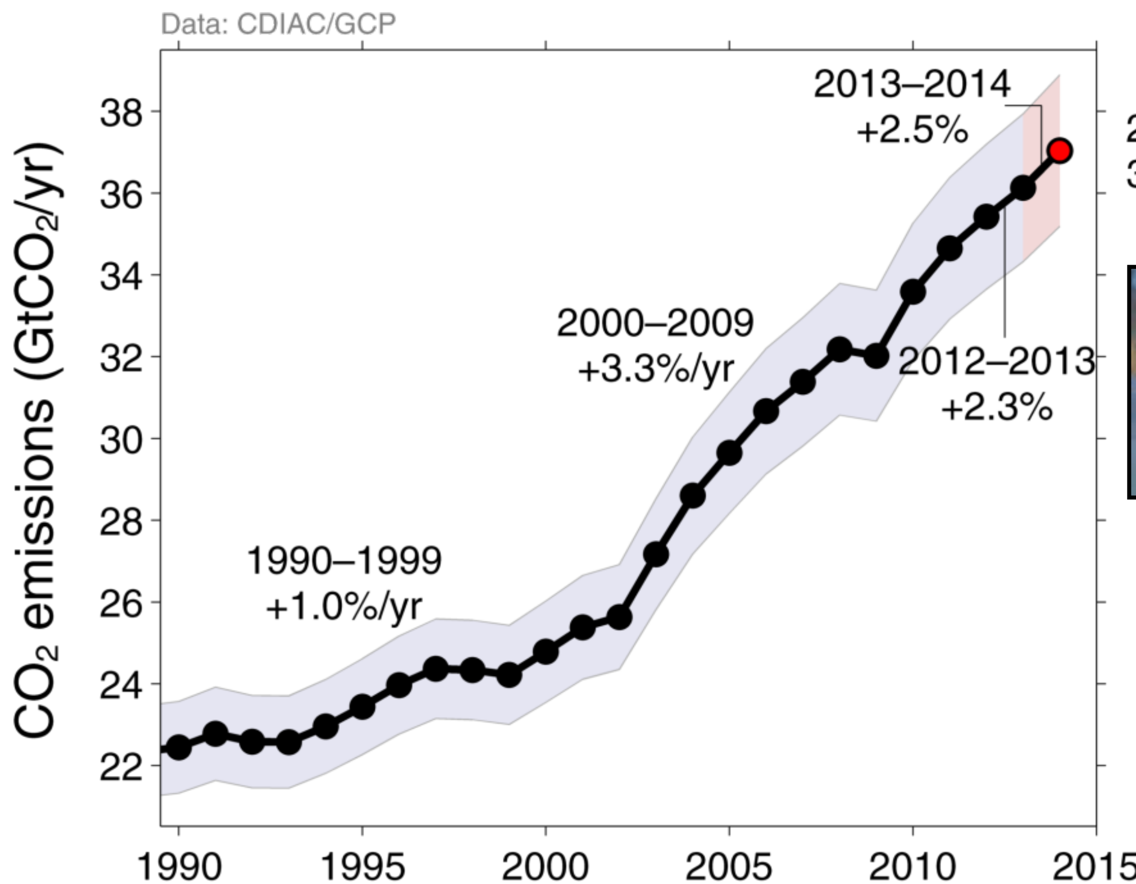
Sources: Petit et al (1999) Nature 399:429-436 and IPCC(2000)


THE GREAT ACCELERATION
SOCIO-ECONOMIC TRENDS
EARTH SYSTEM TRENDS
WORLD POPULATION
BILLION
REAL GDP
TRILLION US DOLLARS
FOREIGN DIRECT INVESTMENT
TRILLION US DOLLARS
CARBON DIOXIDE
ATMOSPHERIC CONC., PPM
NITROUS OXIDE
ATMOSPHERIC CONC., PPB
METHANE
ATMOSPHERIC CONC., PPB
URBAN POPULATION
BILLION
PRIMARY ENERGY USE
EXAJOULE (EJ)
FERTILZER CONSUMPTION
MILLION TONNES
STRATOSPHERIC OZONE
% LOSS
SURFACE TEMPERATURE
TEMPERATURE ANOMALY °C
OCEAN ACIDIFICATION
HYDROGEN ION, NMOL KG⁻¹
LARGE DAMS
THOUSAND DAMS
WATER USE
THOUSAND KM³
PAPER PRODUCTION
MILLION TONNES
MARINE FISH CAPTURE
MILLION TONNES
SHRIMP AQUACULTURE
MILLION TONNES
COASTAL NITROGEN
HUMAN N FLUX, MTON YR⁻¹
TRANSPORTATION
MILLION MOTOR VEHICLES
TELE-COMMUNICATIONS
BILLION PHONE SUBSCRIPTIONS
INTERNATIONAL TOURISM
MILLION ARRIVALS
TROPICAL FOREST LOSS
% LOSS (AREA)
DOMESTICATED LAND
% OF TOTAL LAND AREA
TERRESTRIAL BIOSPHERE DEGRADATION
% DECREASE IN MEAN SPECIES ABUNDANCE
YEAR
1750
1800
1850
1900
1950
2010
REFERENCE: Steffen, W., W. Broadgate, L. Deutsch, O. Gaffney and C. Ludwig (2015), The Trajectory of the Anthropocene: the Great Acceleration, Submitted to The Anthropocene Review.
MAP & DESIGN: Félix Pharand-Deschênes / Globaïa

Fossil Fuel and Cement Emissions

Global fossil fuel and cement emissions: 36.1 ± 1.8 $GtCO_2$ in 2013, 61% over 1990

- Projection for 2014 : 37.0 ± 1.9 $GtCO_2$, 65% over 1990



Uncertainty is ±5% for one standard deviation (IPCC "likely" range)

Estimates for 2011, 2012, and 2013 are preliminary

Source: CDIAC; Le Quéré et al 2014; Global Carbon Budget 2014

Global Carbon Budget

The cumulative contributions to the Global Carbon Budget from 1870
Contributions are shown in parts per million (ppm)

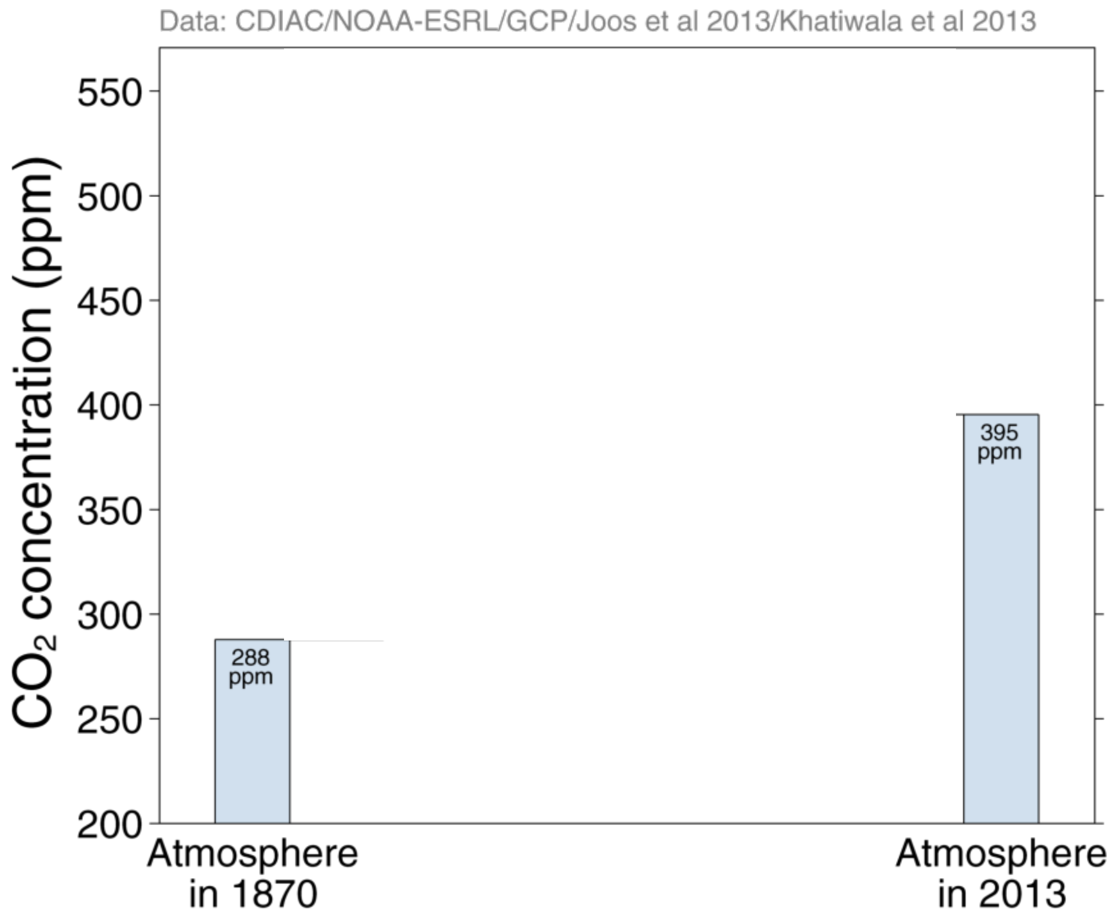
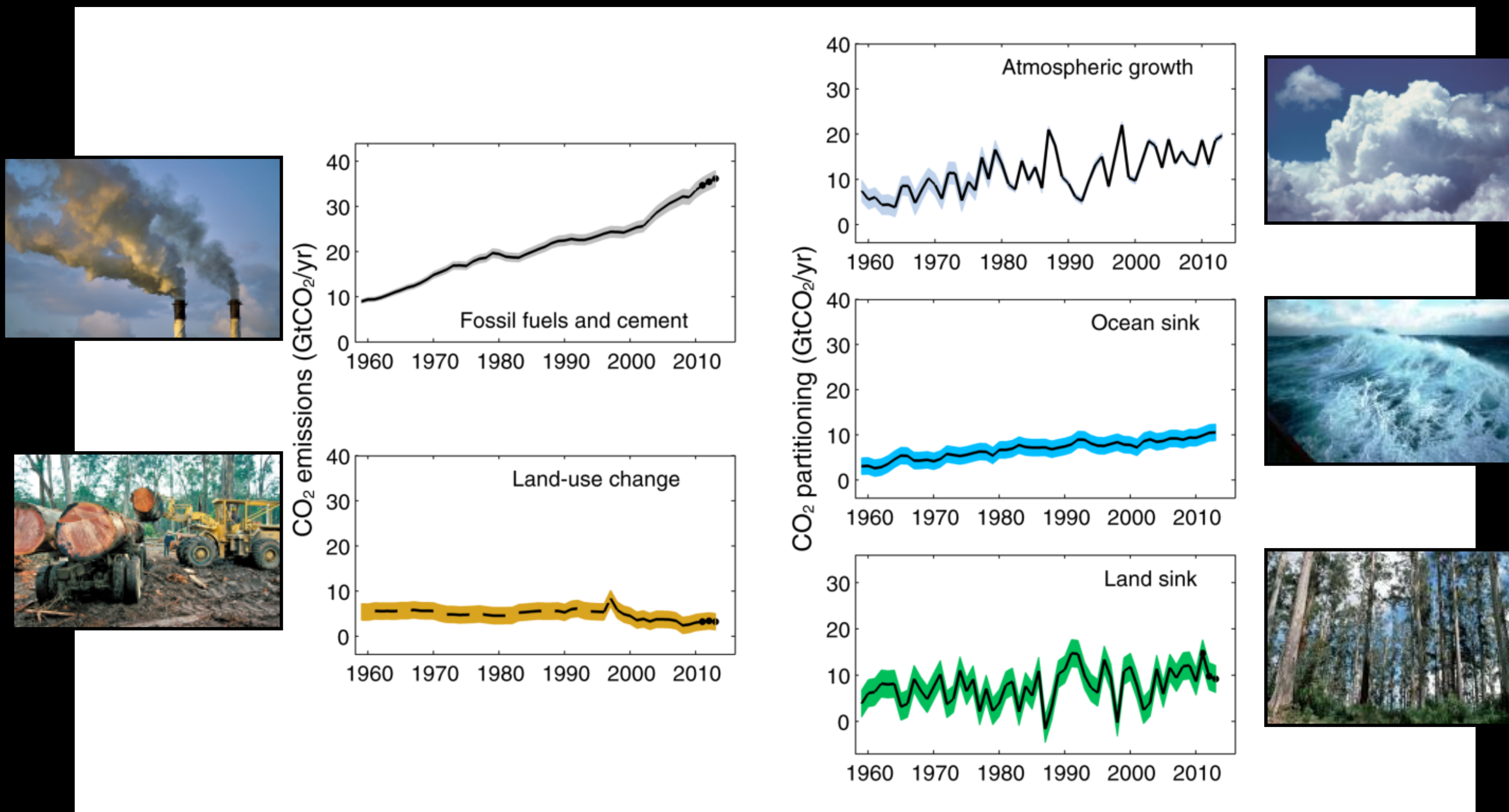


Figure concept from Shrink That Footprint
Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Joos et al 2013; Khatiwala et al 2013; Le Quéré et al 2014; Global Carbon Budget 2014

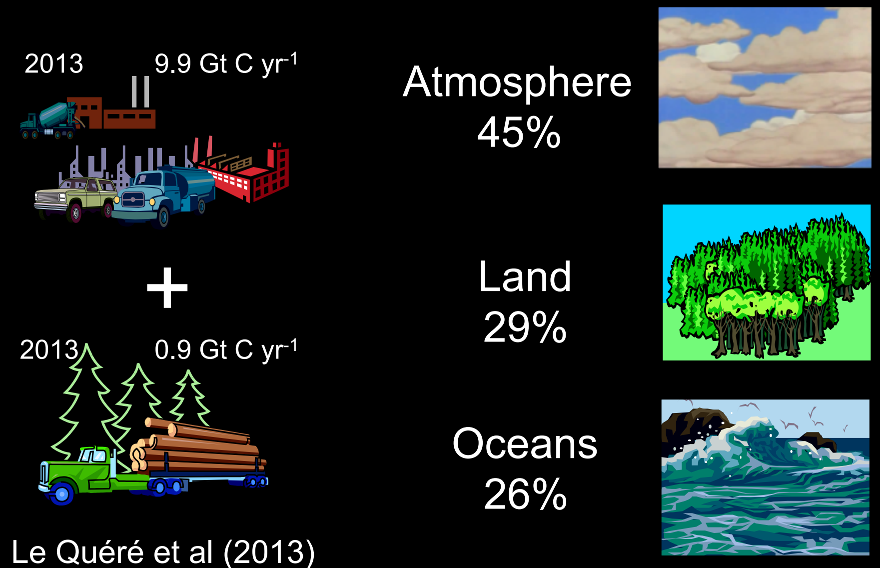
Changes in the Budget over Time

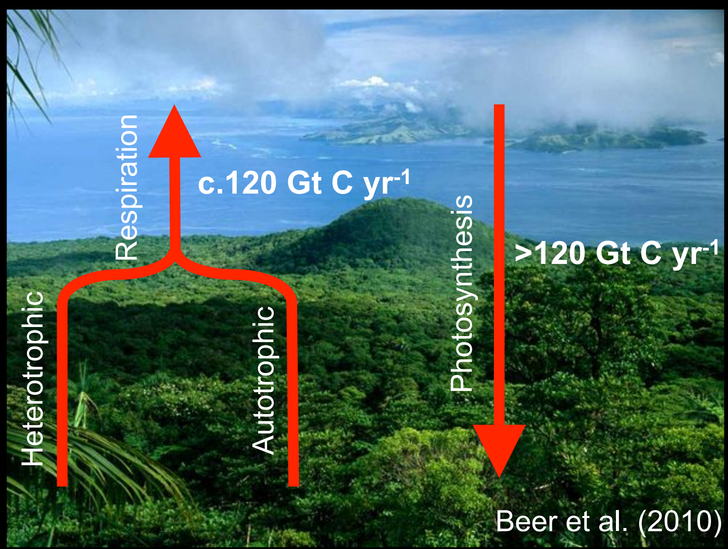
The sinks have continued to grow with increasing emissions, but climate change will affect carbon cycle processes in a way that will exacerbate the increase of CO_2 in the atmosphere

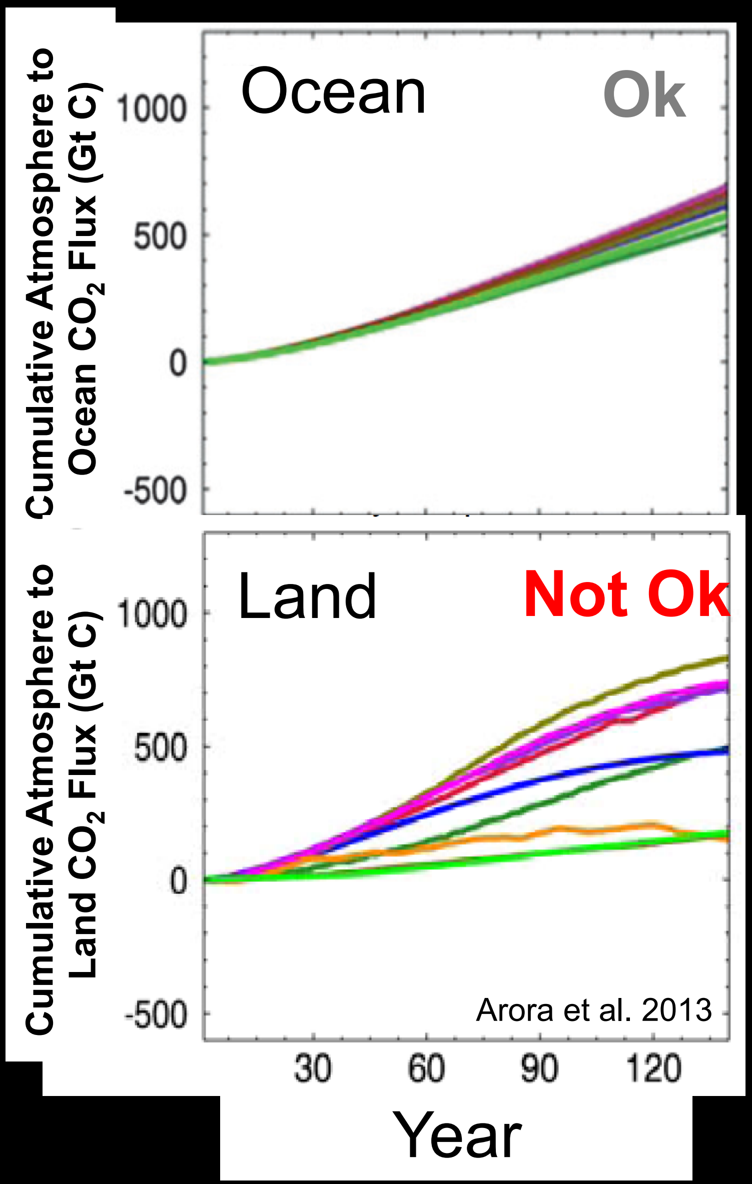


Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Le Quéré et al 2014; Global Carbon Budget 2014

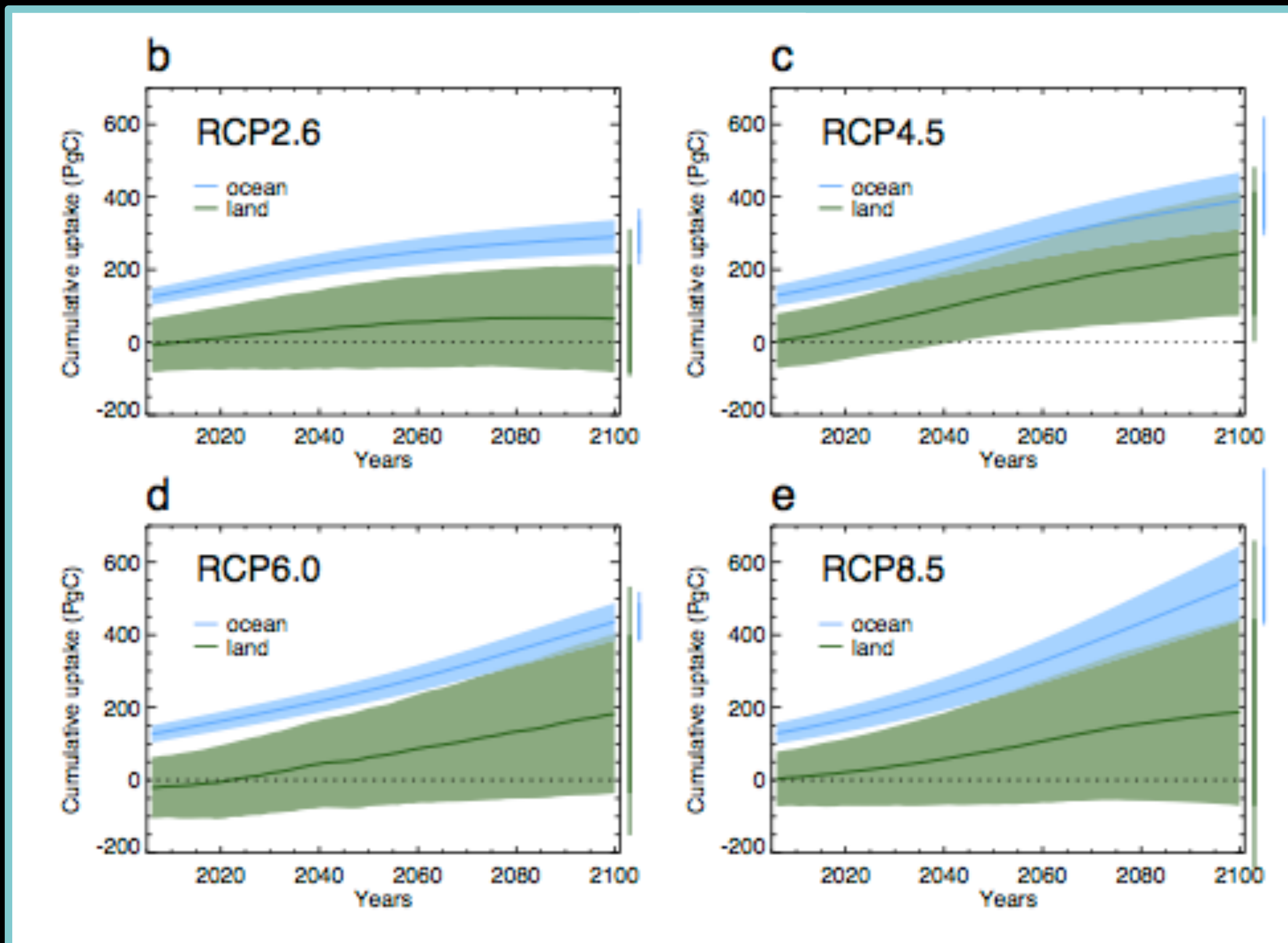
Terrestrial Biosphere CO_2 Flux Dominates Carbon Cycle Prediction Uncertainty



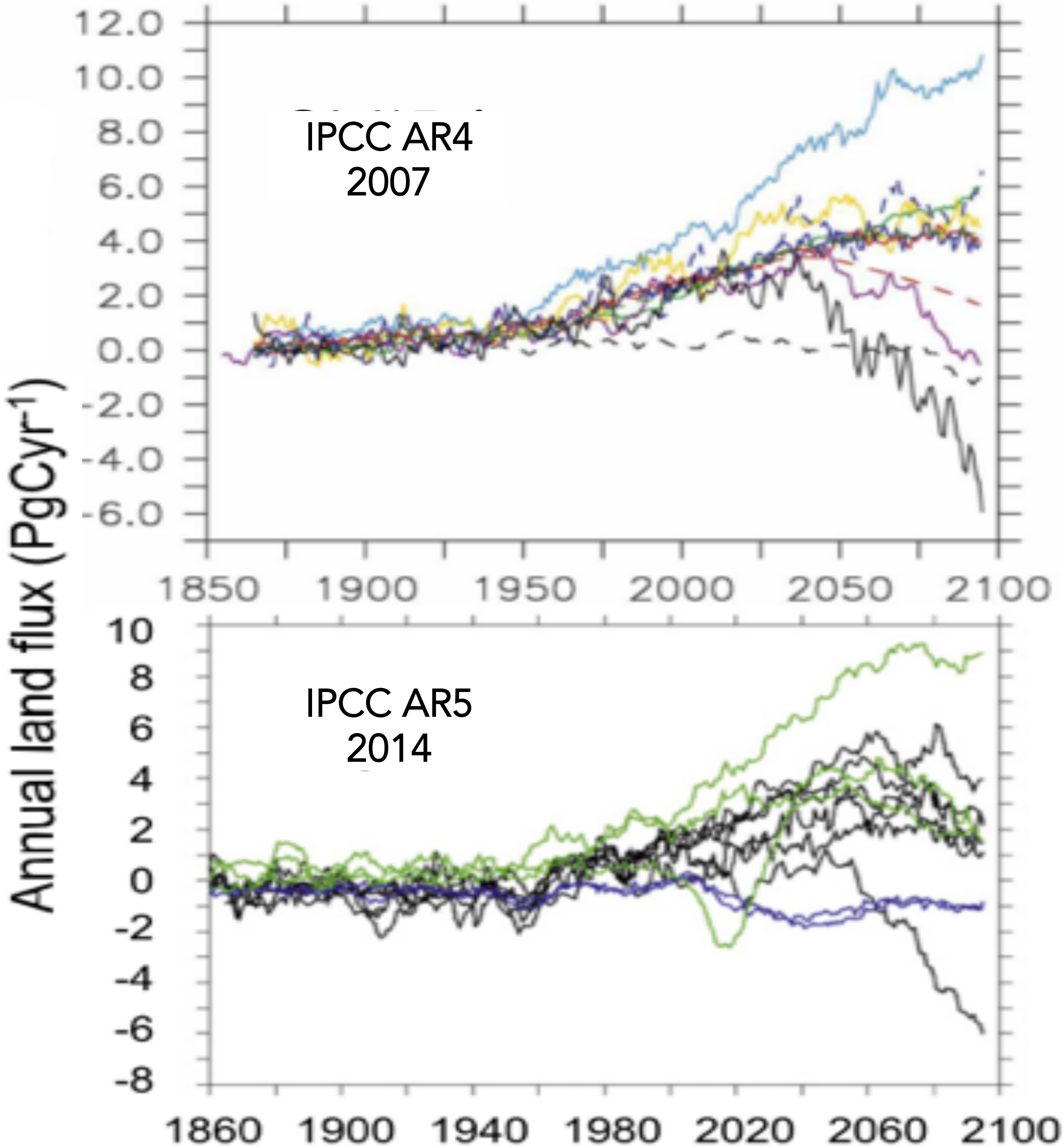


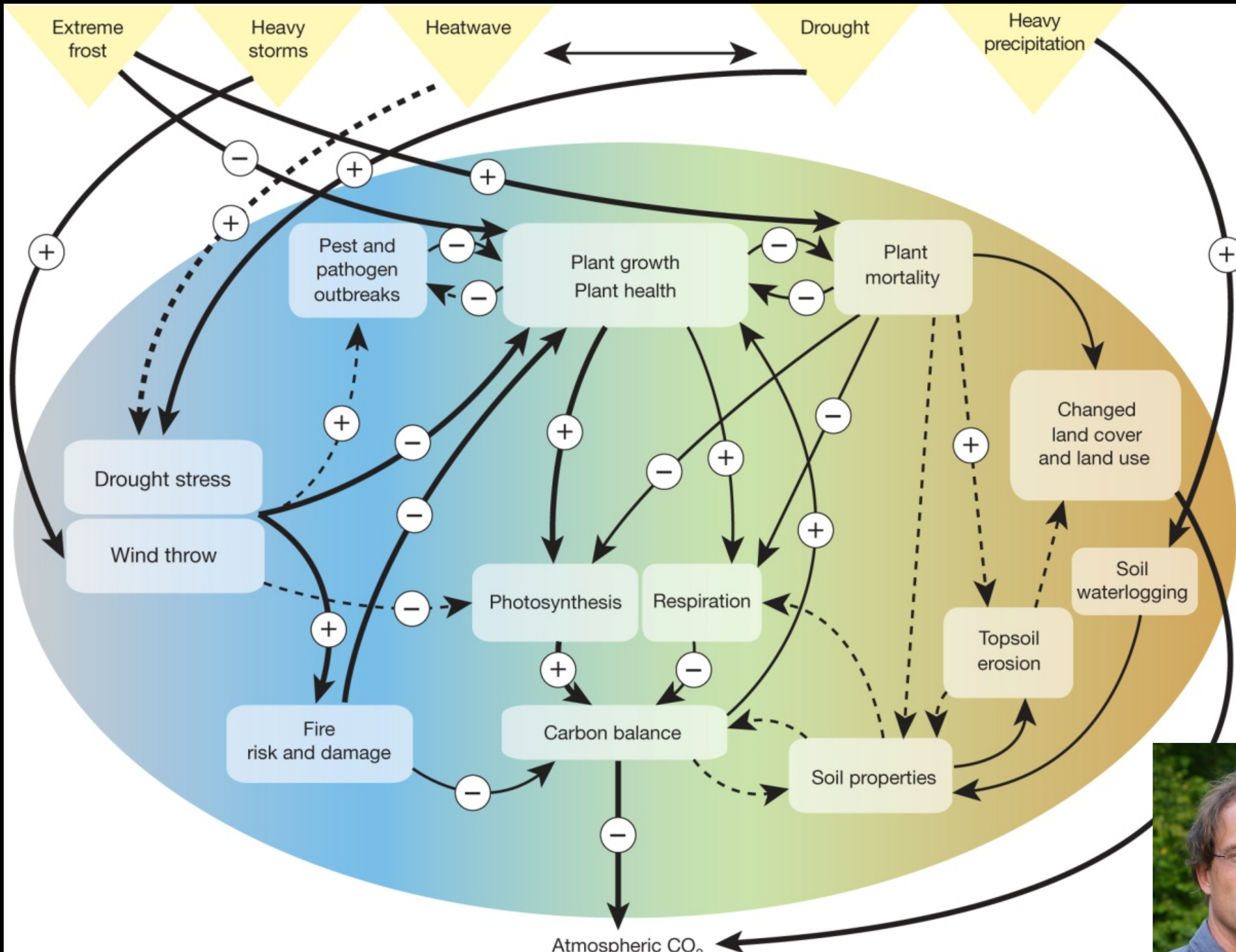


Terrestrial carbon cycle feedback is a leading order uncertainty for climate simulation



IPCC AR5 WG1 CH6


IPCC AR4
2007
IPCC AR5
2014
Annual land flux (PgCyr-1)
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
1850
1900
1950
2000
2050
2100
10
8
6
4
2
0
-2
-4
-6
-8
1860
1900
1940
1980
2020
2060
2100



M Reichstein *et al.* *Nature* **500**, 287-295 (2013) doi:10.1038/nature12350

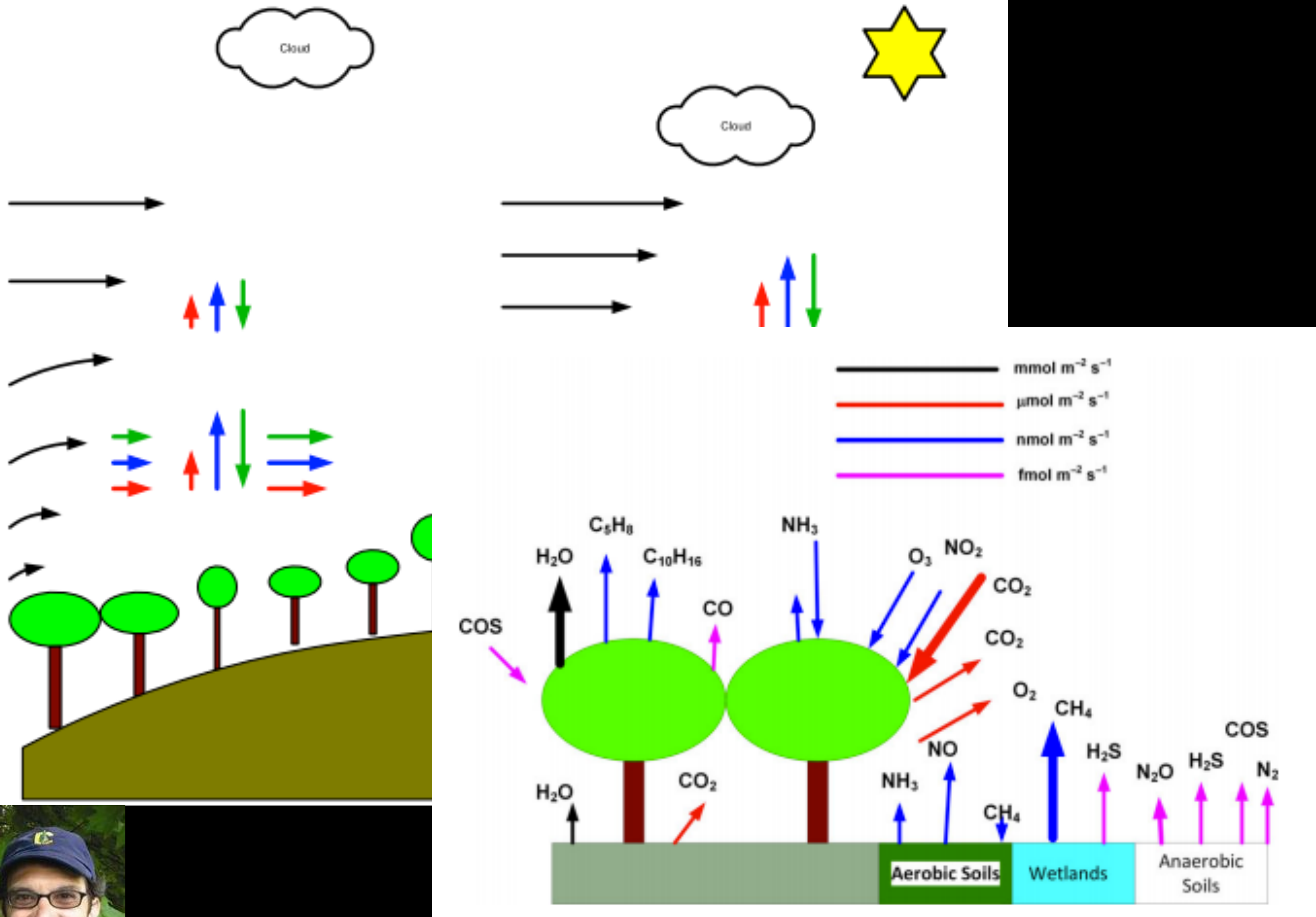
What do I (we) do?

http://flux.aos.wisc.edu

- Probe spatial heterogeneity in biologically-mediated surface-atmosphere exchanges from sites to regions (meters-1000s km)
  - Forests, wetlands, lakes, urban (temperate-boreal-tropical-Mediterranean-alpine, terrestrial-aquatic, management gradients)
  - Multiple greenhouse gases (methane), esp. with eddy covariance
  - Feedbacks from energy balance and a land surface variability on the atmospheric boundary layer and synoptic-PBL interactions in observations and models (LES, PBL, mesoscale, climate)
  - Up/down scaling across multiple measurements: eddy covariance, biometric, airborne budgets, inverse modeling, hyperspectral remote sensing (leaf to satellite)
  - Informing ecosystem and atmospheric models with diverse measurements across space (data assimilation, model informatics) – http://pecanproject.org

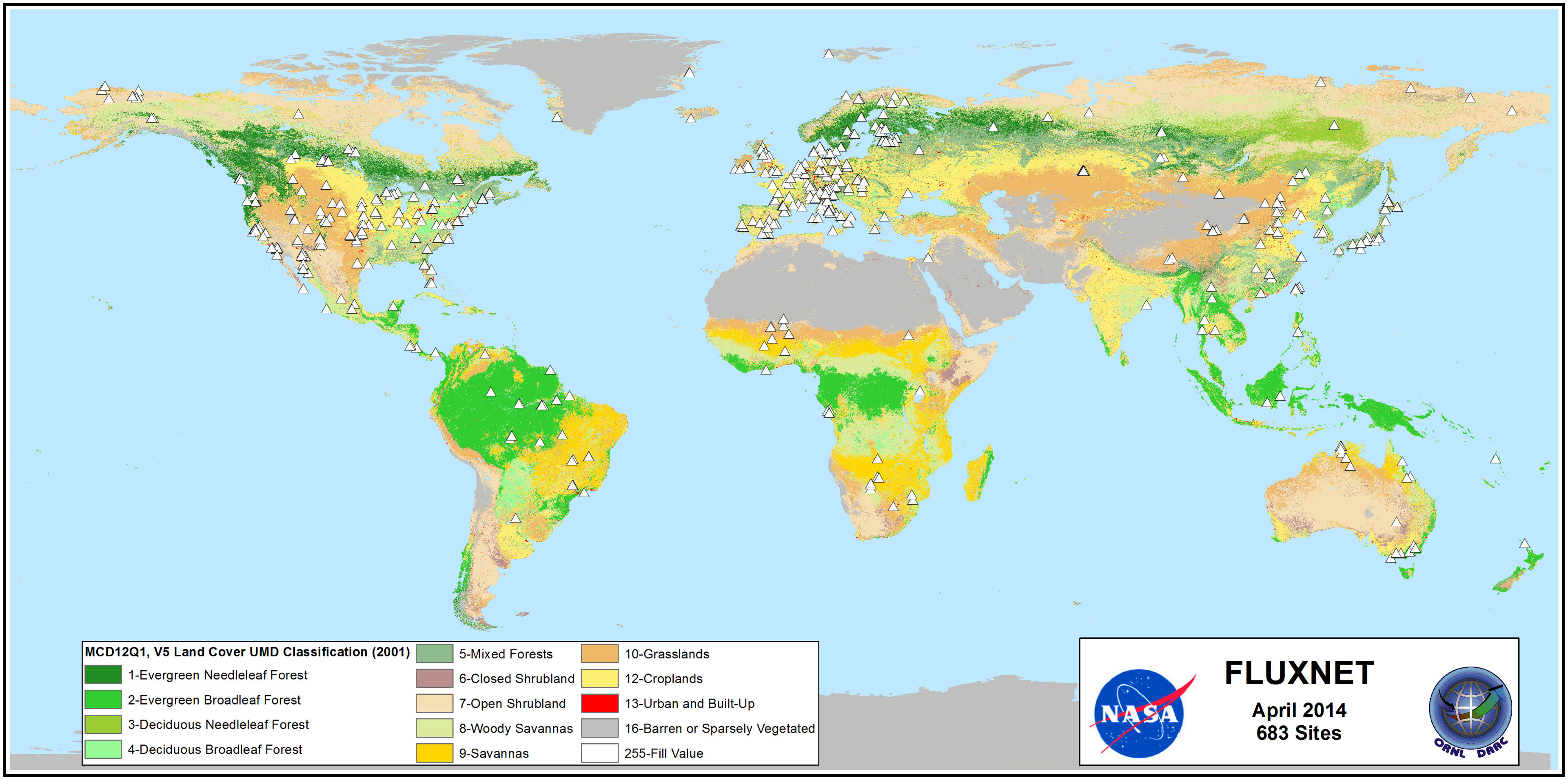
Who we are

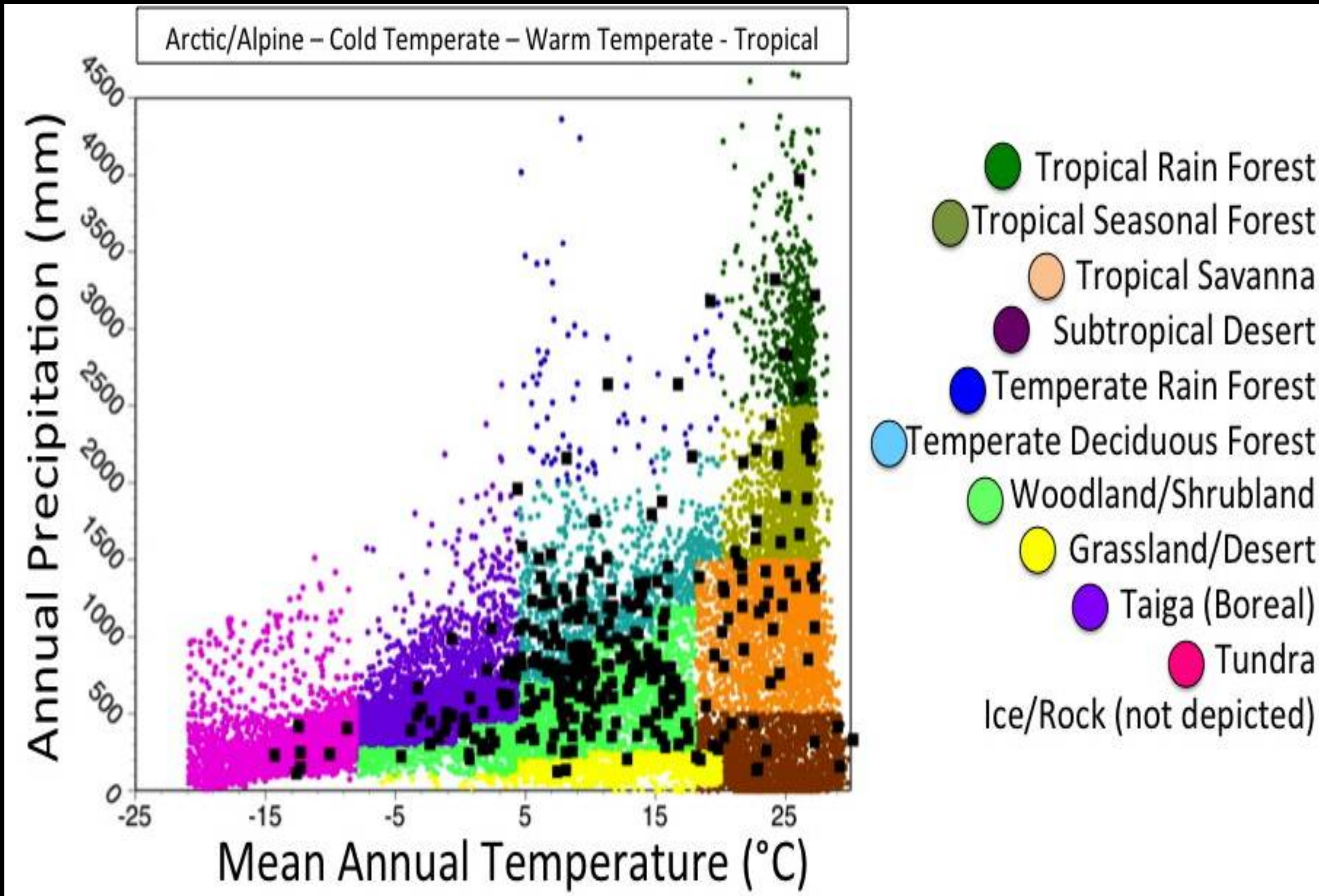
What the flux?

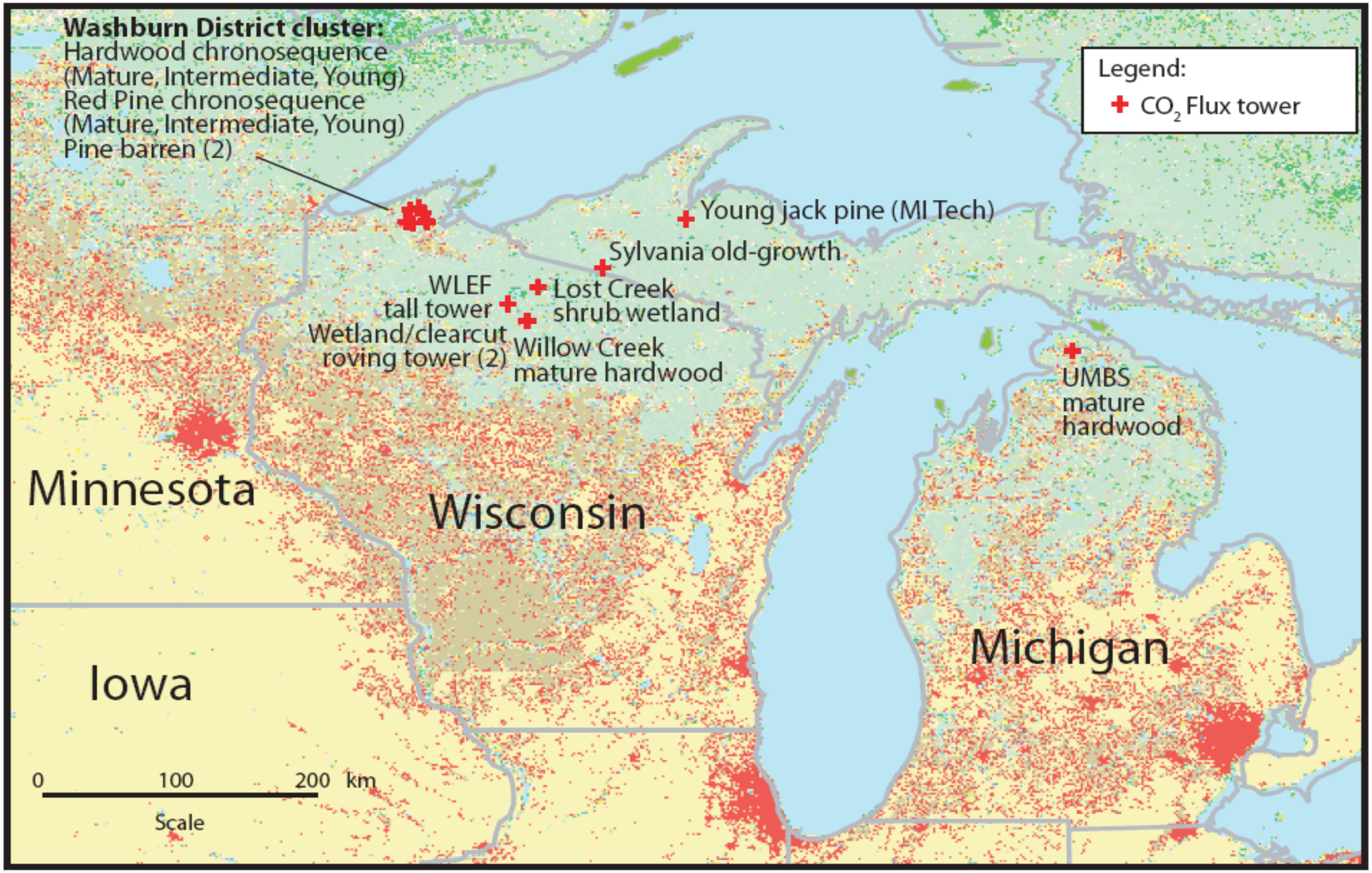

Cloud
Cloud
mmol m⁻² s⁻¹
µmol m⁻² s⁻¹
nmol m⁻² s⁻¹
fmol m⁻² s⁻¹
C_5H_8
H_2O
$C_{10}H_{16}$
NH_3
O_3
NO_2
CO_2
COS
CO
CO_2
O_2
CH_4
H_2S
COS
NO
N_2O
H_2S
N_2
H_2O
CO_2
NH_3
CH_4
Aerobic Soils
Wetlands
Anaerobic Soils

D. Baldocchi

700 points of light?

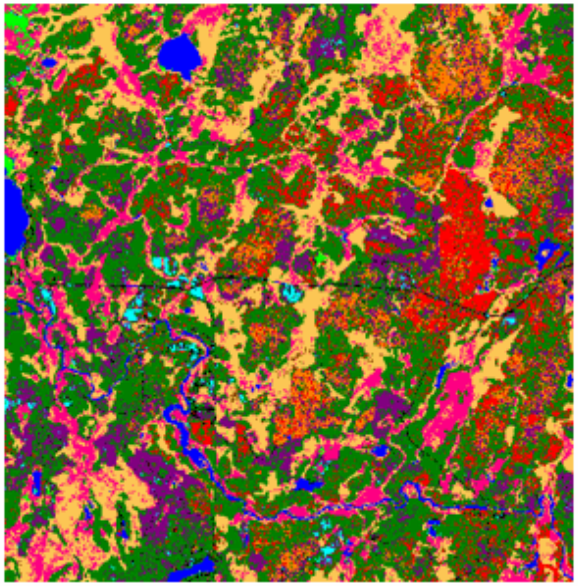
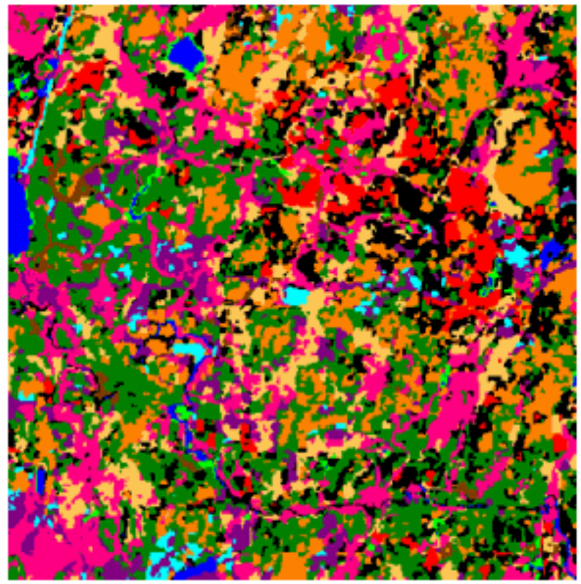
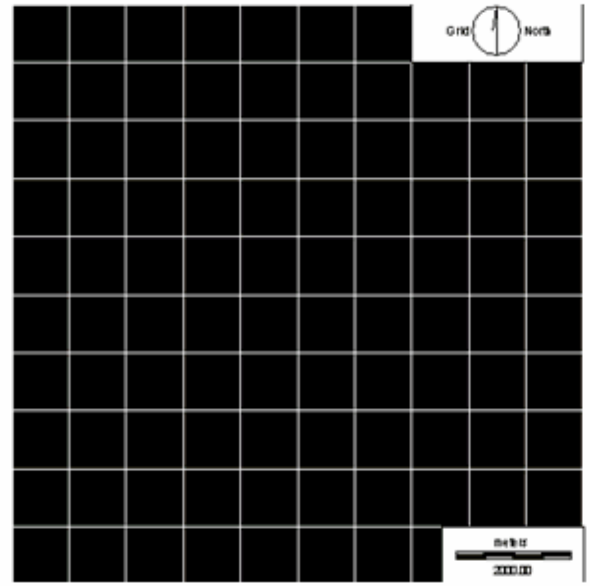



Arctic/Alpine – Cold Temperate – Warm Temperate - Tropical
Annual Precipitation (mm)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-25
-15
-5
5
15
25
Mean Annual Temperature (°C)
Tropical Rain Forest
Tropical Seasonal Forest
Tropical Savanna
Subtropical Desert
Temperate Rain Forest
Temperate Deciduous Forest
Woodland/Shrubland
Grassland/Desert
Taiga (Boreal)
Tundra
Ice/Rock (not depicted)

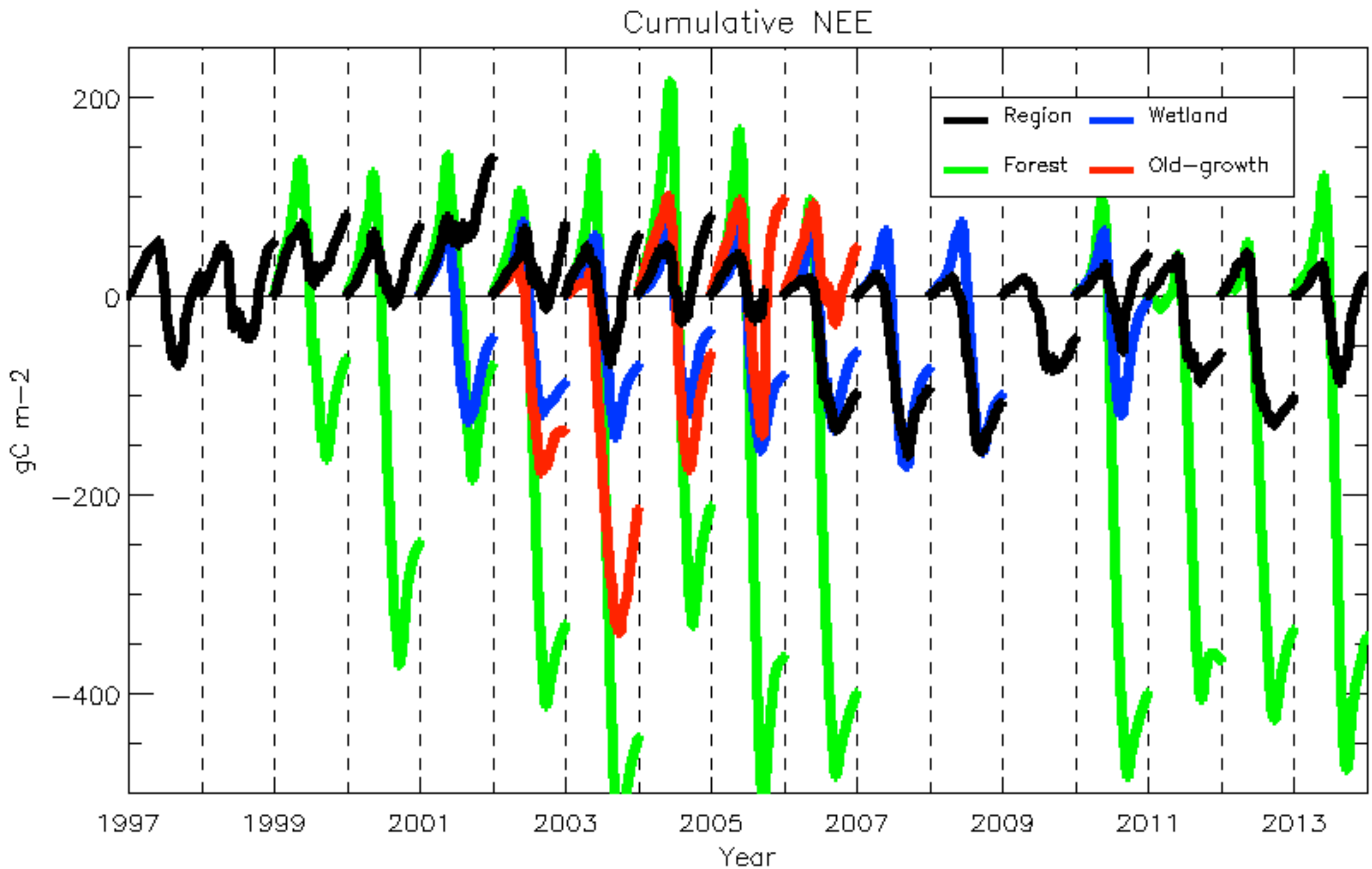


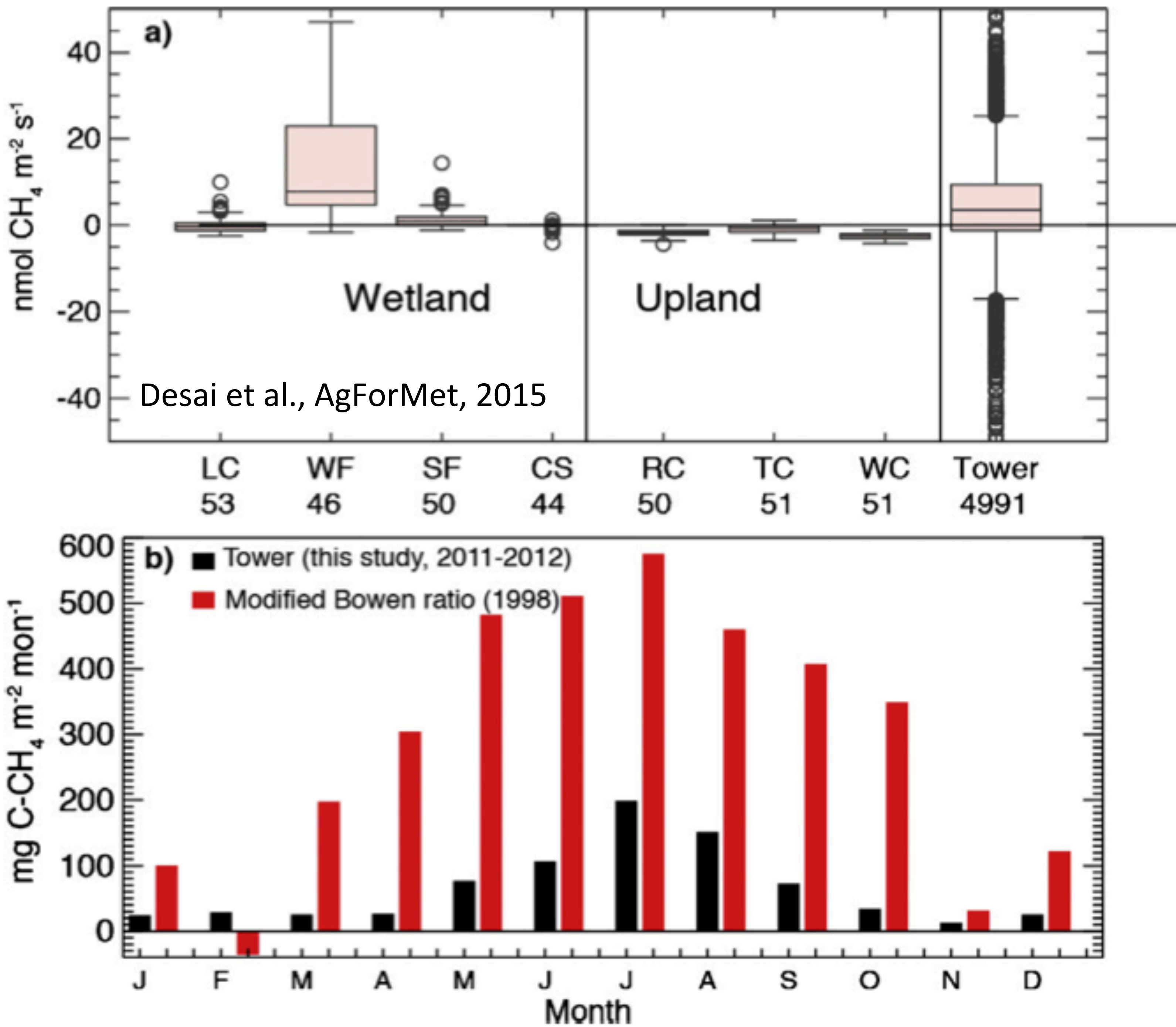
Washburn District cluster:
Hardwood chronosequence
(Mature, Intermediate, Young)
Red Pine chronosequence
(Mature, Intermediate, Young)
Pine barren (2)
Legend:
CO_2 Flux tower
Young jack pine (MI Tech)
Sylvania old-growth
WLEF
tall tower
Lost Creek
shrub wetland
Wetland/clearcut
roving tower (2)
Willow Creek
mature hardwood
UMBS
mature
hardwood
Minnesota
Wisconsin
Michigan
Iowa
0
100
200
km
Scale

Complex Regions: 1+1≠2

a) IKONOS.	b) WISCLAND.	c) MODIS-UMD and IGBP.
		

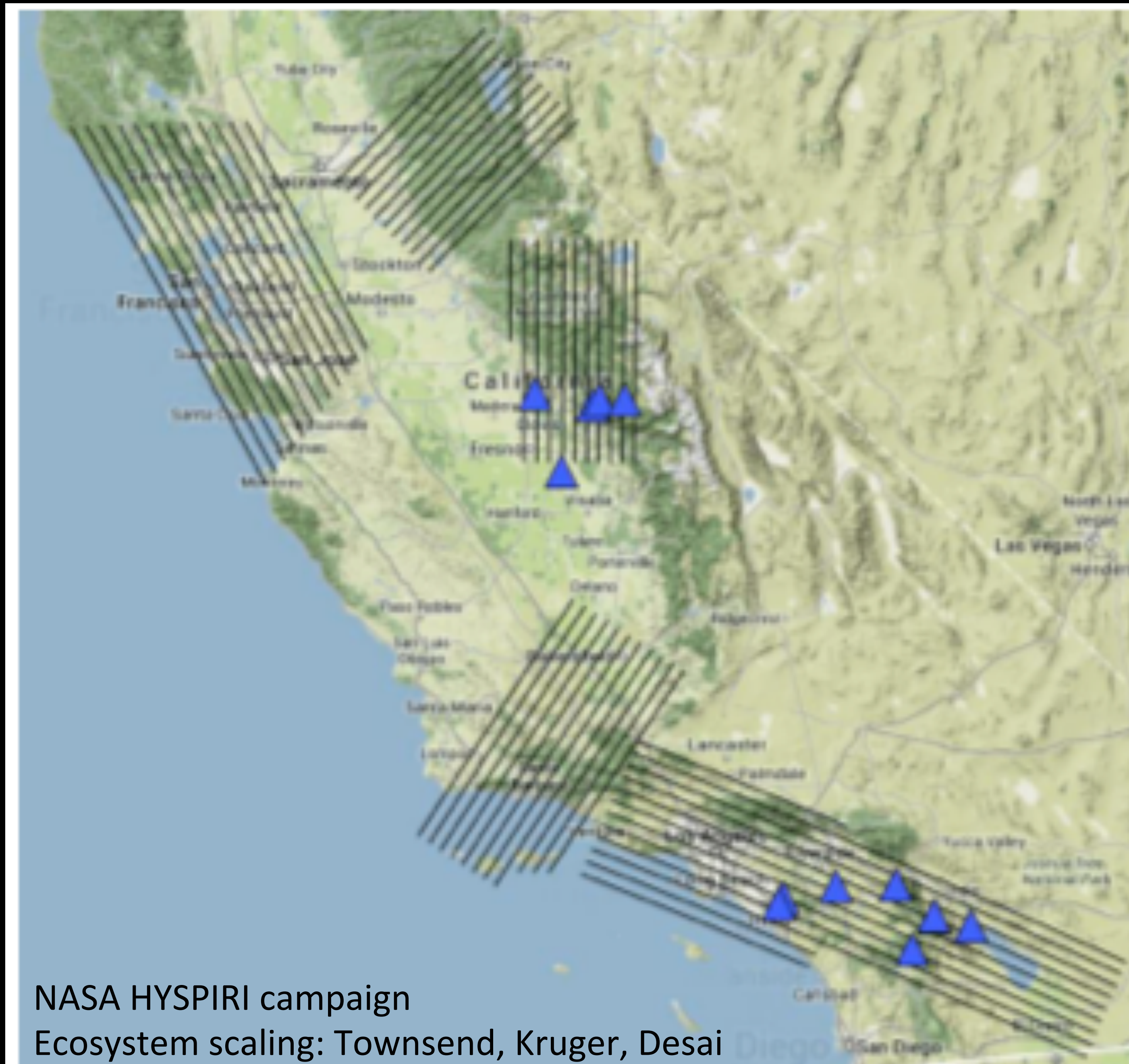
Class	a) IKONOS	b) WISCLAND	c) MODIS-UMD and IGBP
Mixed Forest	—	7.1%	100%
Upland Conifer	13.3%	13.0%	
Aspen-Birch	34.8%	25.3%	
Upland Hardwood	5.7%	14.6%	
Upland Opening/Shrub	12.0%	6.8%	
Grassland	0.9%	1.8%	
Lowland Conifer	17.8%	10.7%	
Lowland Deciduous	0.7%	1.9%	
Lowland Shrub	10.6%	16.3%	
Wet Meadow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


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



a)
nmol CH_4 m^{-2} s^{-1}
40
20
0
-20
-40
Wetland
Upland
Desai et al., AgForMet, 2015
LC 53
WF 46
SF 50
CS 44
RC 50
TC 51
WC 51
Tower 4991
b)
Tower (this study, 2011-2012)
Modified Bowen ratio (1998)
mg C-CH_4 m^{-2} mon^{-1}
600
500
400
300
200
100
0
J
F
M
A
M
J
J
A
S
O
N
D
Month

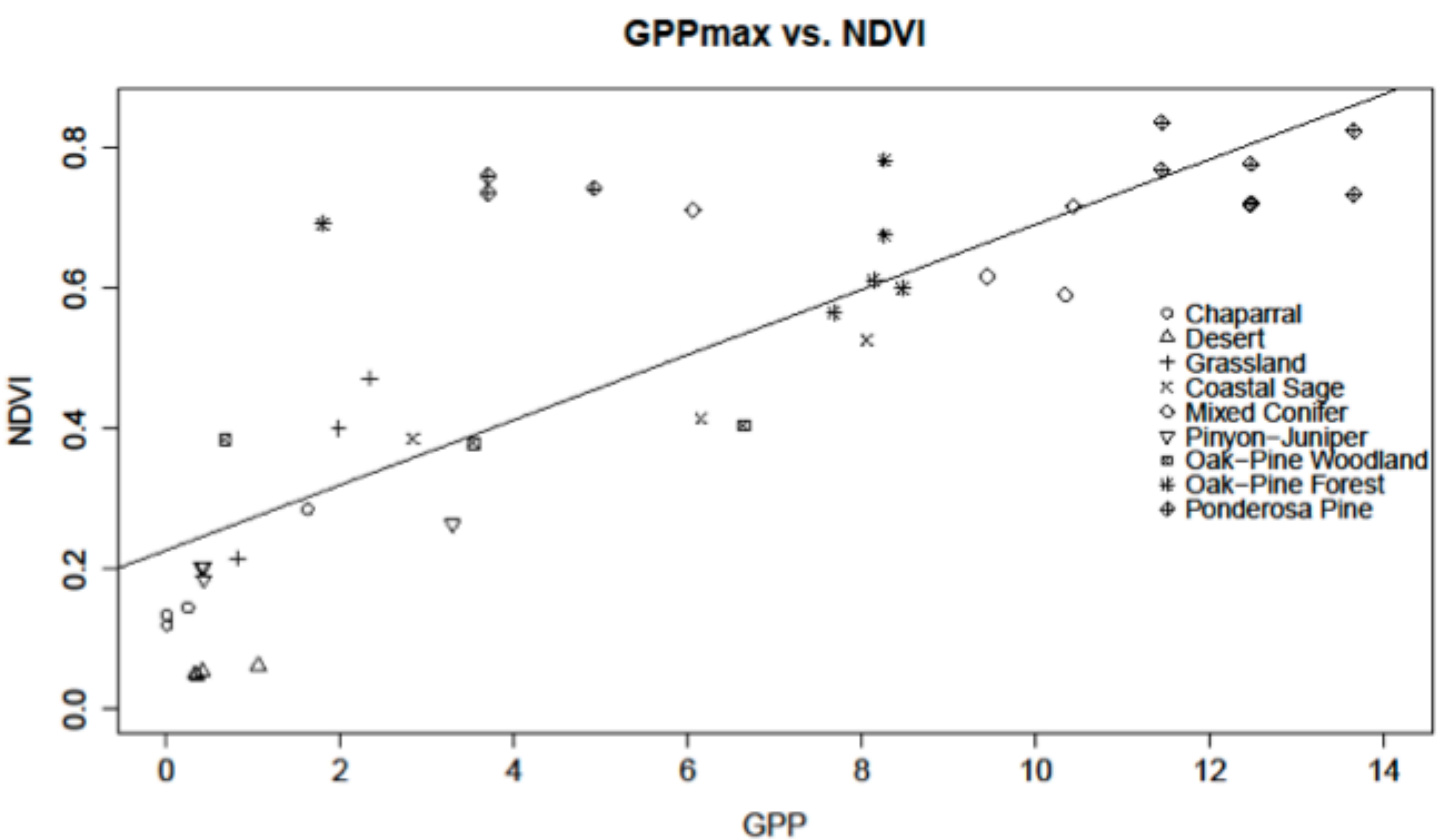
Didn’t remote sensing solve the problem?



NASA HYSPIRI campaign

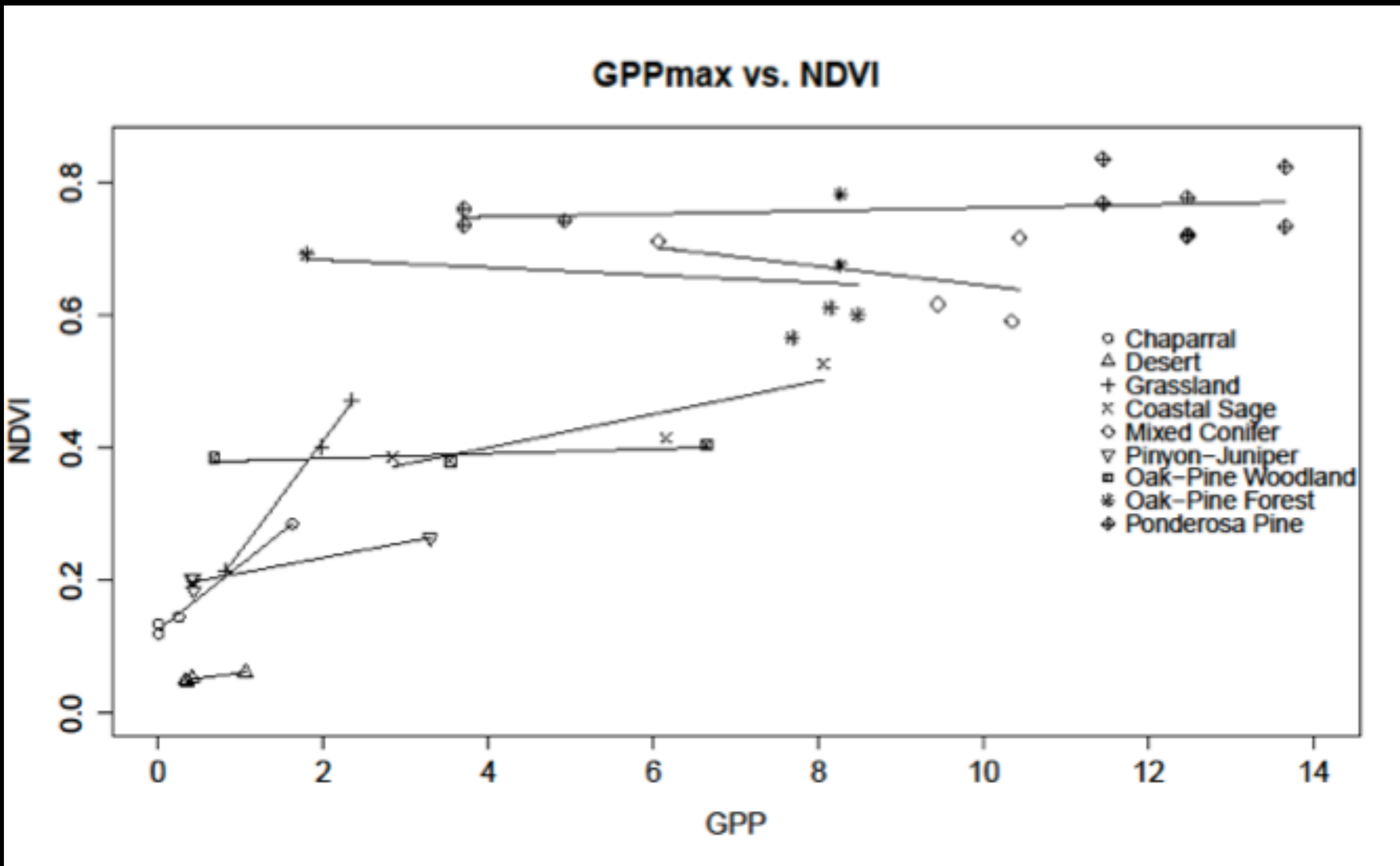
Ecosystem scaling: Townsend, Kruger, Desai

Maybe?



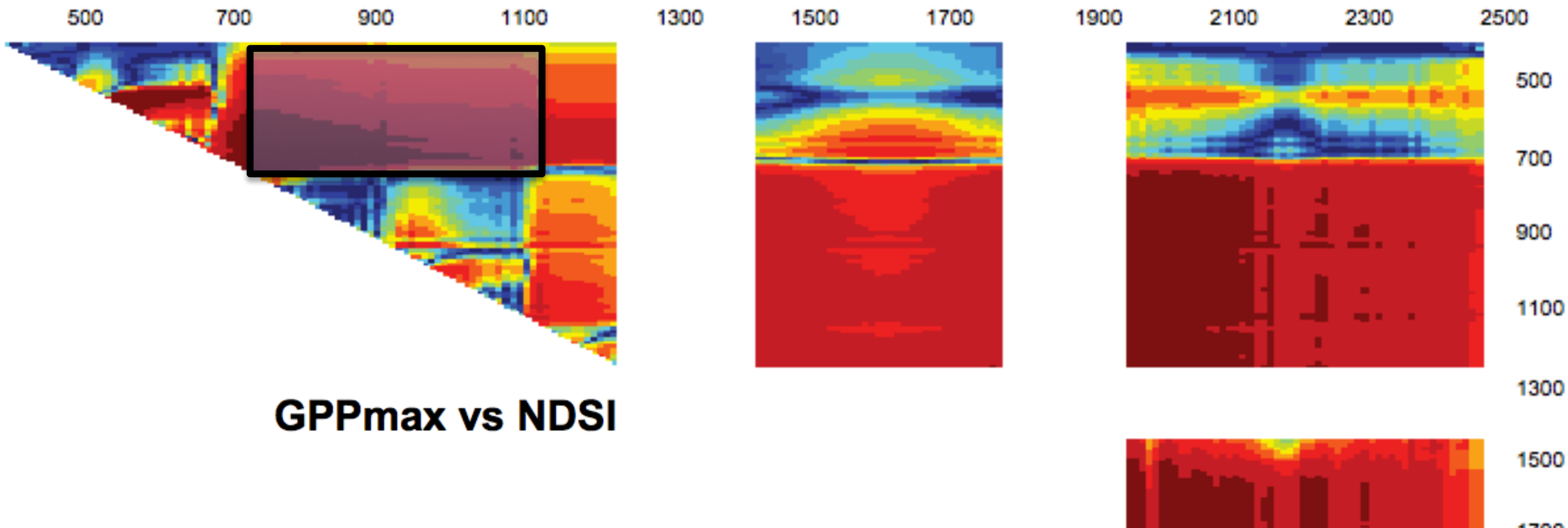
S. Dubois, MS thesis

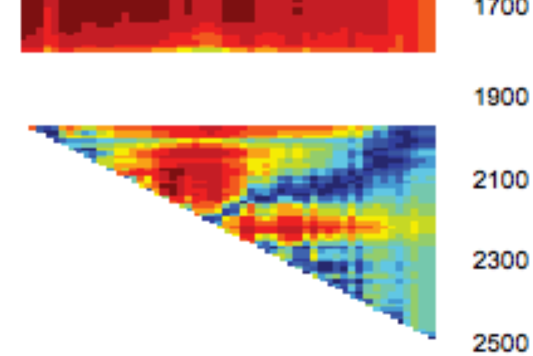
Maybe not?



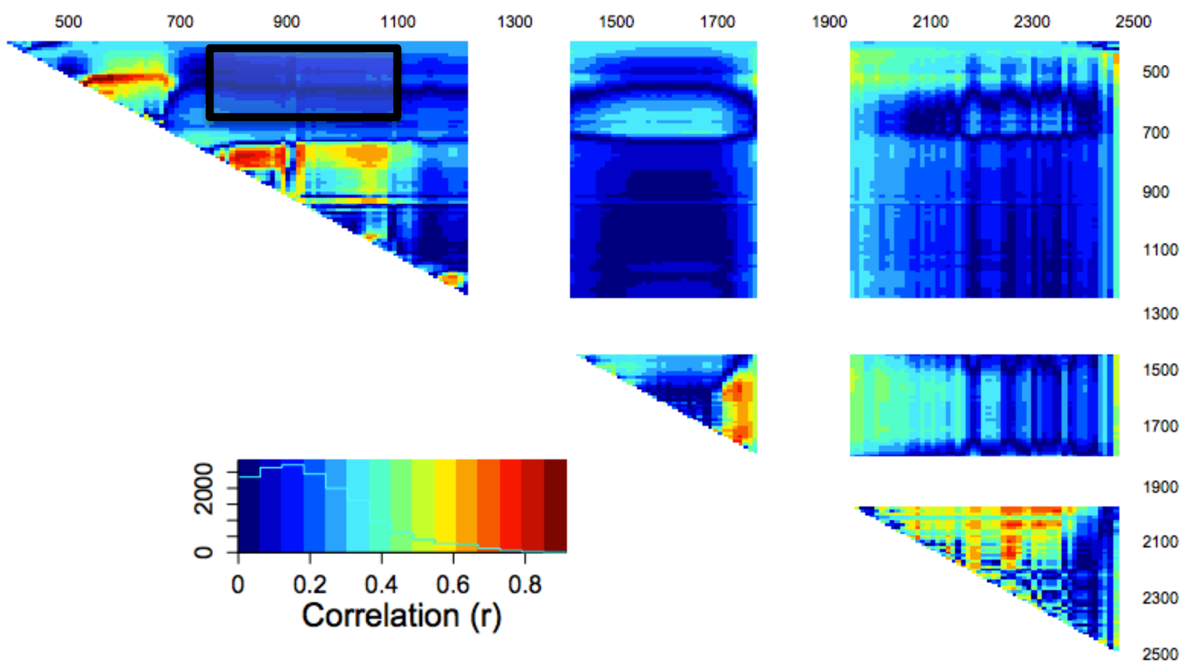
GPPmax vs. NDVI
NDVI
GPP
0.0
0.2
0.4
0.6
0.8
0
2
4
6
8
10
12
14
Chaparral
Desert
Grassland
Coastal Sage
Mixed Conifer
Pinyon–Juniper
Oak–Pine Woodland
Oak–Pine Forest
Ponderosa Pine

GPPmax vs NDSI for all sites



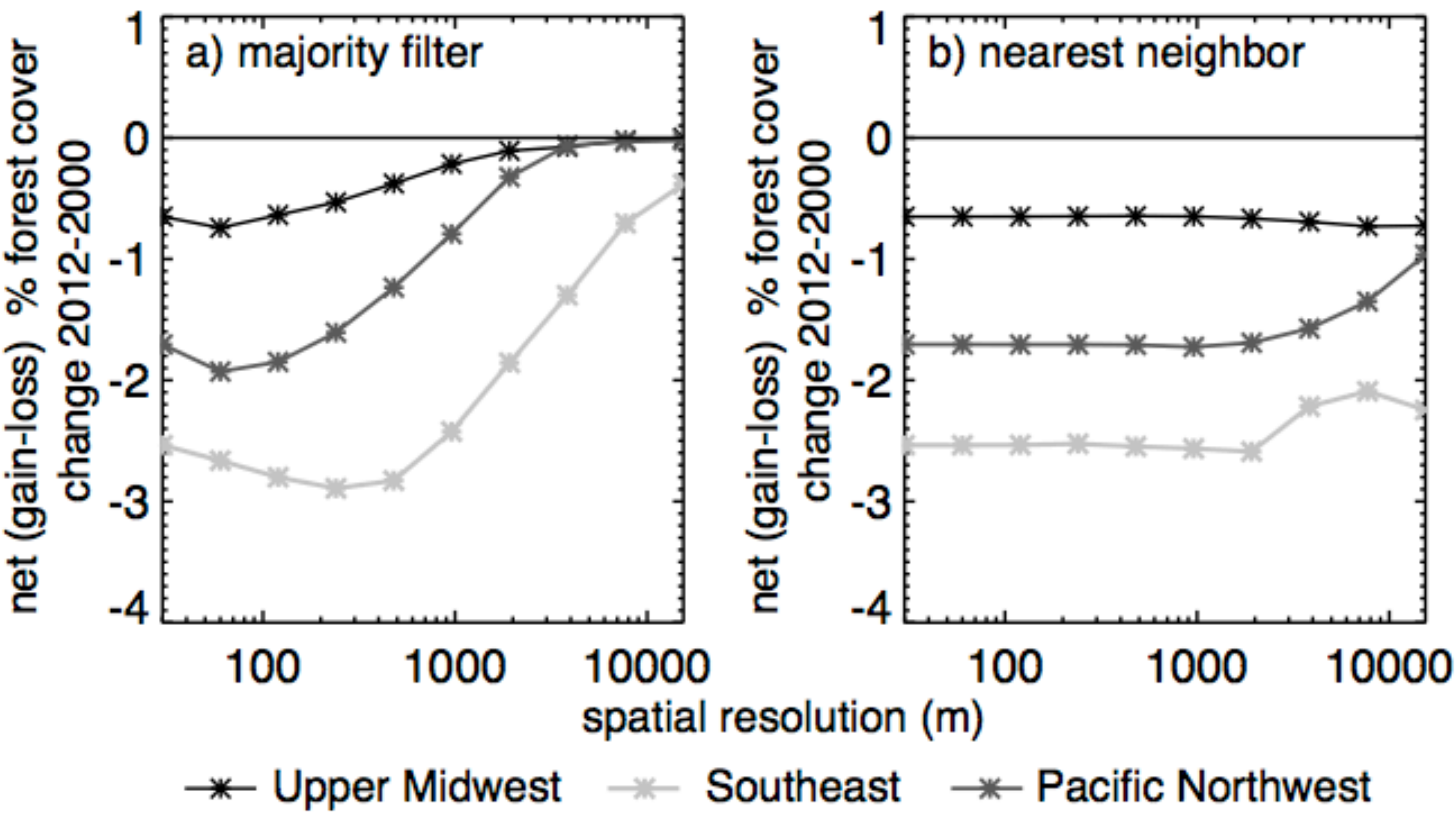


GPPmax vs NDSI



It gets weirder once we put in humans

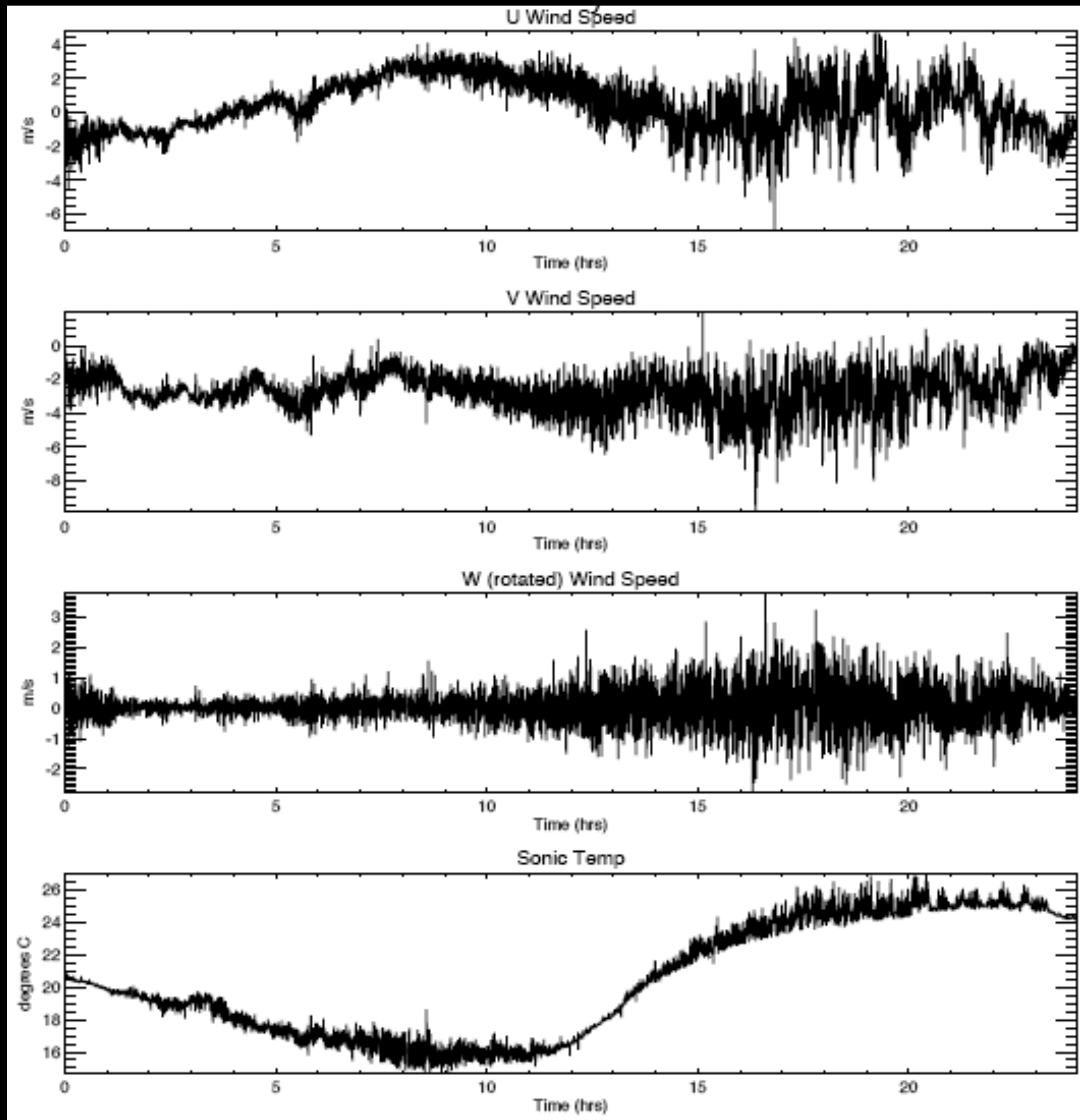
The scale and method we monitor land use matters



Becknell et al., Bioscience, 2015

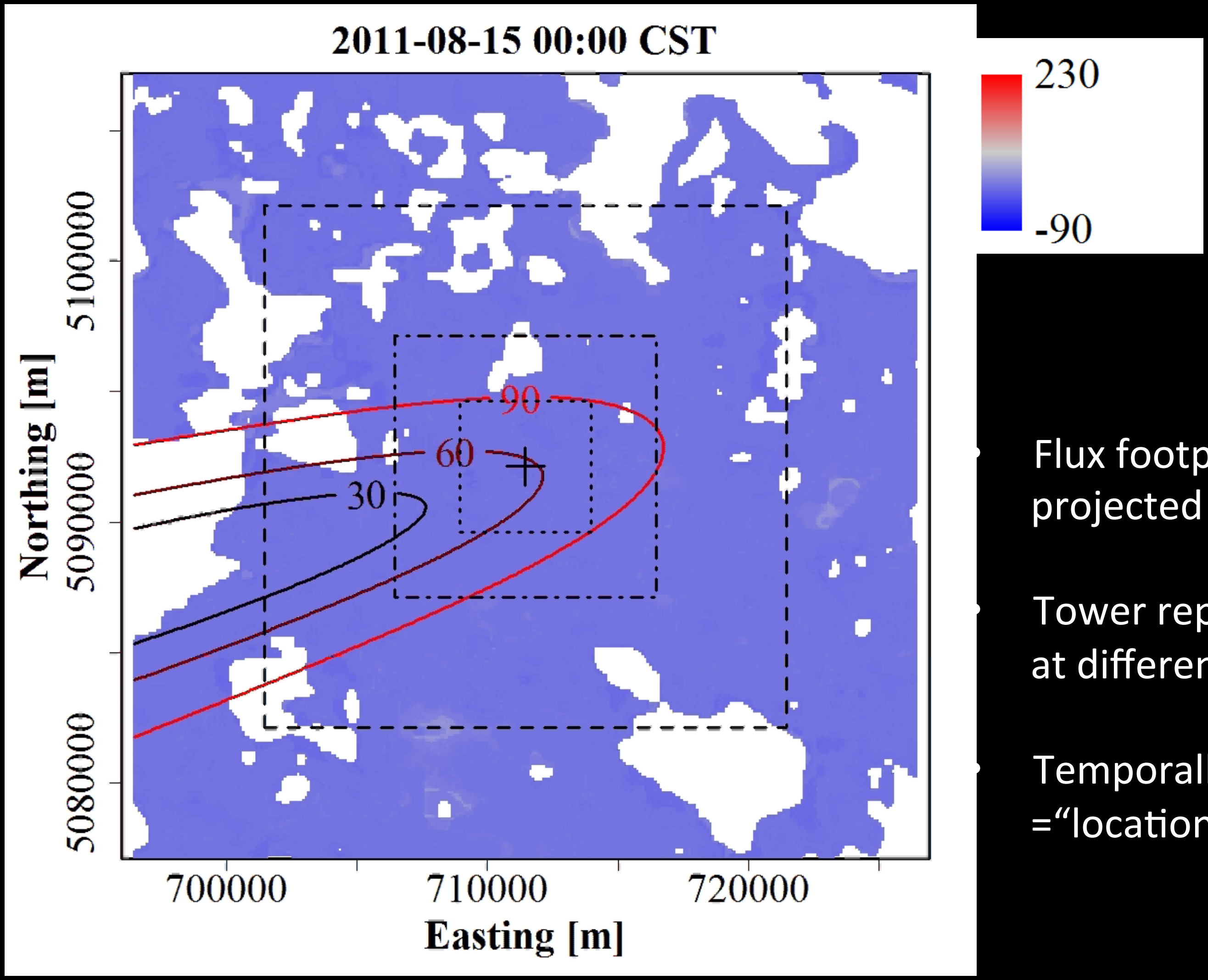
Does the atmosphere care?


B.D. Cook

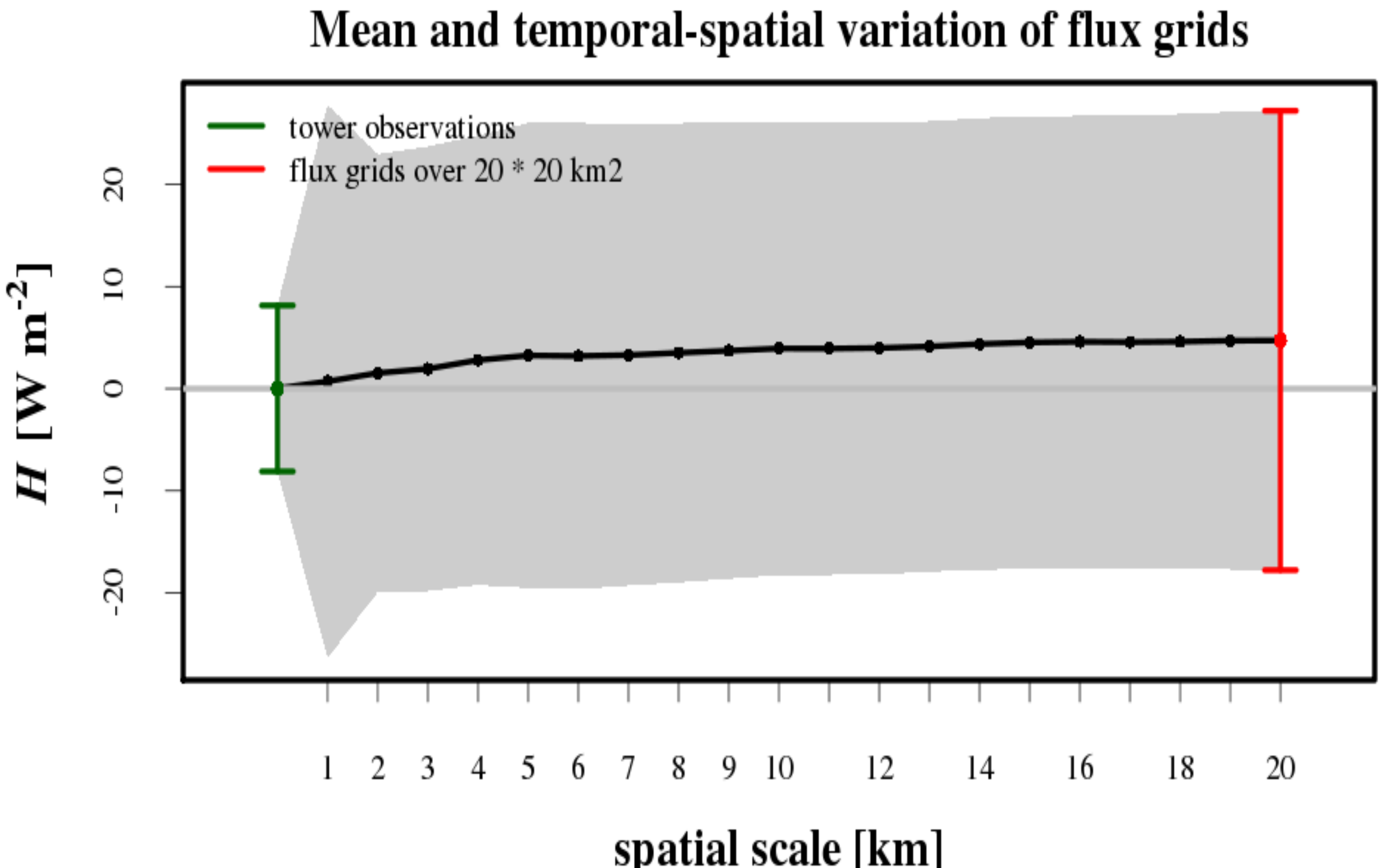


U Wind Speed
m/s
Time (hrs)
V Wind Speed
m/s
Time (hrs)
W (rotated) Wind Speed
m/s
Time (hrs)
Sonic Temp
degrees C
Time (hrs)

Sensible heat flux [W m^{-2}]



- Flux footprint varies in space, projected fluxes varies in time
- Tower represents different surfaces at different times
- Temporally transient location bias ="location drift"



Mean and temporal-spatial variation of flux grids
tower observations
flux grids over 20 * 20 km2
H [W m-2]
20
10
0
-10
-20
1
2
3
4
5
6
7
8
9
10
12
14
16
18
20
spatial scale [km]

Large eddy simulation (LES)

- A form of spatial filtering to the full turbulent conservation equations of momentum, mass, heat, and moisture – resolve and subgrid fluxes
- Works because of dissipative and scale-free nature of small-scale shear turbulence in the turbulent atmospheric boundary layer
- Unlike traditional “closure” ensemble-average solutions, resolves energy carrying turbulent motions
- Requires high spatial resolution (meters), and consequently, high temporal resolution (seconds)
- But: Good for testing effect of small scale spatial boundary conditions on atmosphere!

Energy Cascade

- Big whorls have little whorls
- That feed on their velocity,
- And little whorls have lesser whorls
- And so on to viscosity
- (in the molecular sense)
  - -- Lewis F. Richardson, 1922, cf. J Swift

Energy Cascade

Garratt

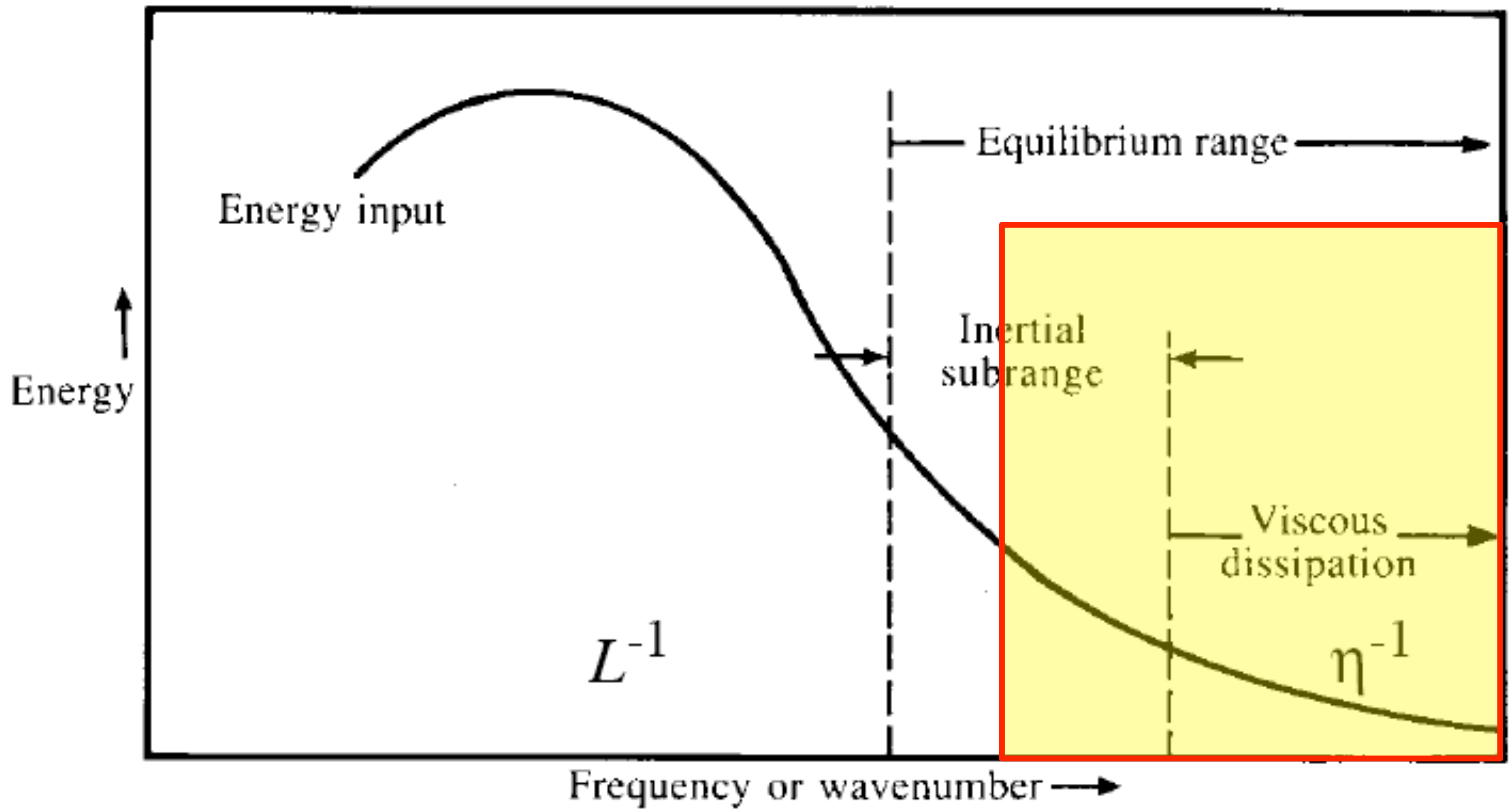


Fig. 2.1 Schematic representation of the energy spectrum of turbulence.

Tower data at 30 – 122 – 396 m to evaluate the simulations

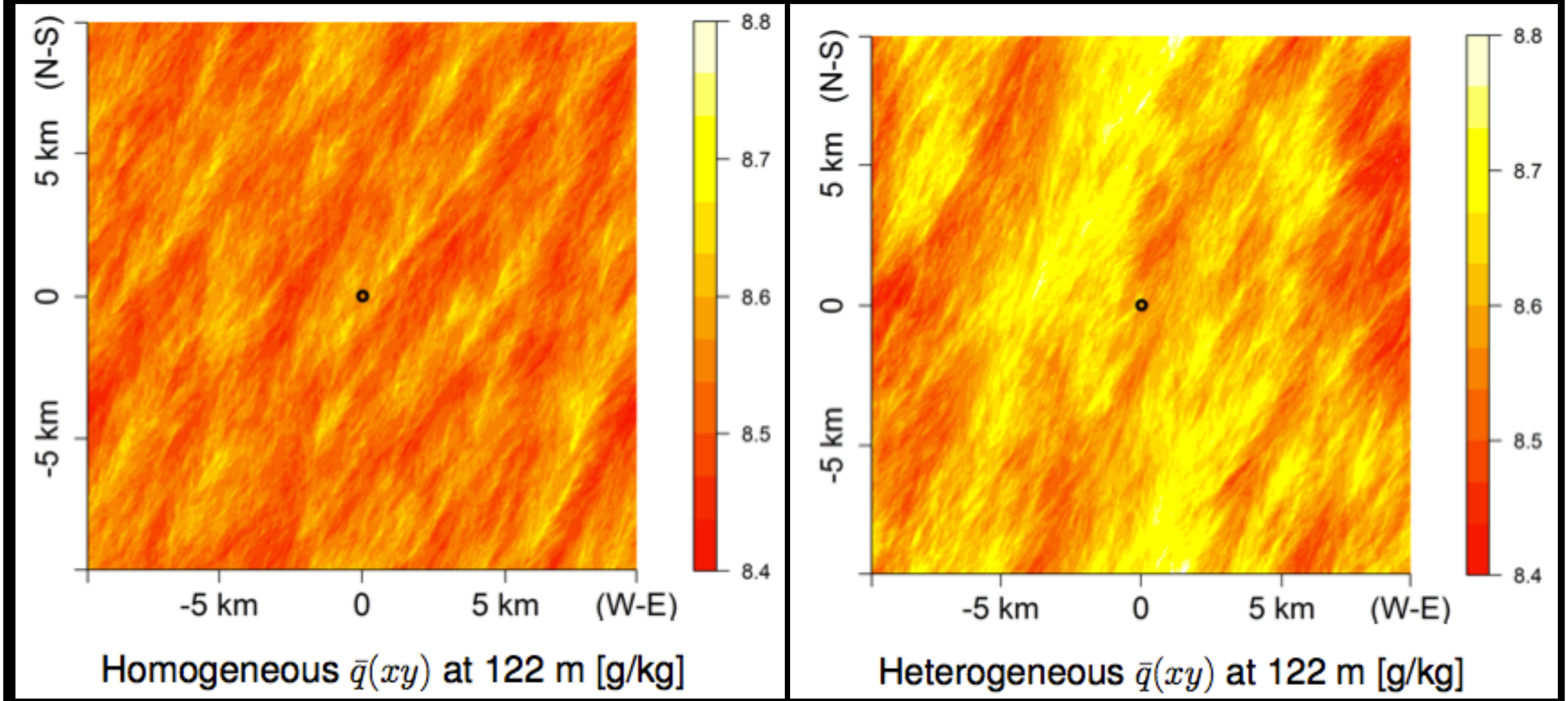
Boundary layer characteristics
$L = -1.4 \cdot 10^2\,\mathrm{m}$
$z_i = 1.3 \cdot 10^3\,\mathrm{m}$
$u_\star = 8.2 \cdot 10^{-1}\,\mathrm{m/s}$

Simulation design	
Timestep	$0.5 - 1$ s
Horizontal grid resolution	$10 - 20$ m
Gridpoints	$O(10^3 \times 10^3 \times 10^2)$
Vertical grid resolution	$5 - 10$ m
Horizontal area	$100 - 400\ \mathrm{km}^2$

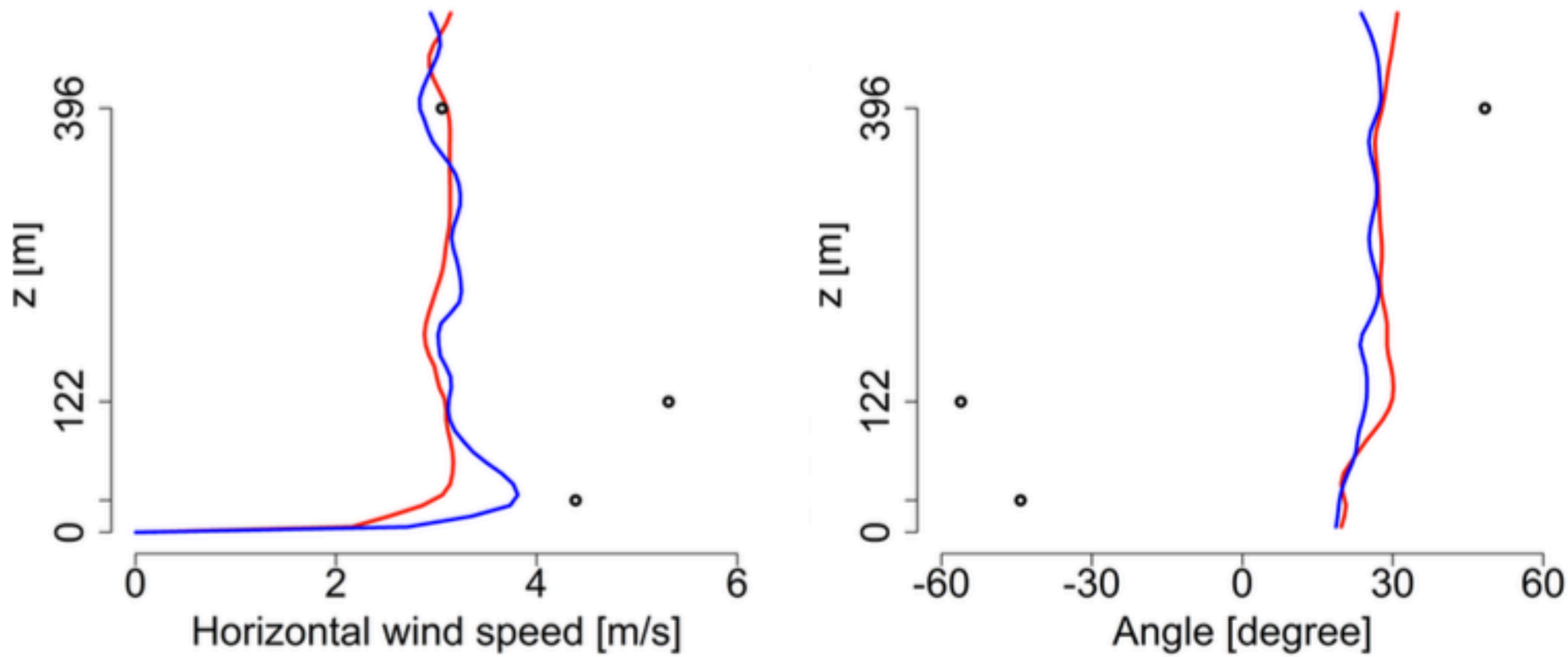
$\sigma_{xy}(\cdot)_{het} - \sigma_{xy}(\cdot)_{hom}$	30 m	122 m	396 m
T [K]	$+8.7 \cdot 10^{-3}$	$+9.6 \cdot 10^{-3}$	$+1.1 \cdot 10^{-2}$
q [g/kg]	$+2.2 \cdot 10^{-2}$	$+2.3 \cdot 10^{-2}$	$+2.3 \cdot 10^{-2}$
w [m/s]	$-5.6 \cdot 10^{-3}$	$-2.2 \cdot 10^{-2}$	$-3.8 \cdot 10^{-2}$

Frederick deRoo (KIT IMK-IFU), TERRENO

LES simulations around the tall tower show shifts in organized structures with heterogeneity of surface forcing

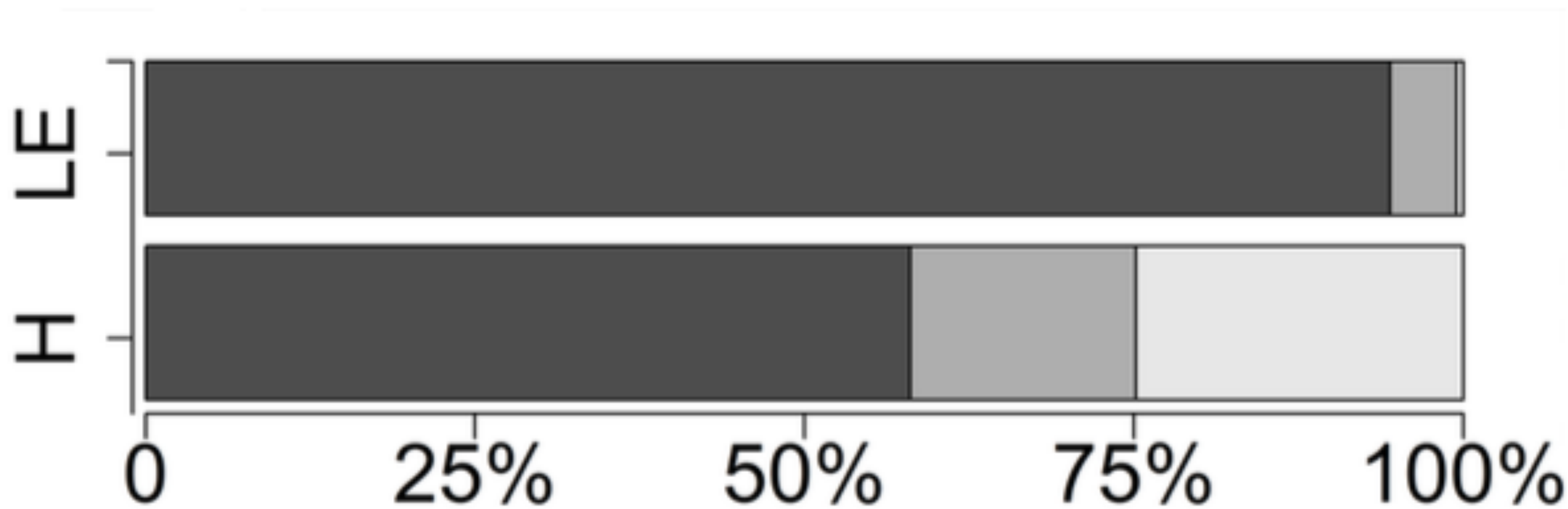


BUT: A problem...



Red: ERF-driven LES; blue: homogeneous; dots: tower data

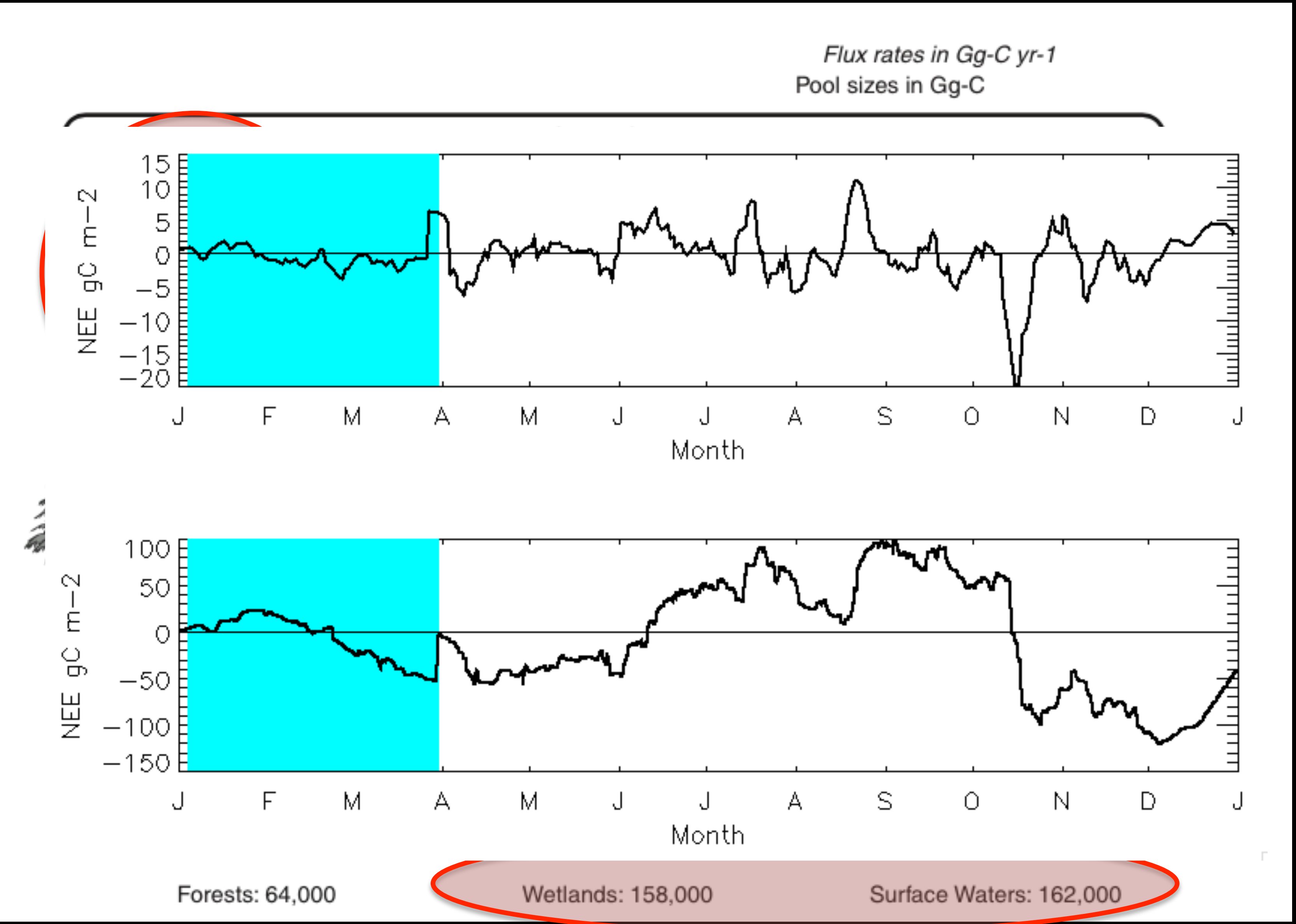
Eddy fluxes from the homogeneous LES correspond better to the tower data



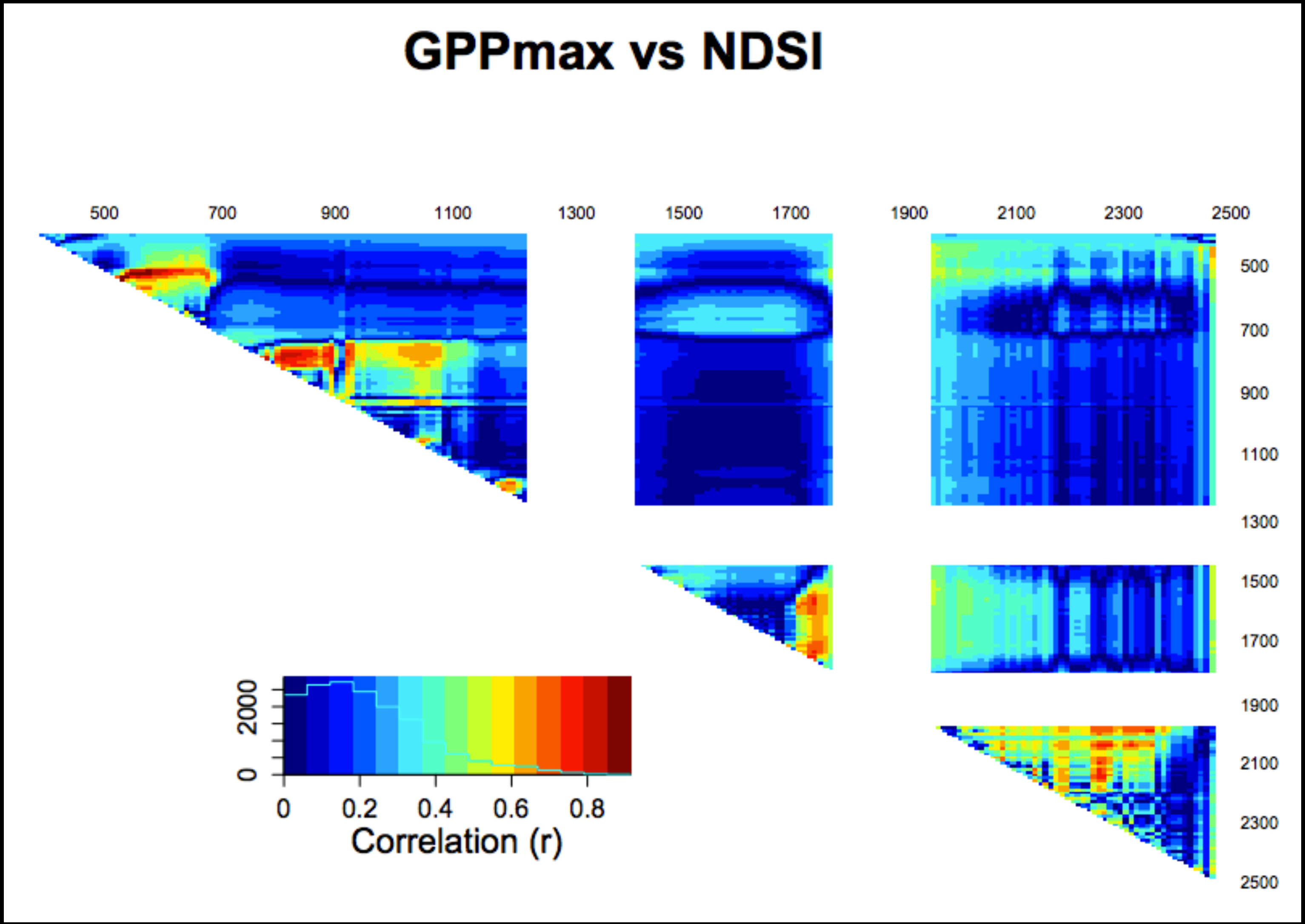
Virtual EC fluxes as fraction of the tower measurement at 12:00-13:00, 30 m
Darkgray: heterogeneous; Medium-gray: homogeneous

What are we trying to do about it?

1. Be smarter about scaling

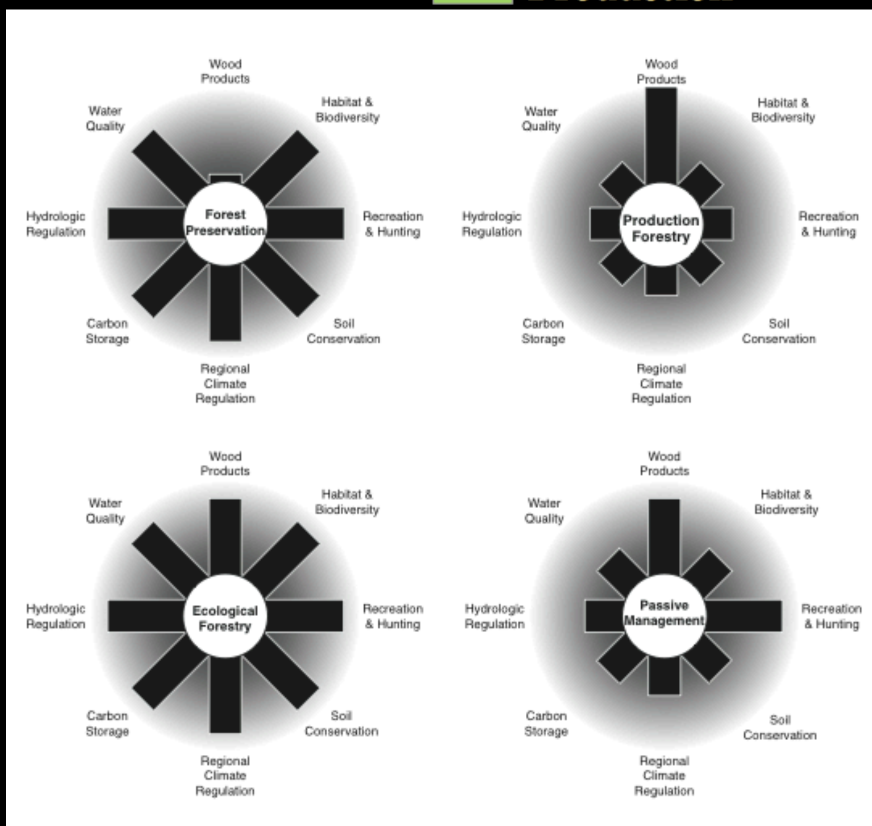


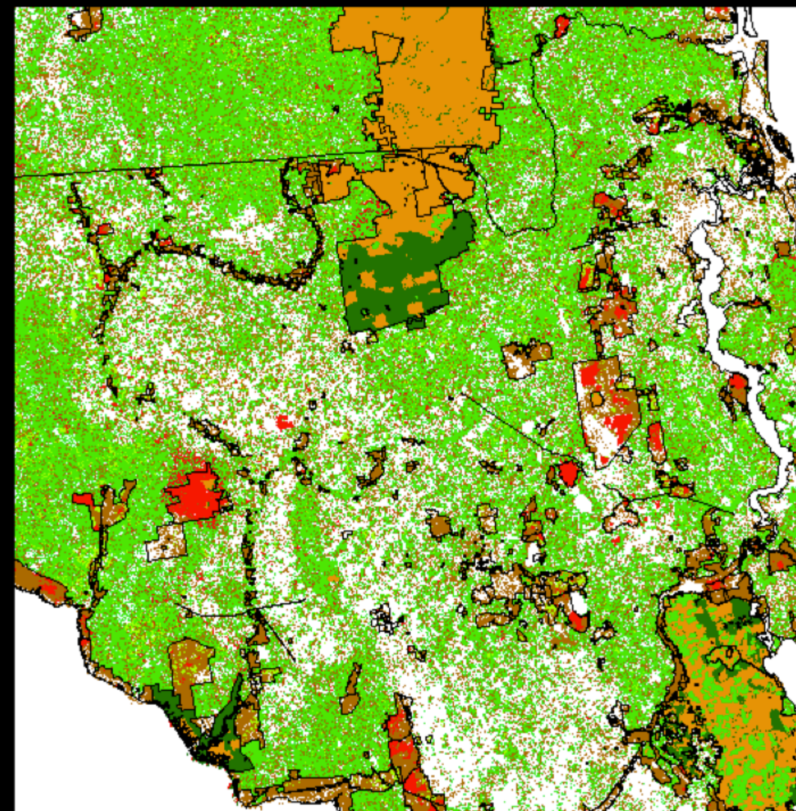
2. Find the appropriate scale



3. Map human impacts like ecosystems

Passive
Preservation
Preservation/Change
Production





MANDIFORE
Macrosystems Biology

4. Par… odels

Variability

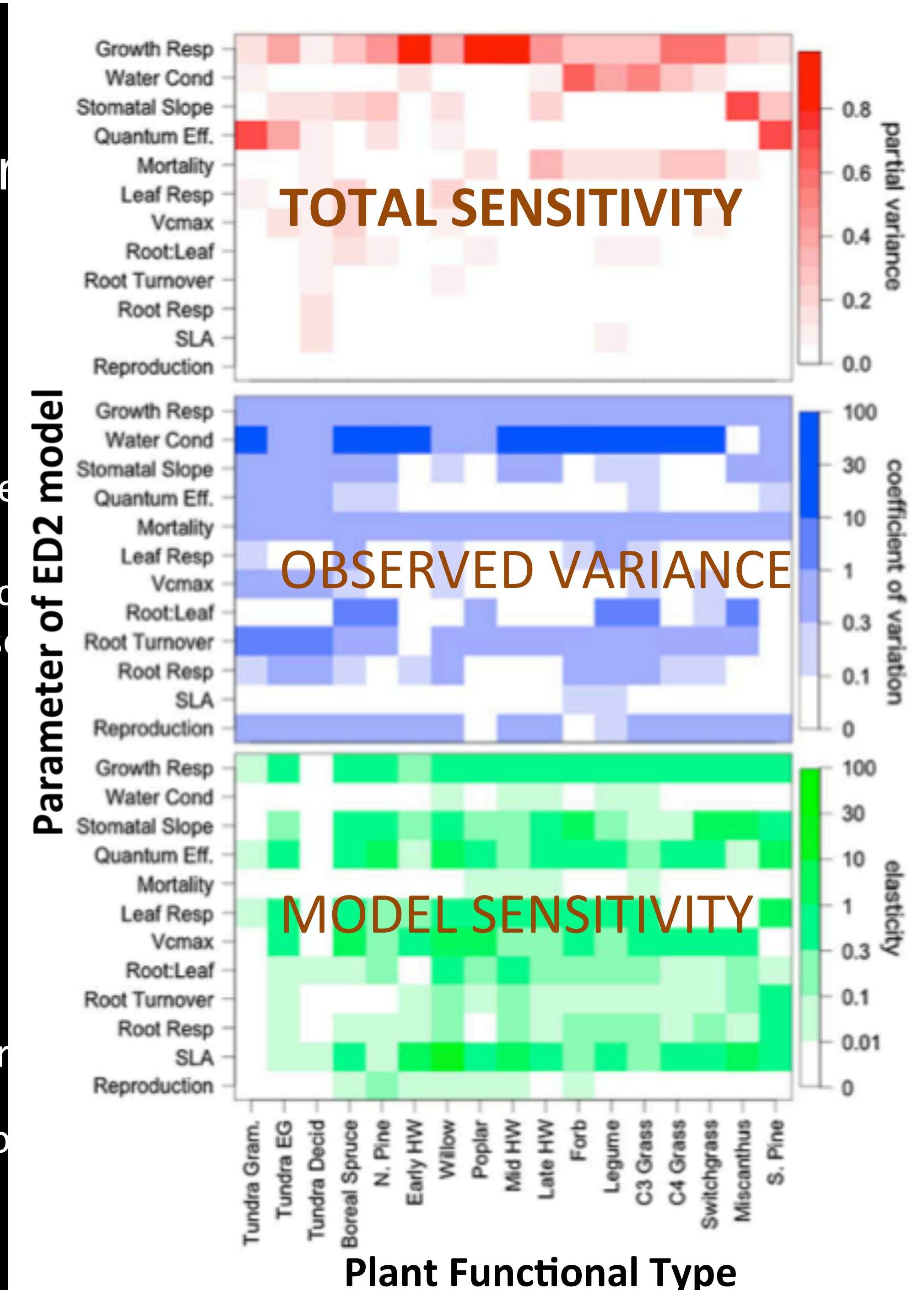
describes the proce…

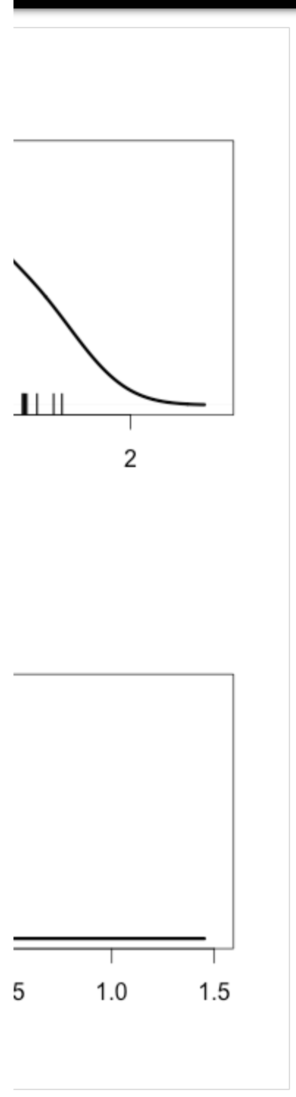
can be better charac…
but doesn't decreas…

Uncertainty

describes our ignor…

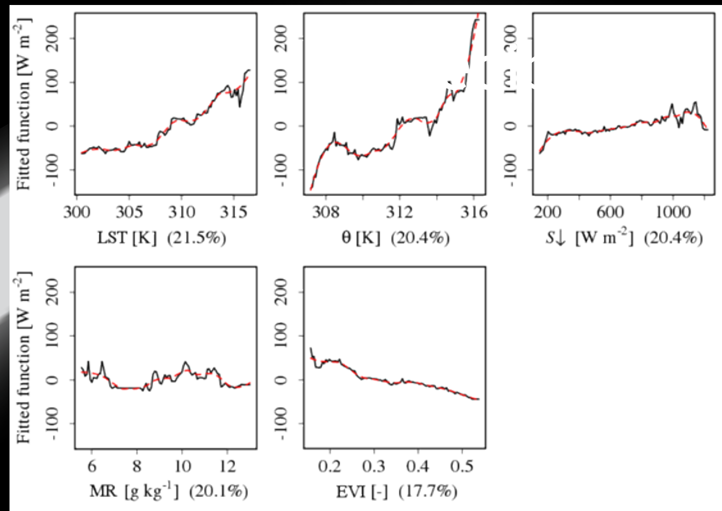
decreases asympto…





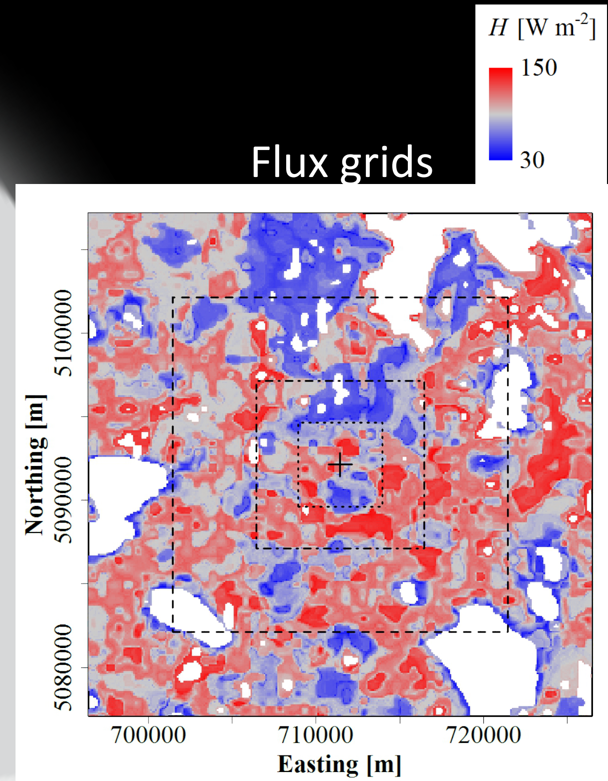
Pecanproject.org
Dietze, 2014, JGR-G

5. Make flux towers useful



Environmental response functions

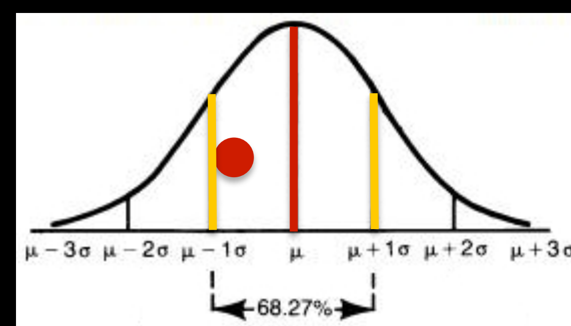
Flux grids



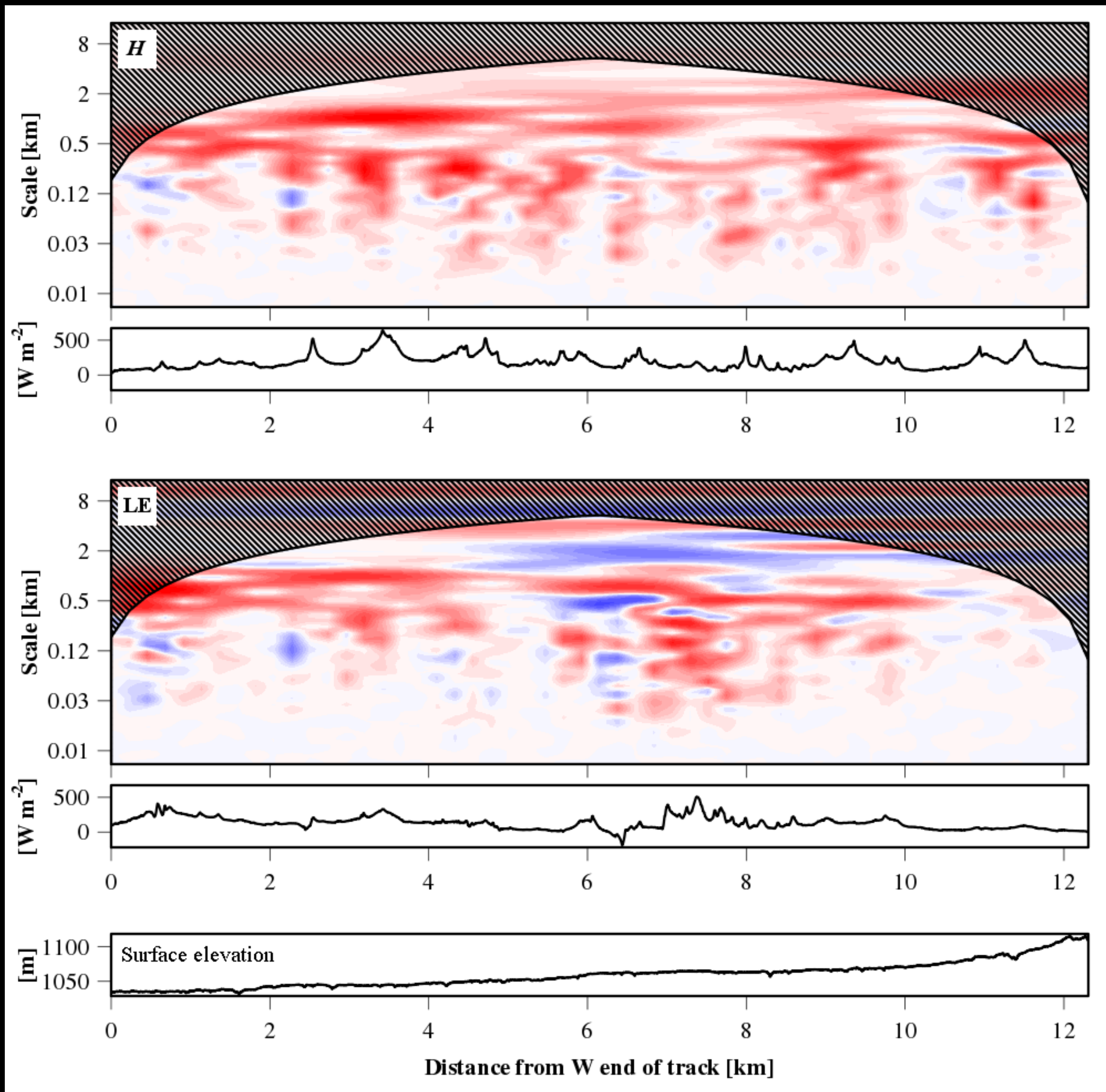
Ameriflux Park Falls 'very tall tower' (447 m): Eddy flux at 122 m.

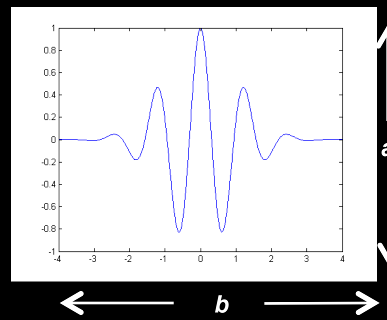
Credit: Matt Rydzik (U Wisconsin)

Before:

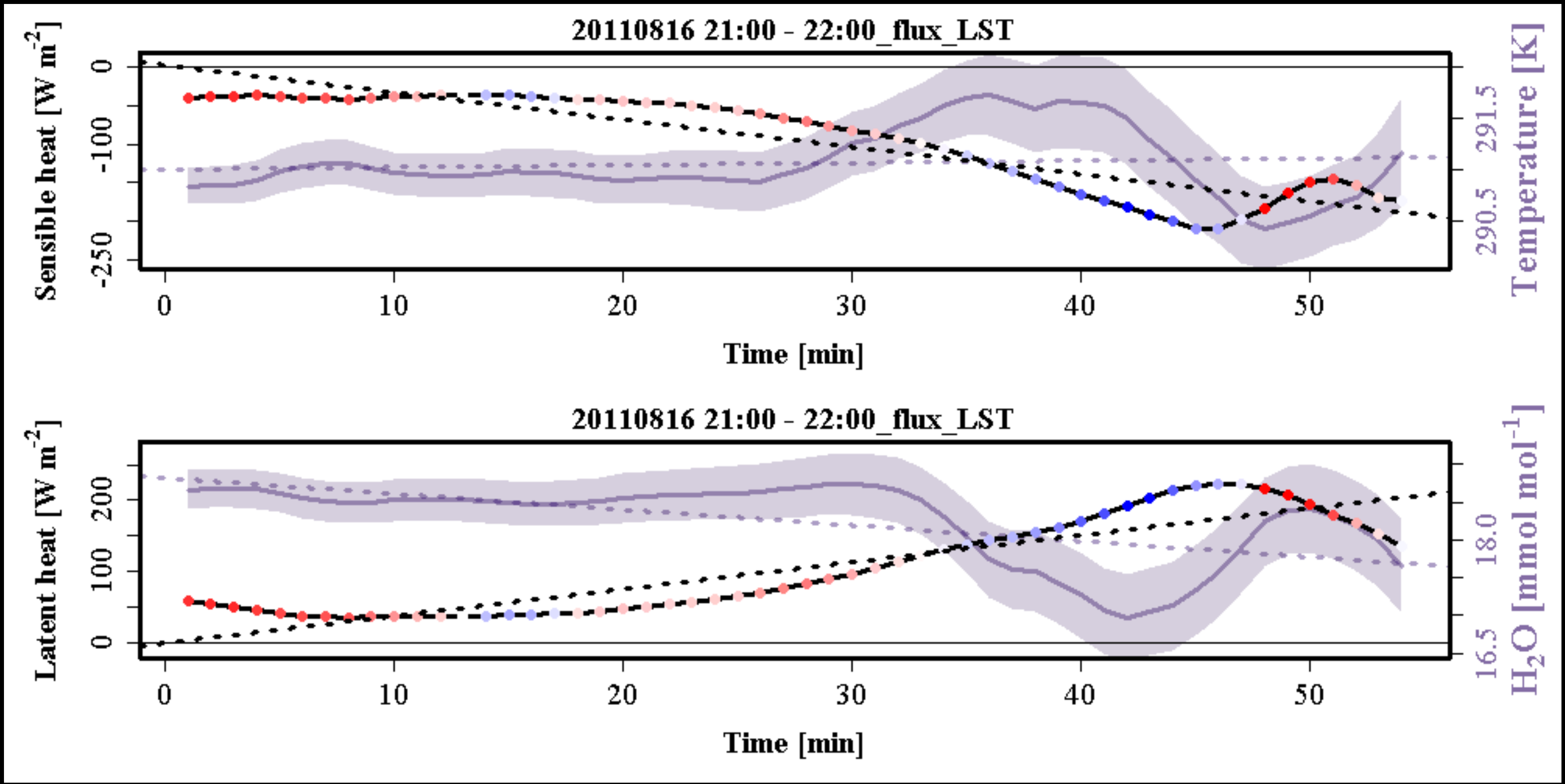


Wavelet cross-scalogram

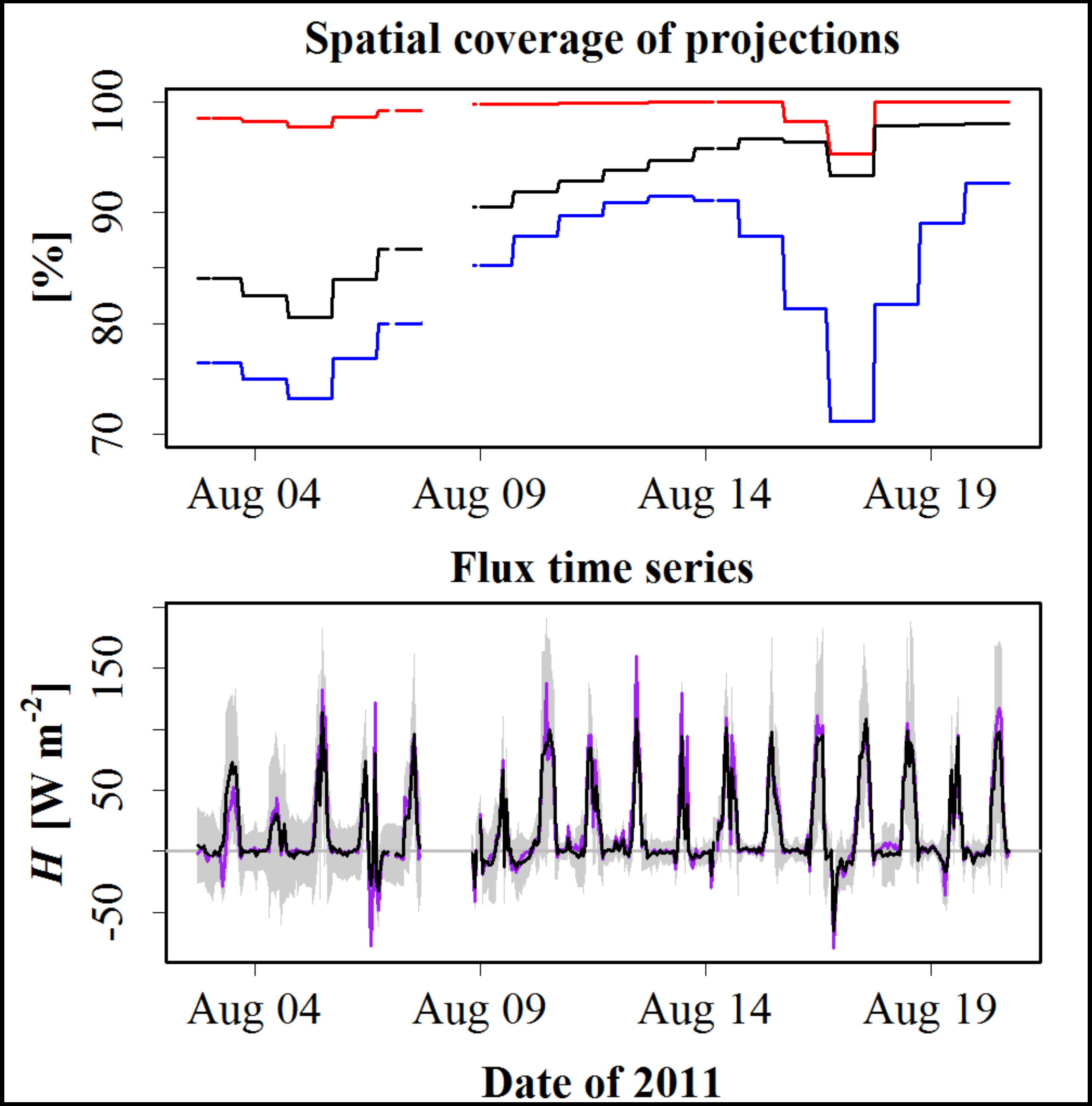




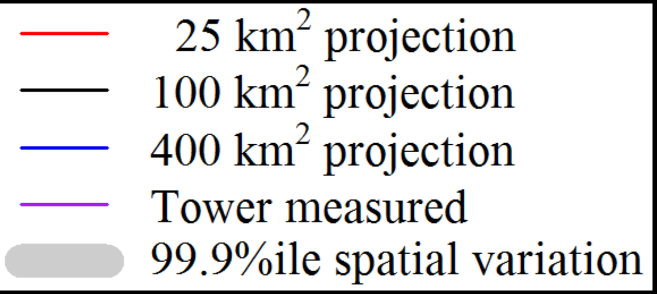
- …Process attribution!



Target area versus spatio-temporally varying patch II



- ≥70 % spatial coverage
- Spatially pre-blended fluxes less erratic
- Explicit information on spatial variation



Thank you!

- I hope my examples convinced you that scale is fundamental to understanding ecosystem-atmosphere interactions
- I hope some of the innovations I presented actually solve some of our problems of scale
- None of this can be done without my lab, collaborators, funders, and the opportunity to discuss these with you!