How scale-dependent is surface-atmosphere exchange?

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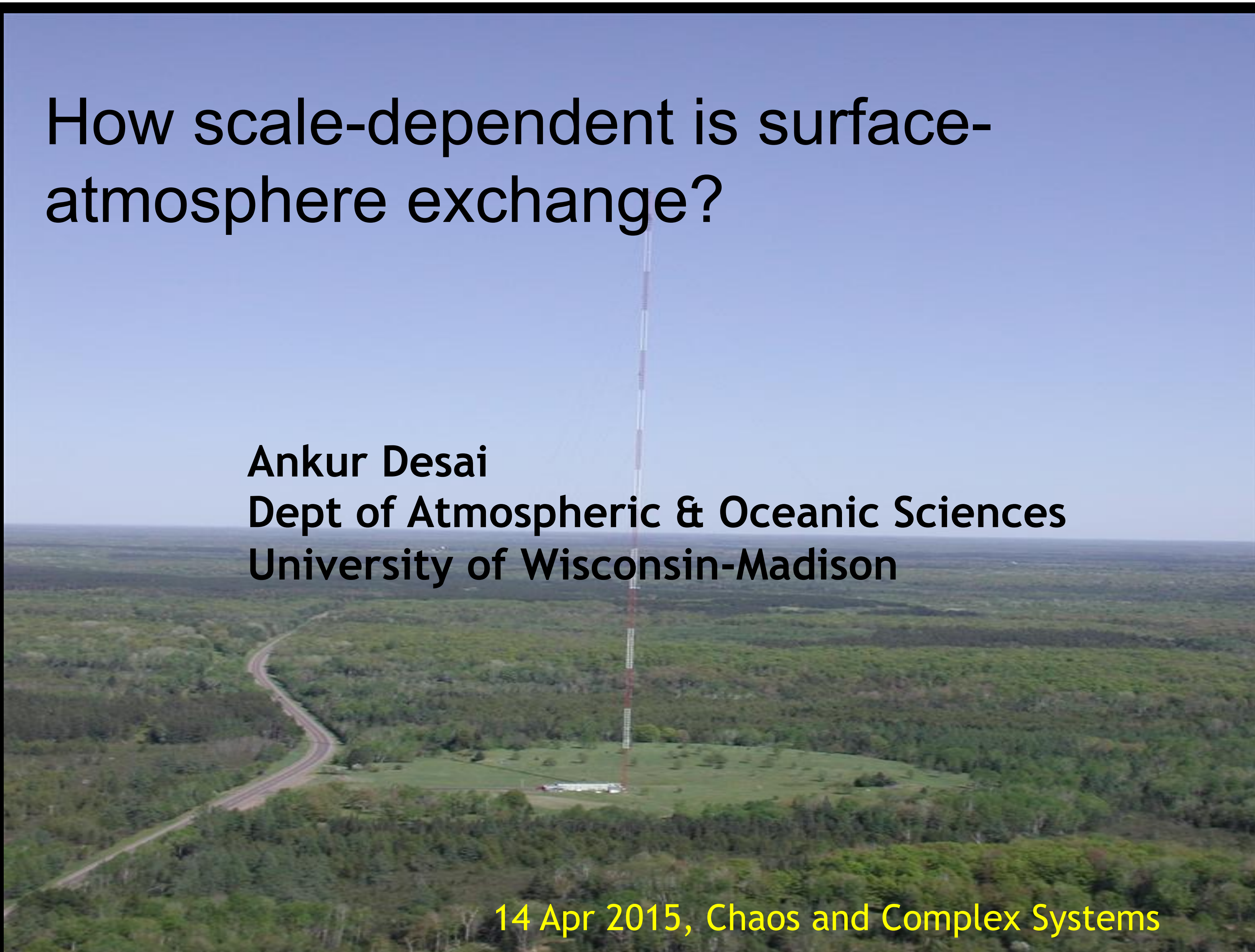
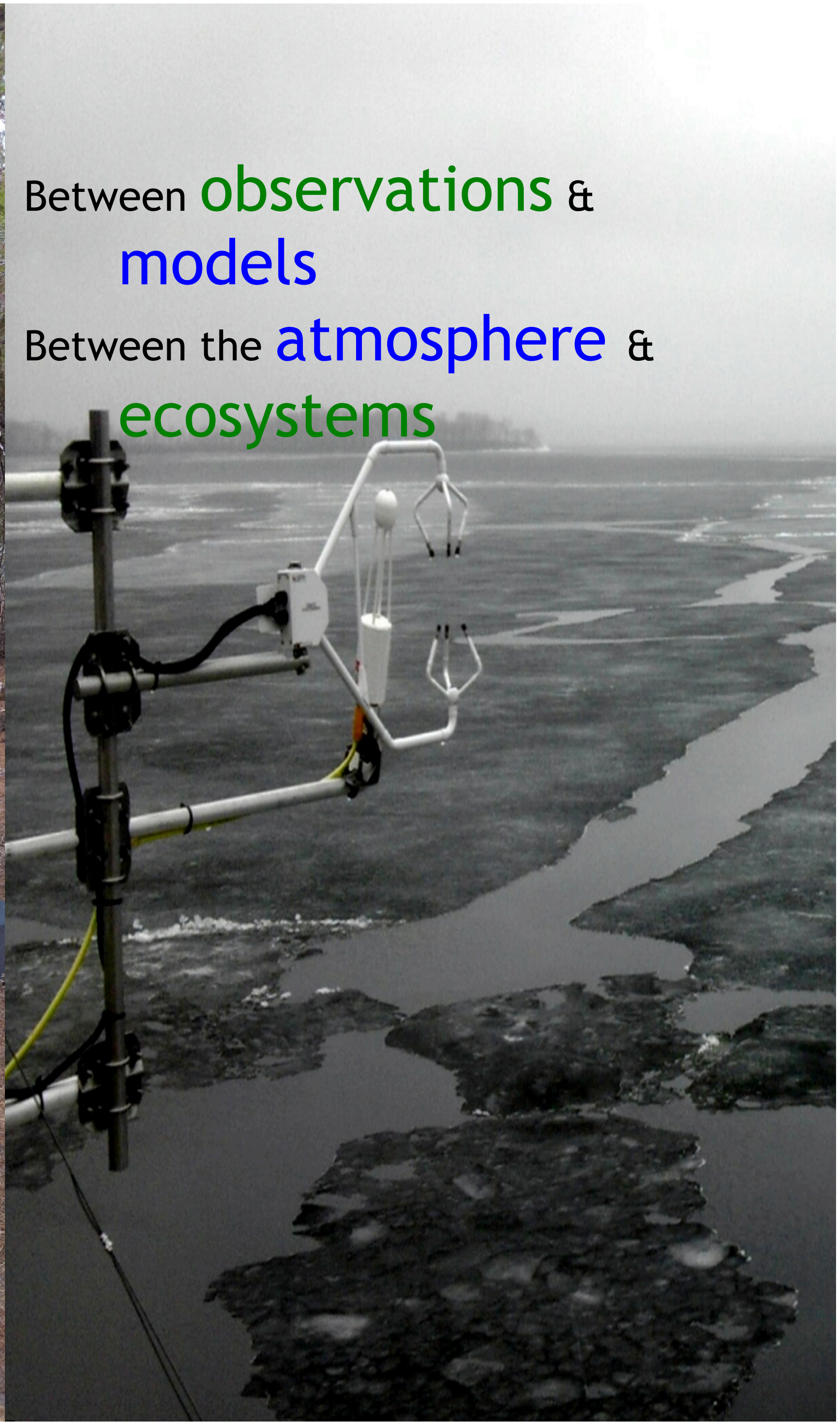


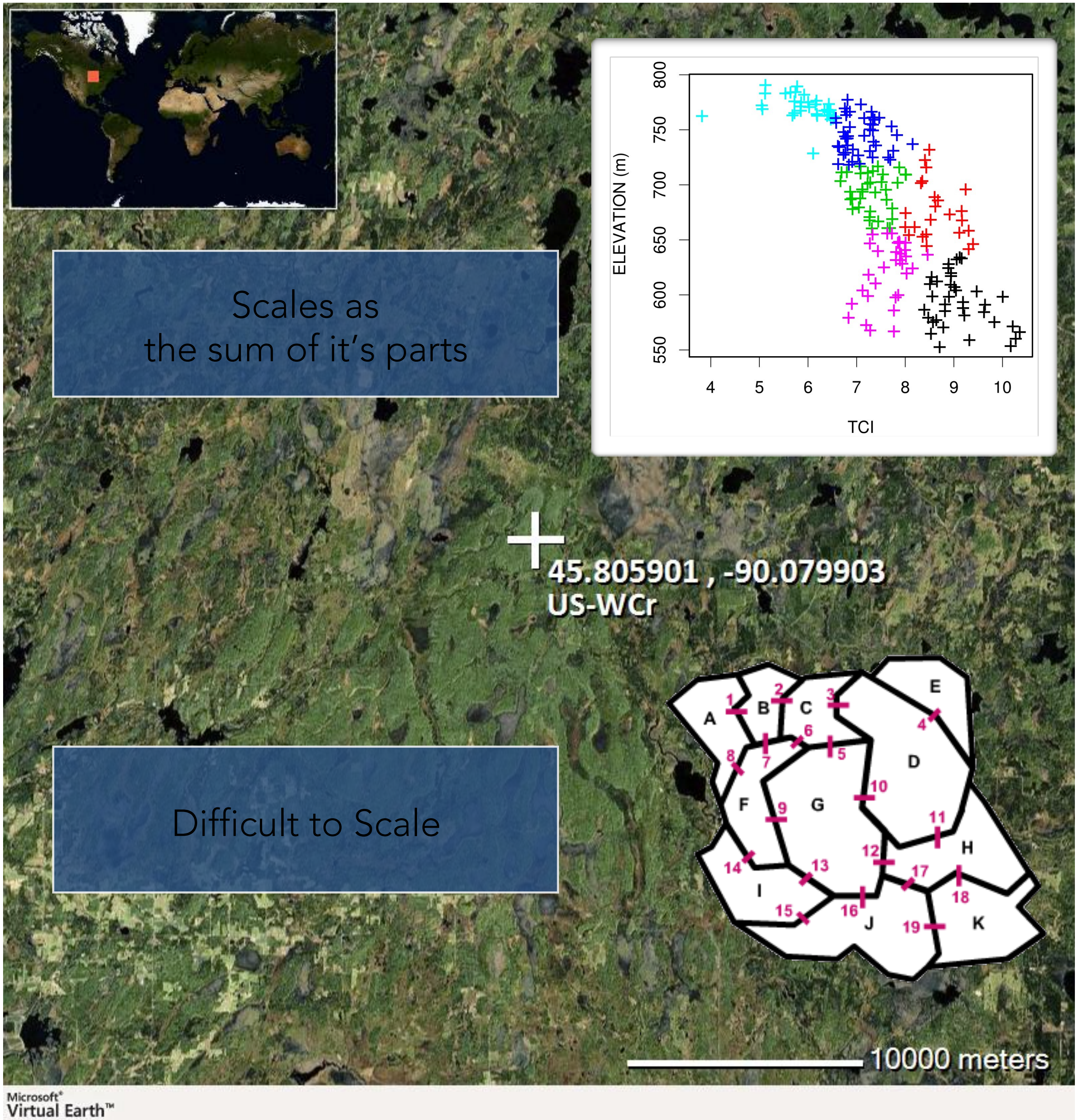
14 Apr 2015, Chaos and Complex Systems


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

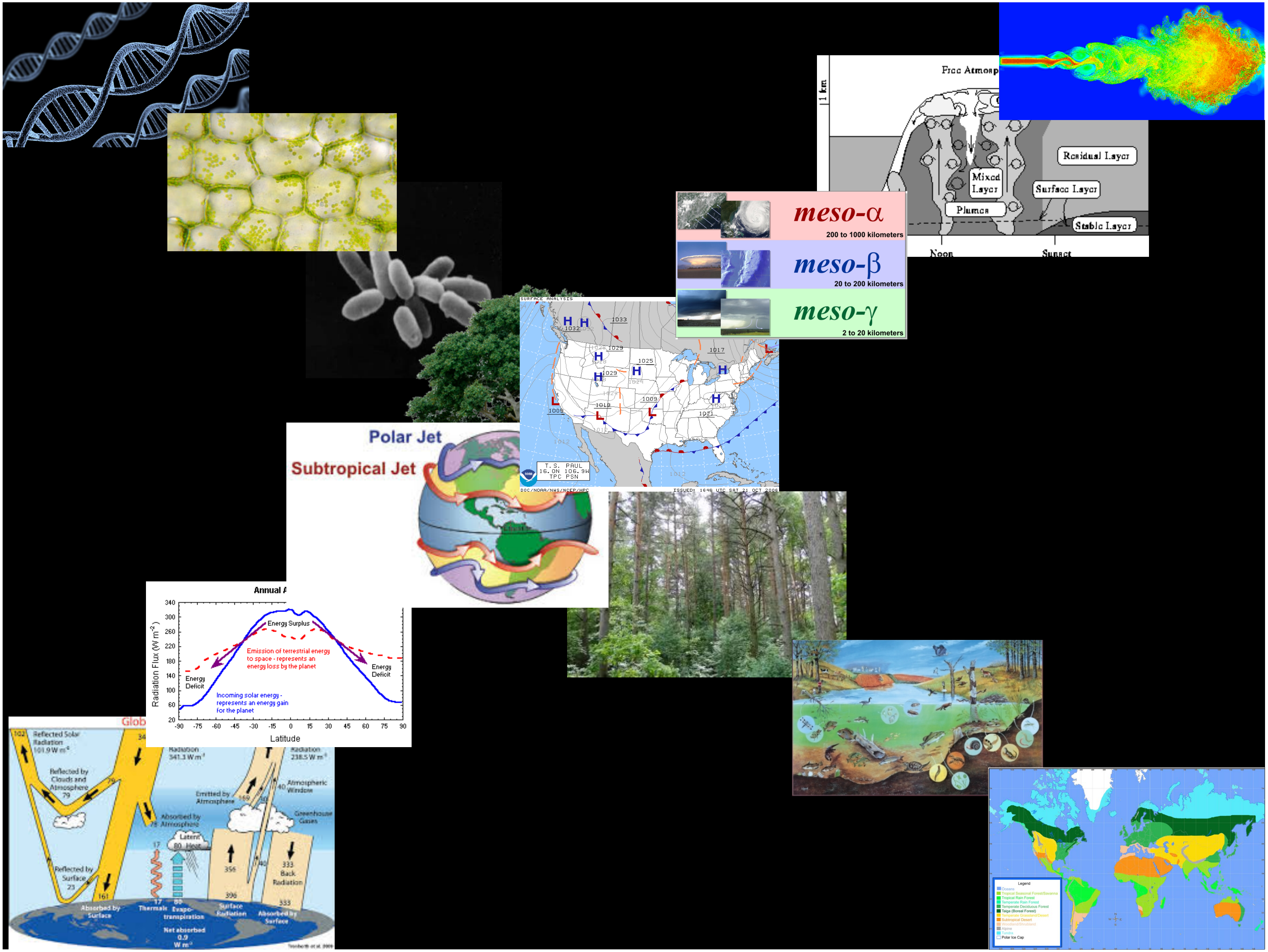


Spatial Heterogeneity

- Amount
- Frequency Distribution

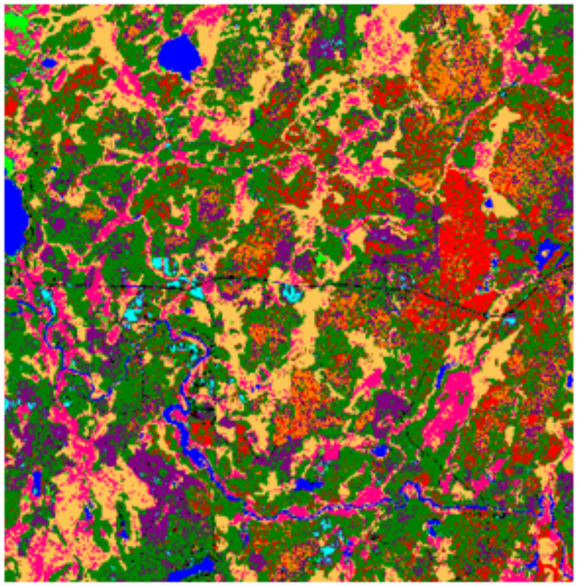
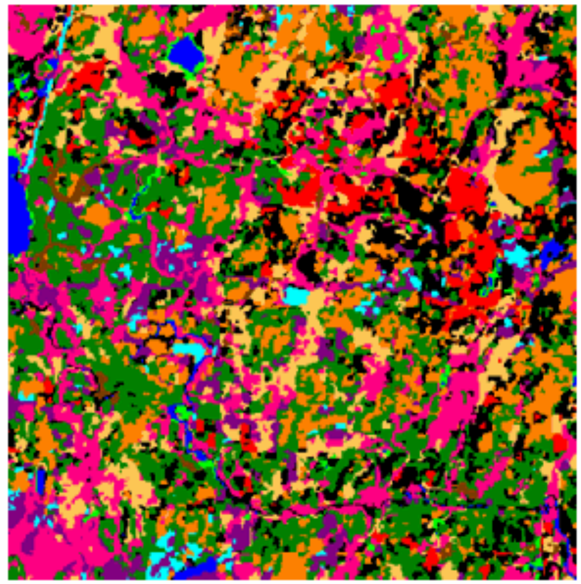
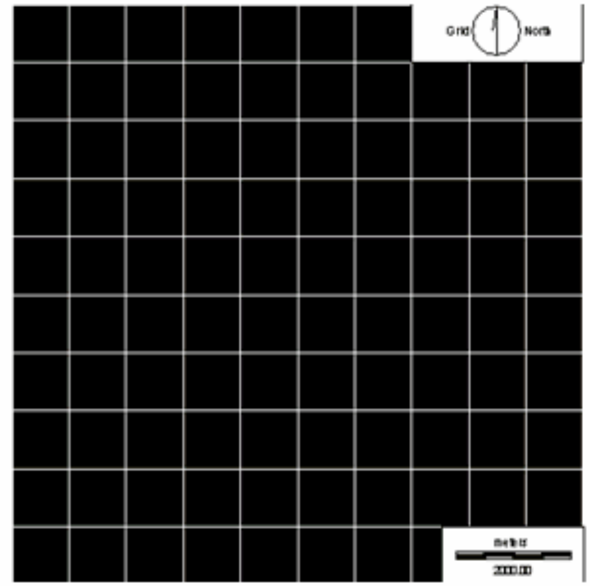
Spatial Process

- Arrangement
- Location
- Distance

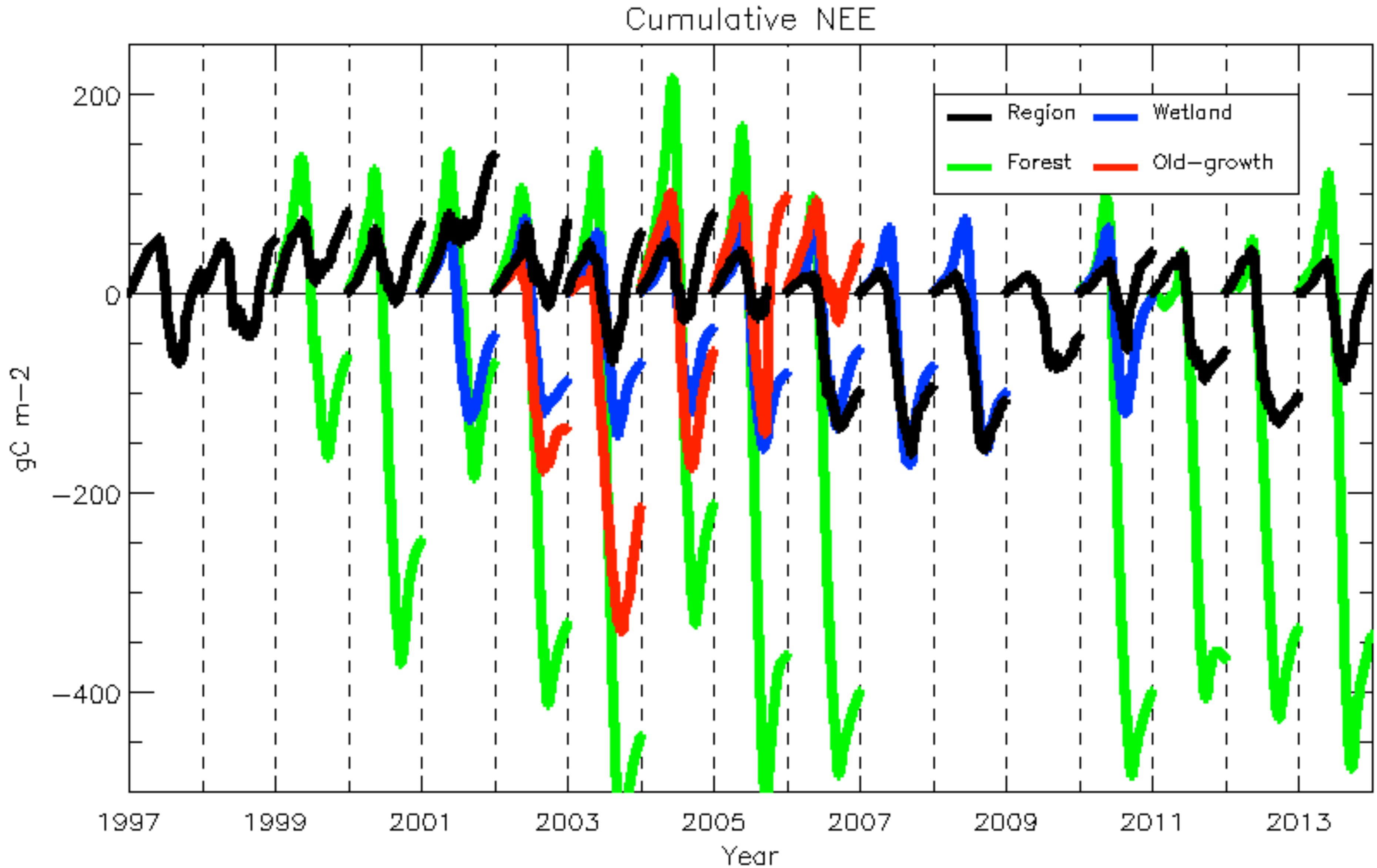


Free Atmosp
1 km
Residual Layer
Mixed Layer
Surface Layer
Plumes
Stable Layer
Noon
Sunset
meso-α
200 to 1000 kilometers
meso-β
20 to 200 kilometers
meso-γ
2 to 20 kilometers
Polar Jet
Subtropical Jet
Energy Surplus
Emission of terrestrial energy to space - represents an energy loss by the planet
Energy Deficit
Energy Deficit
Incoming solar energy - represents an energy gain for the planet
Radiation Flux (W m-2)
Latitude

Complex Regions: 1+1≠2

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

	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%	—	

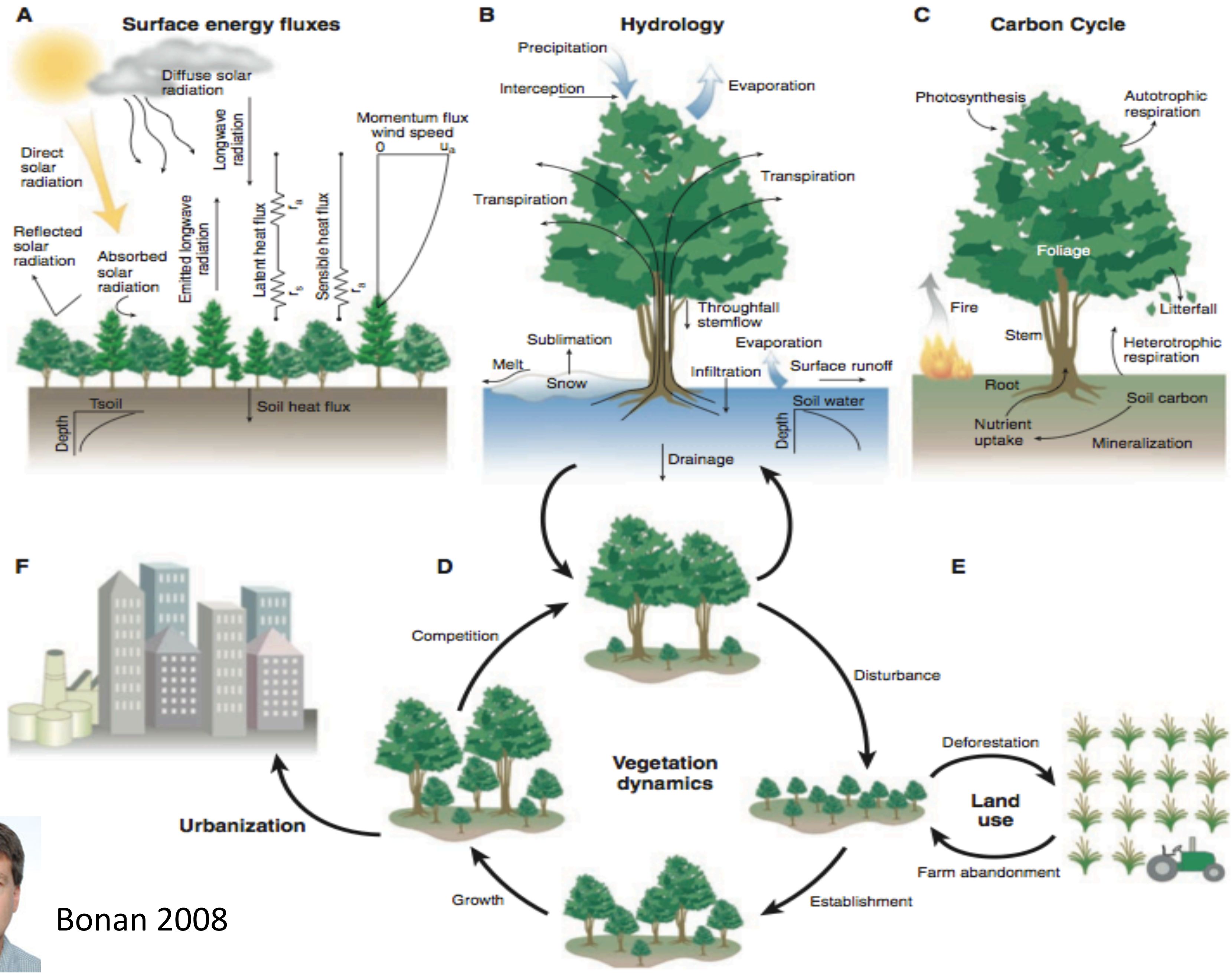

Cumulative NEE
Region
Wetland
Forest
Old−growth
200
0
−200
−400
gC m−2
1997
1999
2001
2003
2005
2007
2009
2011
2013
Year

Global NPP 1983 version

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		
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													3										
-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.

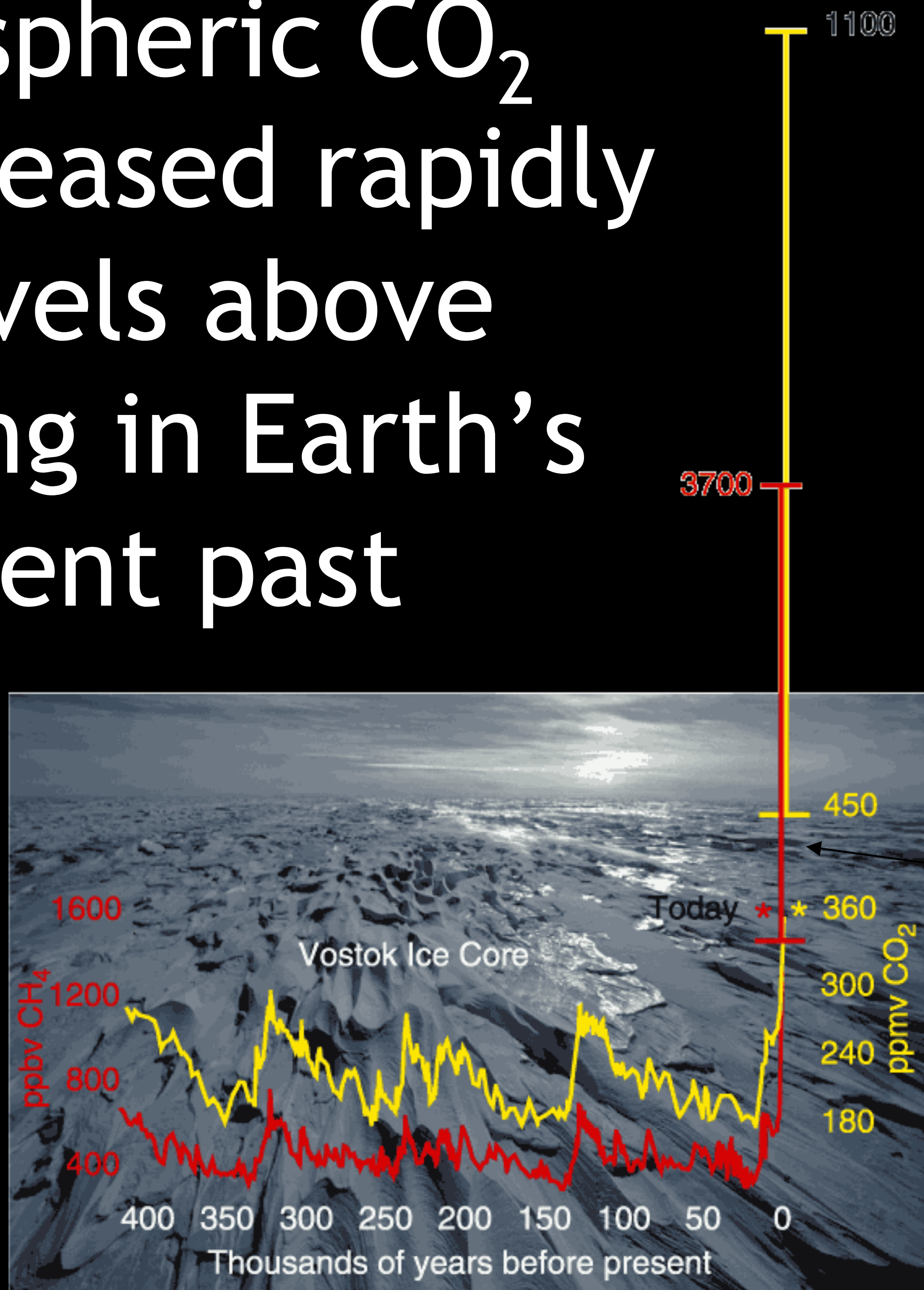
Forests in Flux



Bonan 2008

Why does it matter?

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



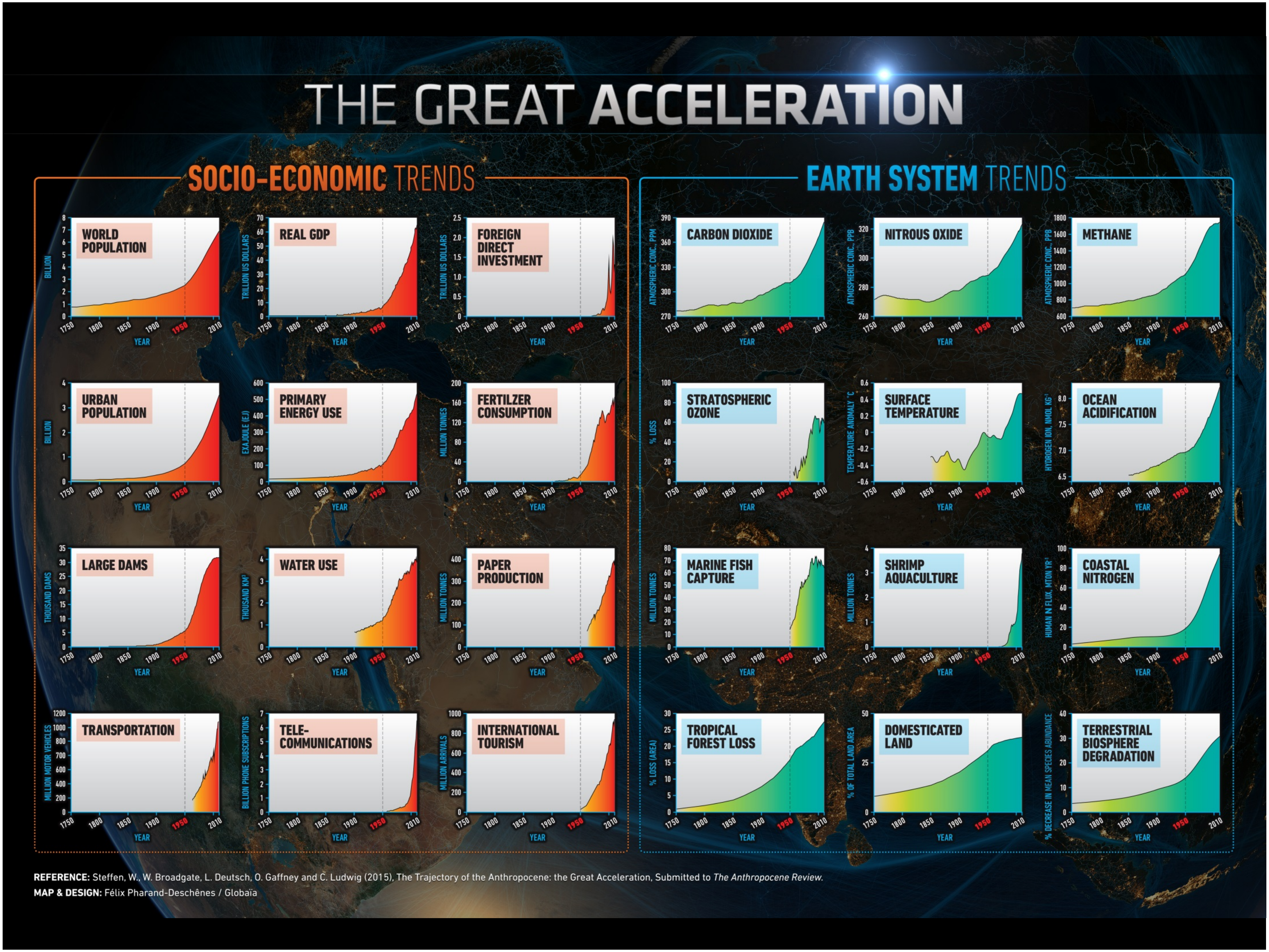
2100?

Today

400 ppm CO_2

2 ppm CH_4

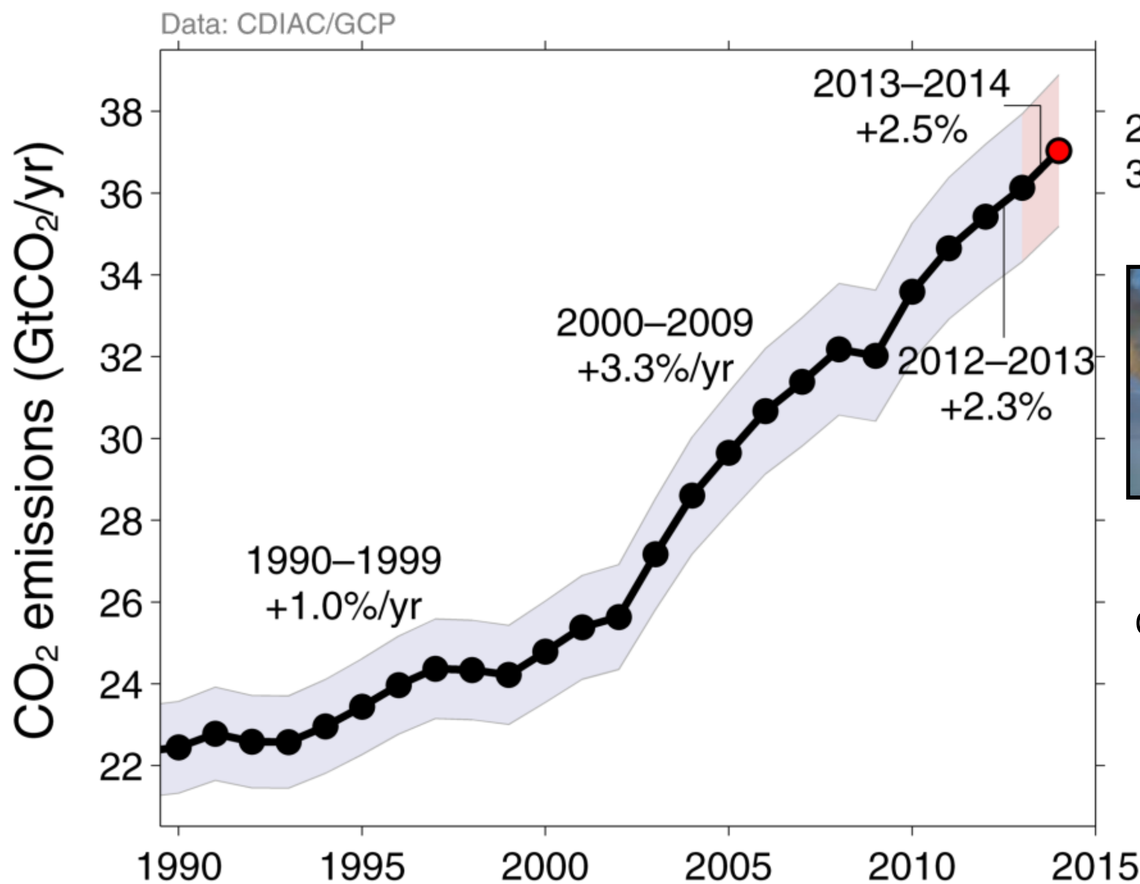
Sources: Petit et al (1999) Nature 399:429-436 and IPCC(2000)


THE GREAT ACCELERATION
SOCIO-ECONOMIC TRENDS
EARTH SYSTEM TRENDS
WORLD POPULATION
REAL GDP
FOREIGN DIRECT INVESTMENT
URBAN POPULATION
PRIMARY ENERGY USE
FERTILZER CONSUMPTION
LARGE DAMS
WATER USE
PAPER PRODUCTION
TRANSPORTATION
TELE-COMMUNICATIONS
INTERNATIONAL TOURISM
CARBON DIOXIDE
NITROUS OXIDE
METHANE
STRATOSPHERIC OZONE
SURFACE TEMPERATURE
OCEAN ACIDIFICATION
MARINE FISH CAPTURE
SHRIMP AQUACULTURE
COASTAL NITROGEN
TROPICAL FOREST LOSS
DOMESTICATED LAND
TERRESTRIAL BIOSPHERE DEGRADATION
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

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

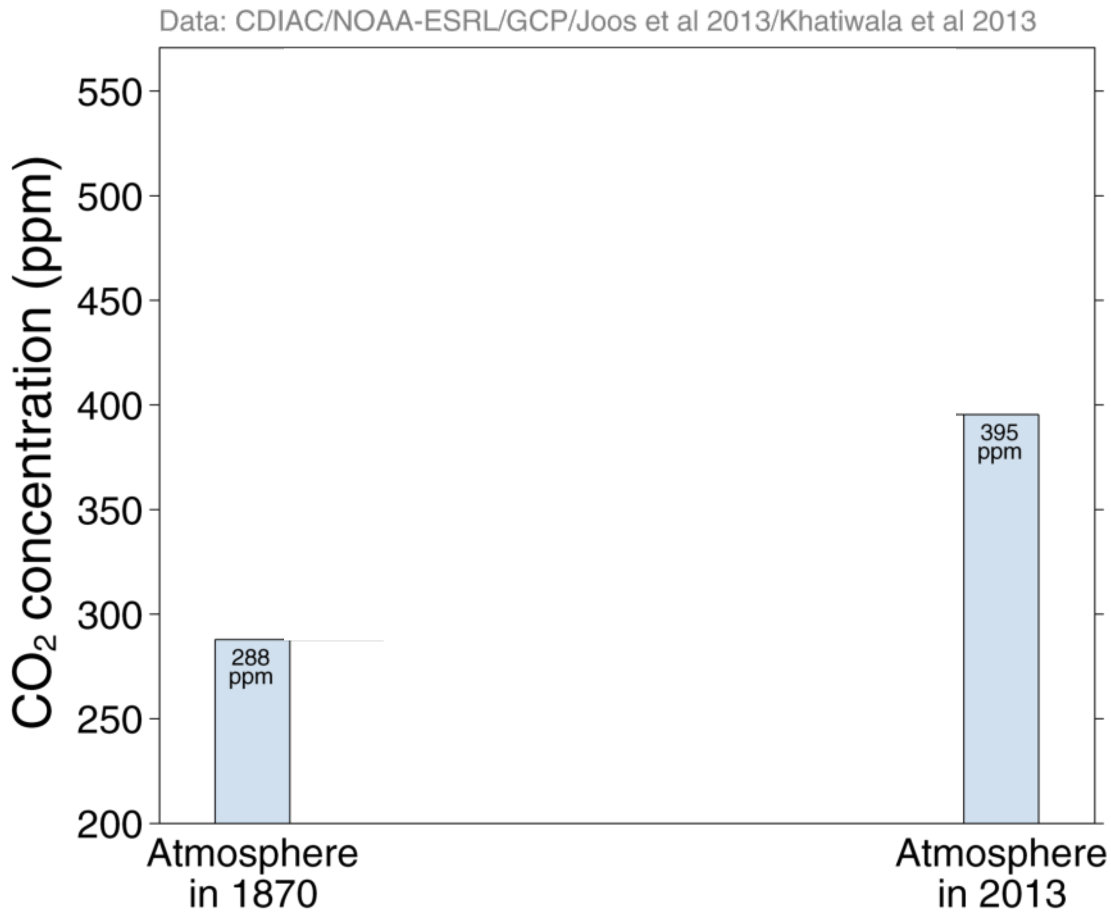
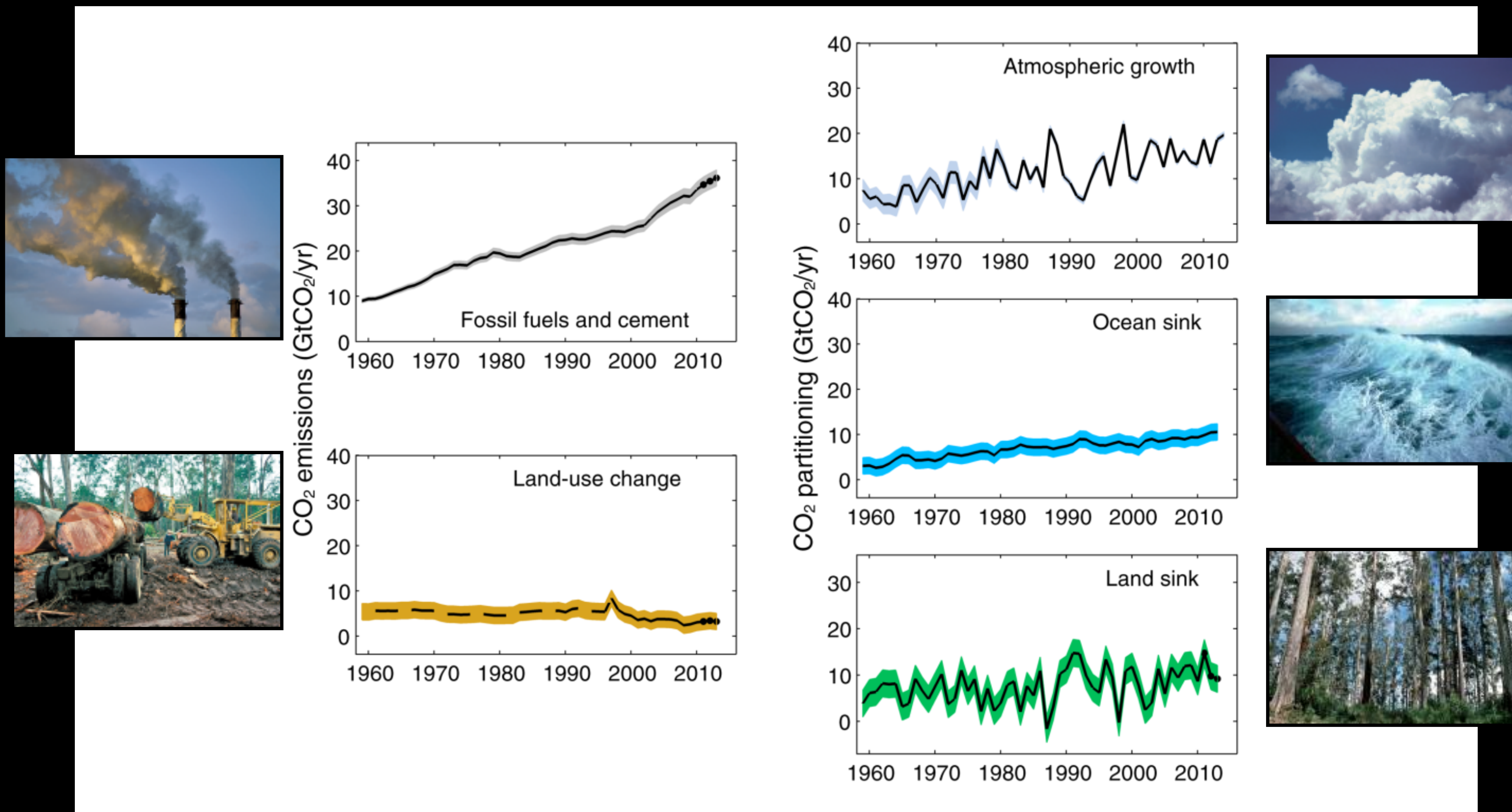


Figure concept from Shrink That Footprint
Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Joos et al 2013; Khatiwala et al 2013; Le Quéré et al 2014; Global Carbon Budget 2014

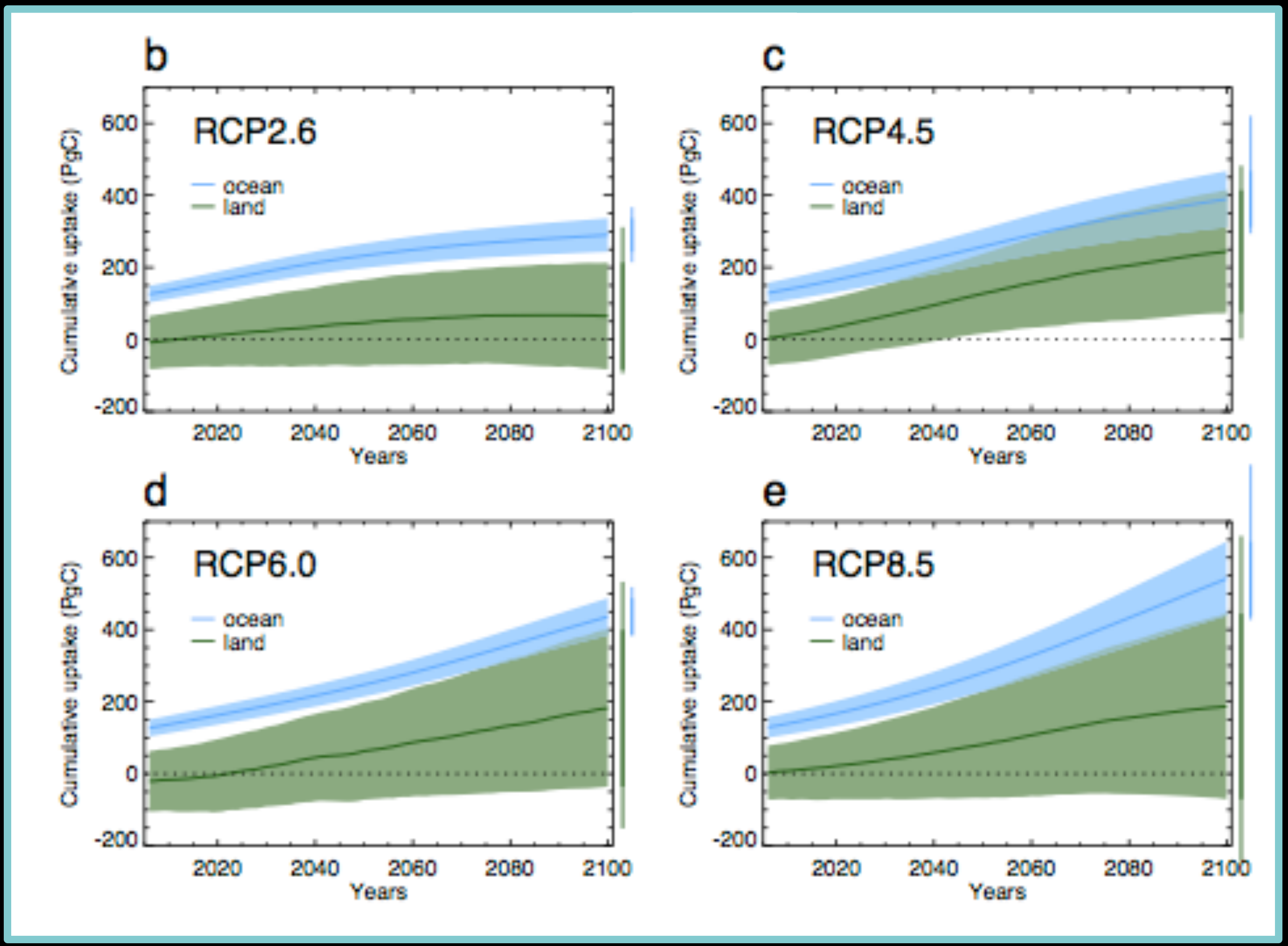
Changes in the Budget over Time

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

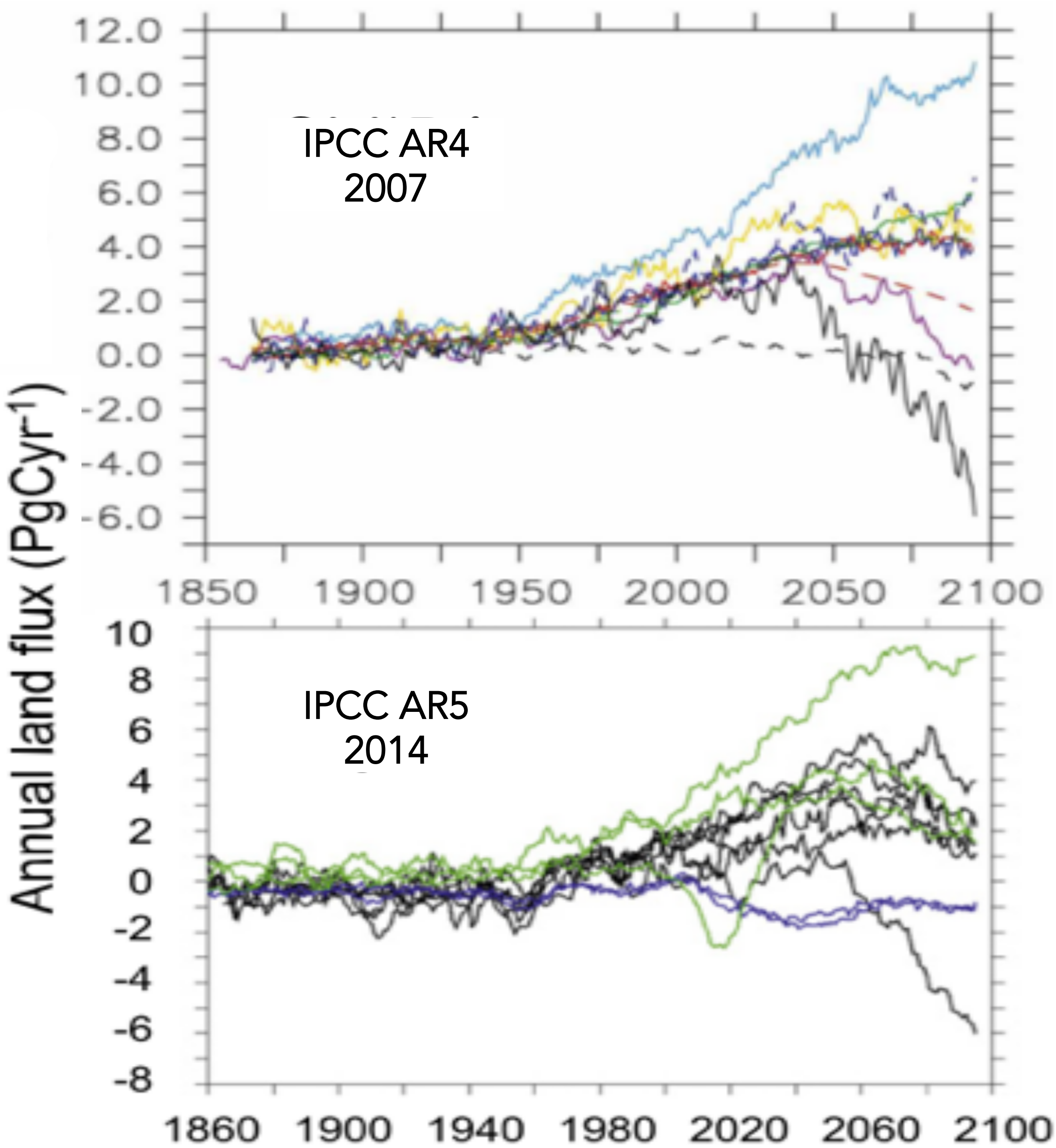


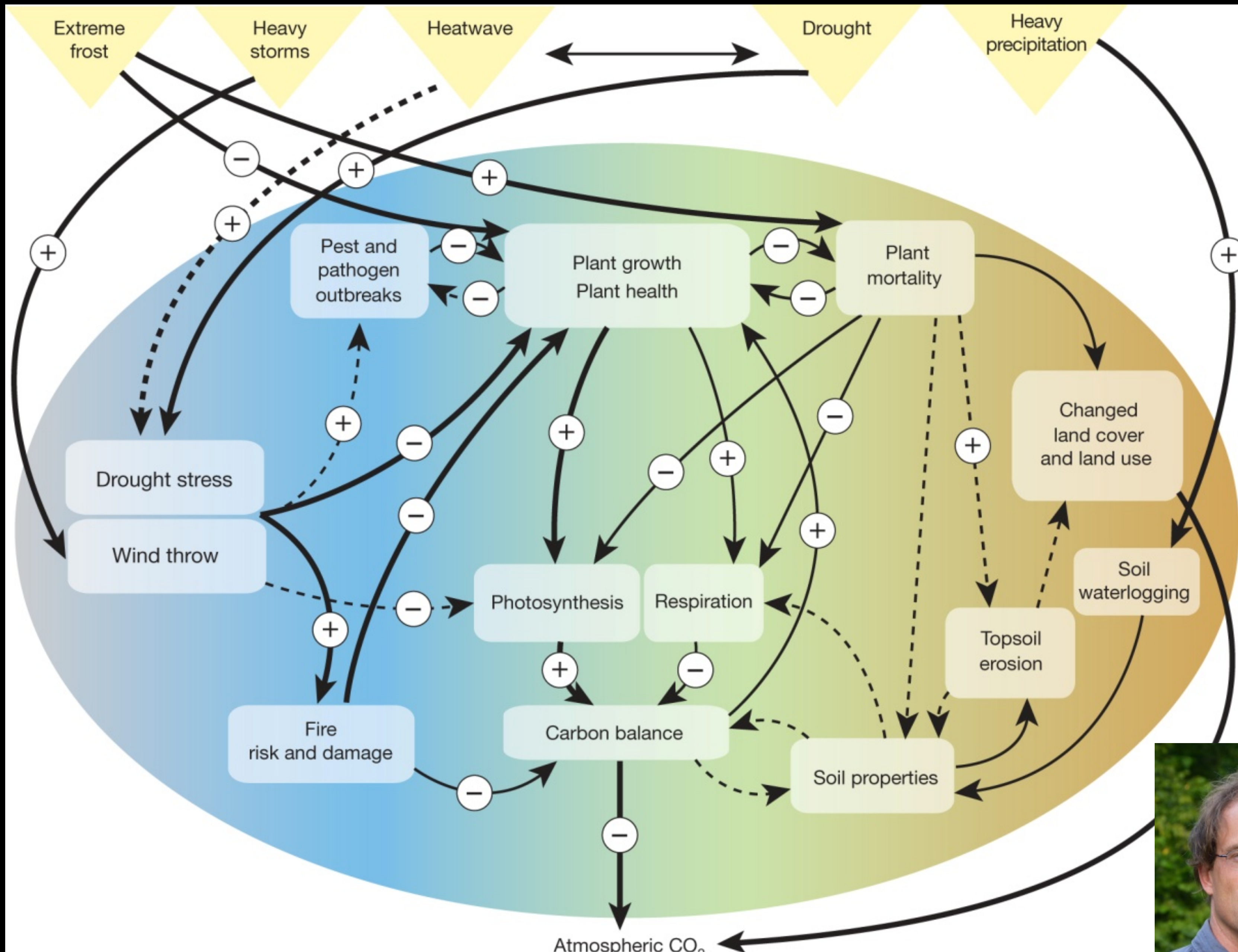
Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Le Quéré et al 2014; Global Carbon Budget 2014

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



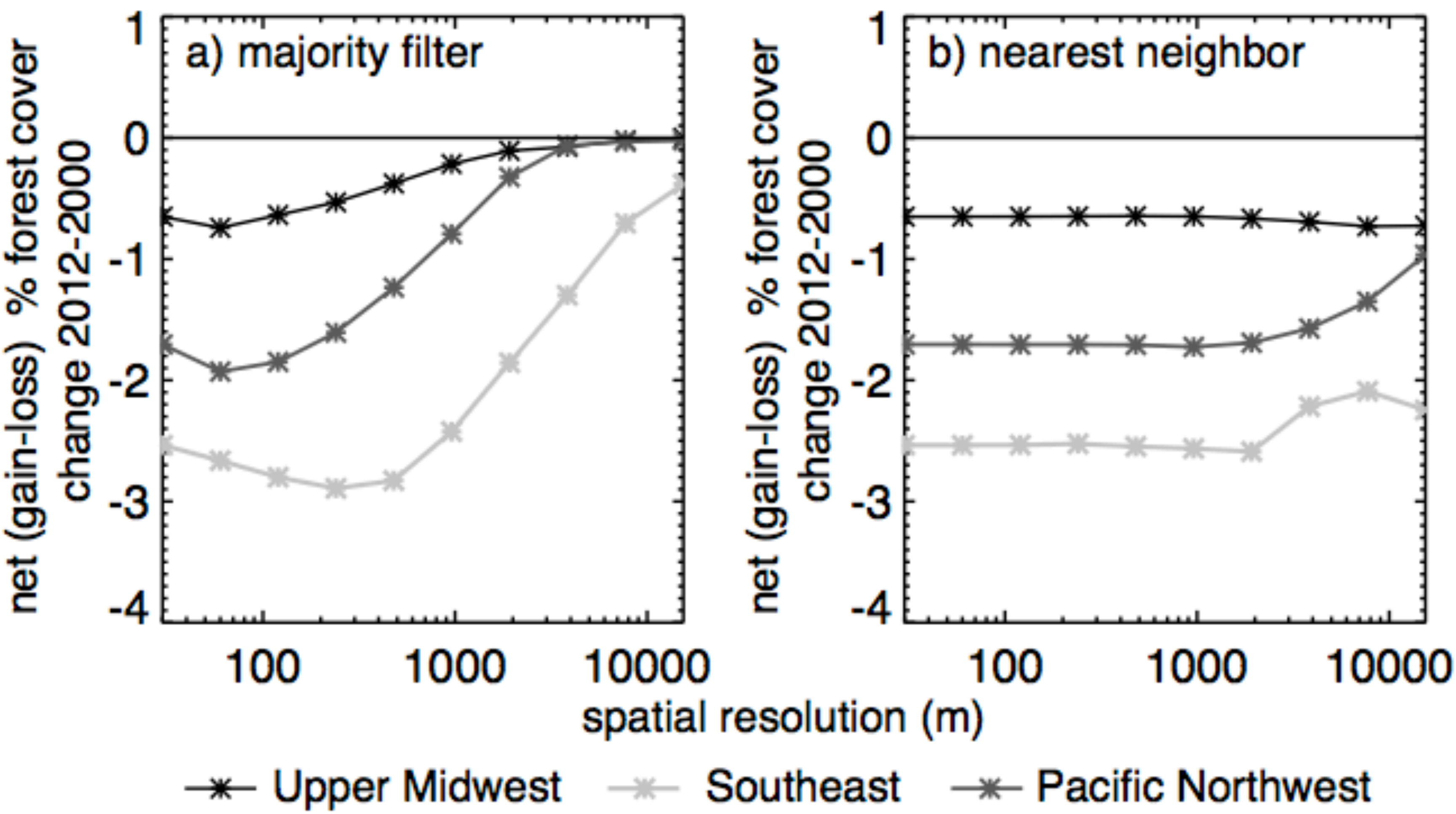
IPCC AR5 WG1 CH6


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

The scale and method we monitor land use matters



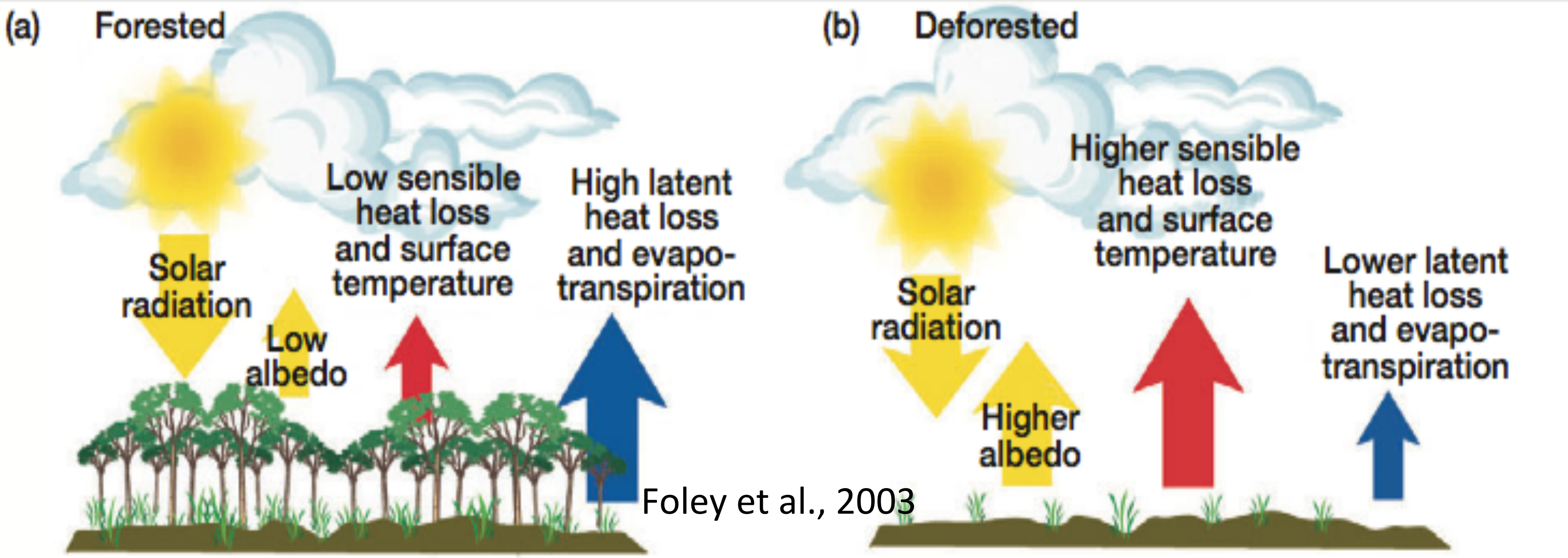
Becknell et al., Bioscience, 2015

What do I (we) do?

http://flux.aos.wisc.edu

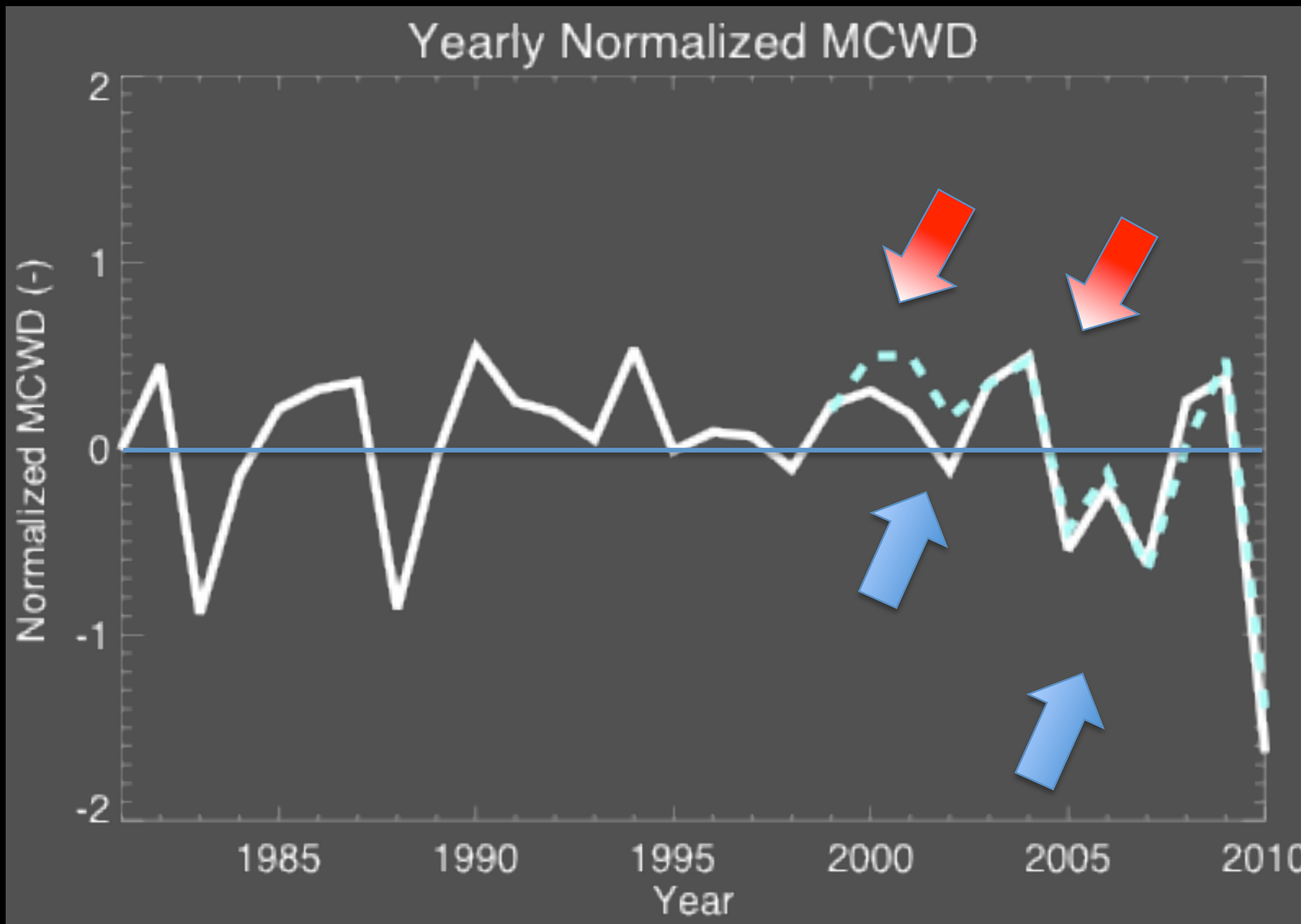
- Probe spatial heterogeneity in biologically-mediated surface-atmosphere exchanges from sites to regions (meters-1000s km)
  - Forests, wetlands, lakes, urban (temperate-boreal-tropical-Mediterranean-alpine, terrestrial-aquatic, management gradients)
  - Multiple greenhouse gases (methane), esp. with 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


Bagley et al., 2014,
J. Clim

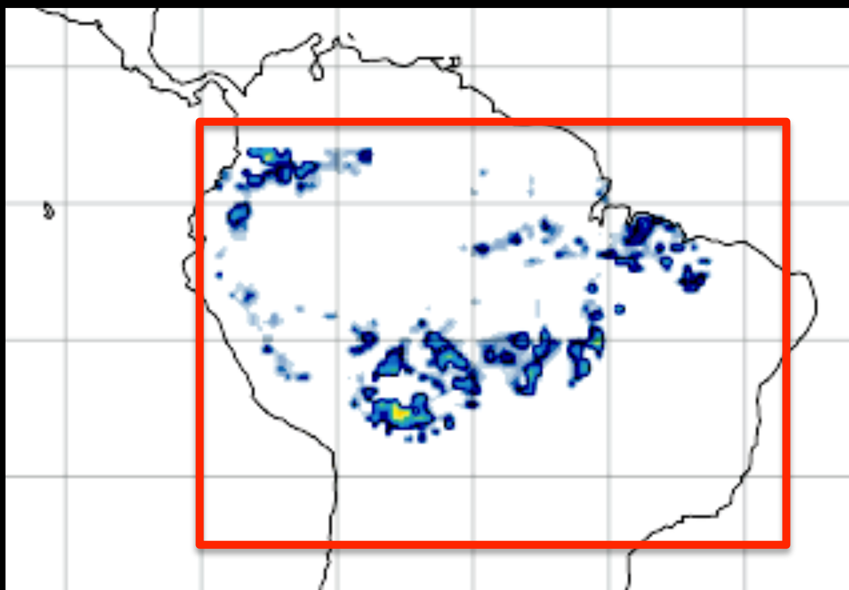


Foley et al., 2003

A history of drought and floods in the Amazon
Bagley et al., 2014, J. Clim



WRF-Noah Setup



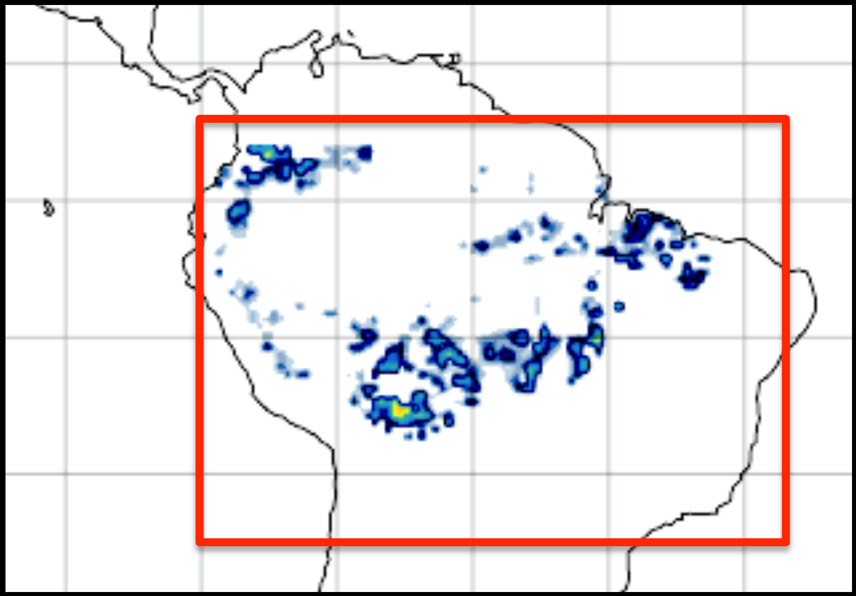
• Spatial Resolution: 20km x 20km

•Timestep: 60 seconds

•For 2003, 2004, 2005, 2007, 2009, and 2010 the model was run from March 15 – October 15 with and without deforestation

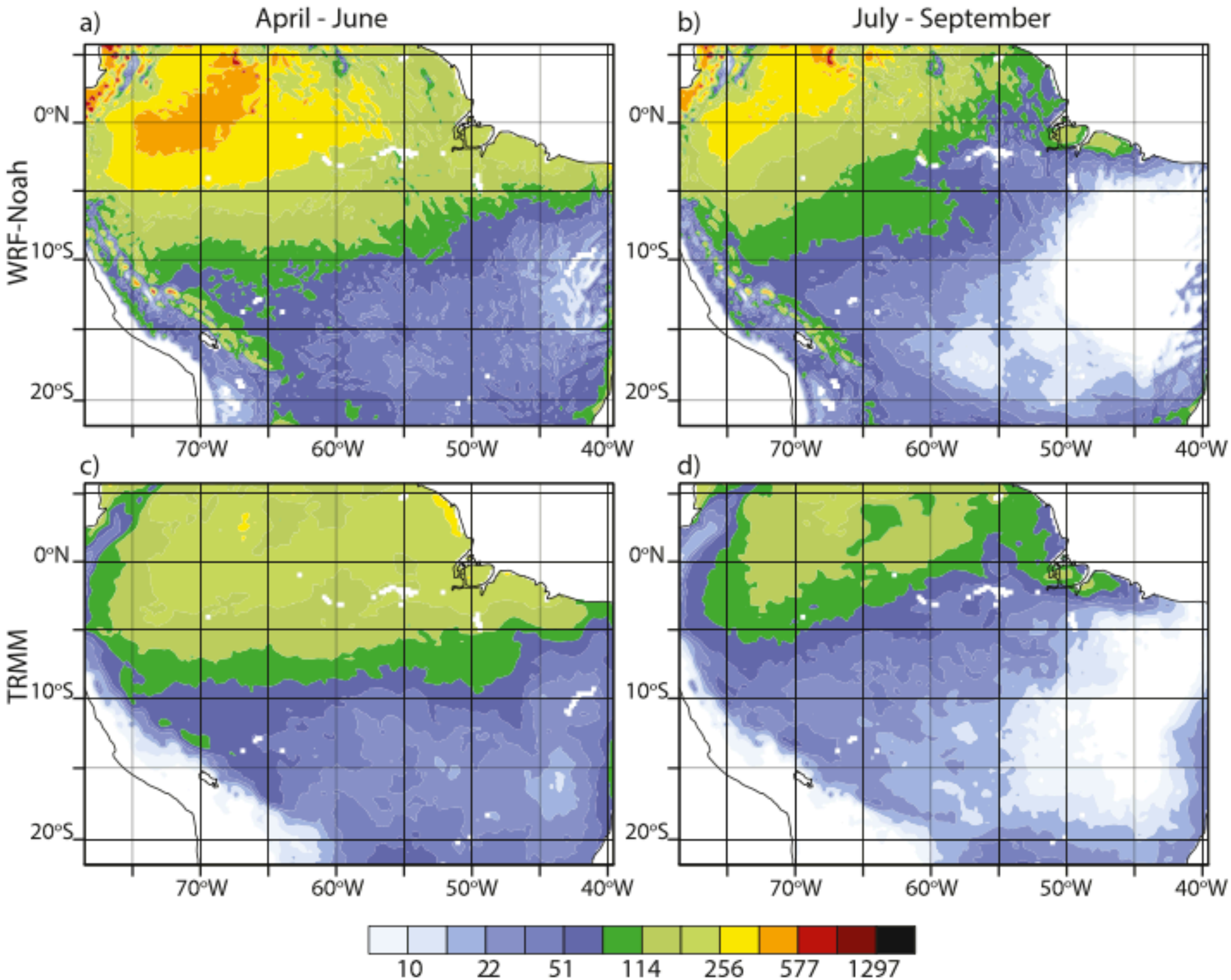
•Total of 12 seven-month simulations completed with hourly output

WRF-Noah Setup



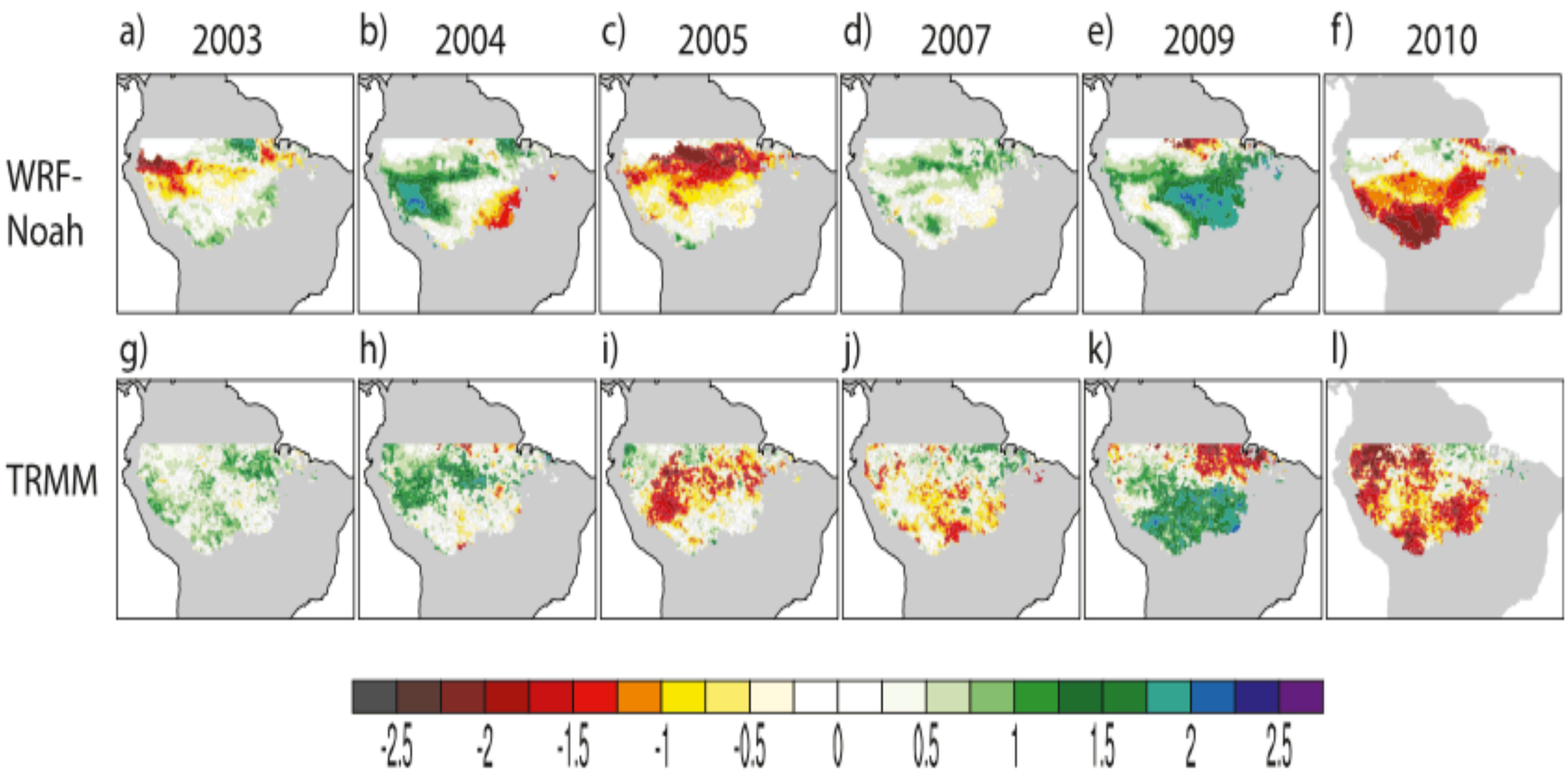
•Gridpoints with land use > 50% converted to pasture

•Gridpoints with land use between 5%-50% converted to mixed forest and land use



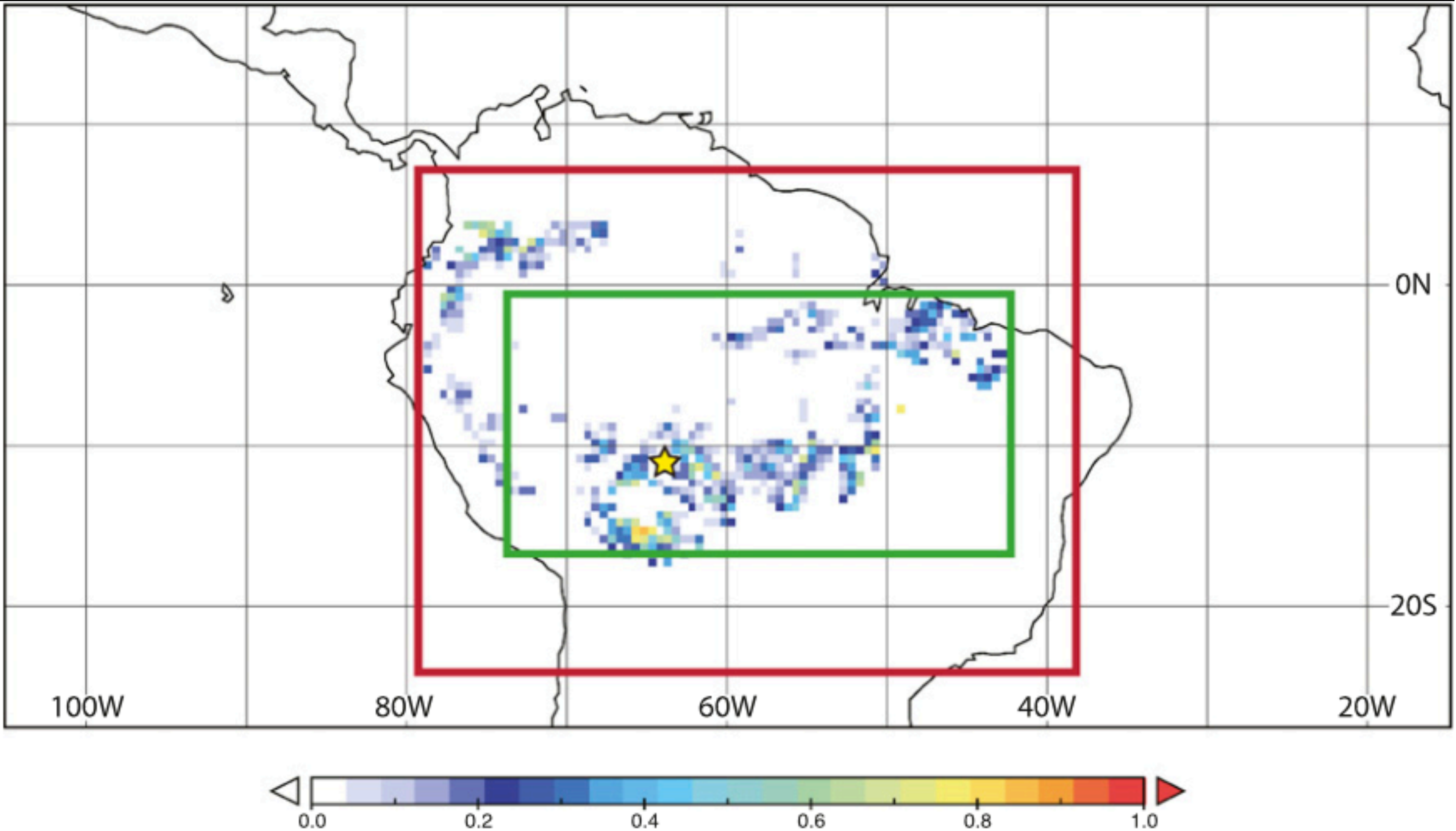
a)
April - June
b)
July - September
c)
d)
WRF-Noah
TRMM
0°N
10°S
20°S
70°W
60°W
50°W
40°W
10
22
51
114
256
577
1297

[redacted]



[redacted]

[redacted]



[redacted]

ABRACOS/WRF/ PEGASUS

* WRF-Noah

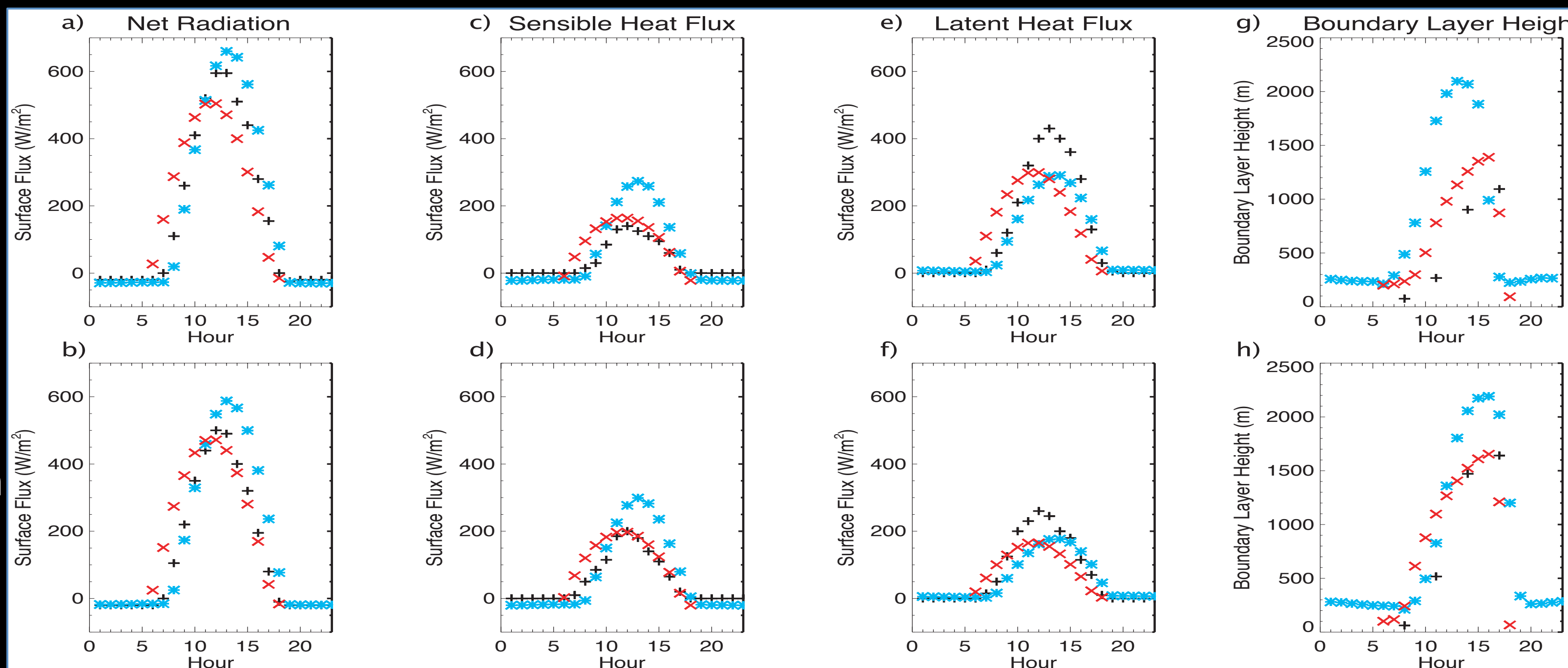
\+ ABRACOS Observations

X PEGASUS

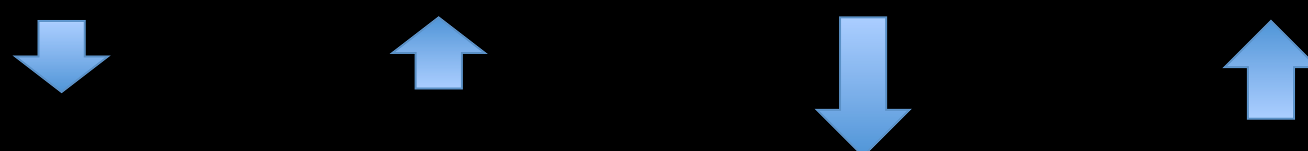
Net Radiation | SHF | LHF | BLH

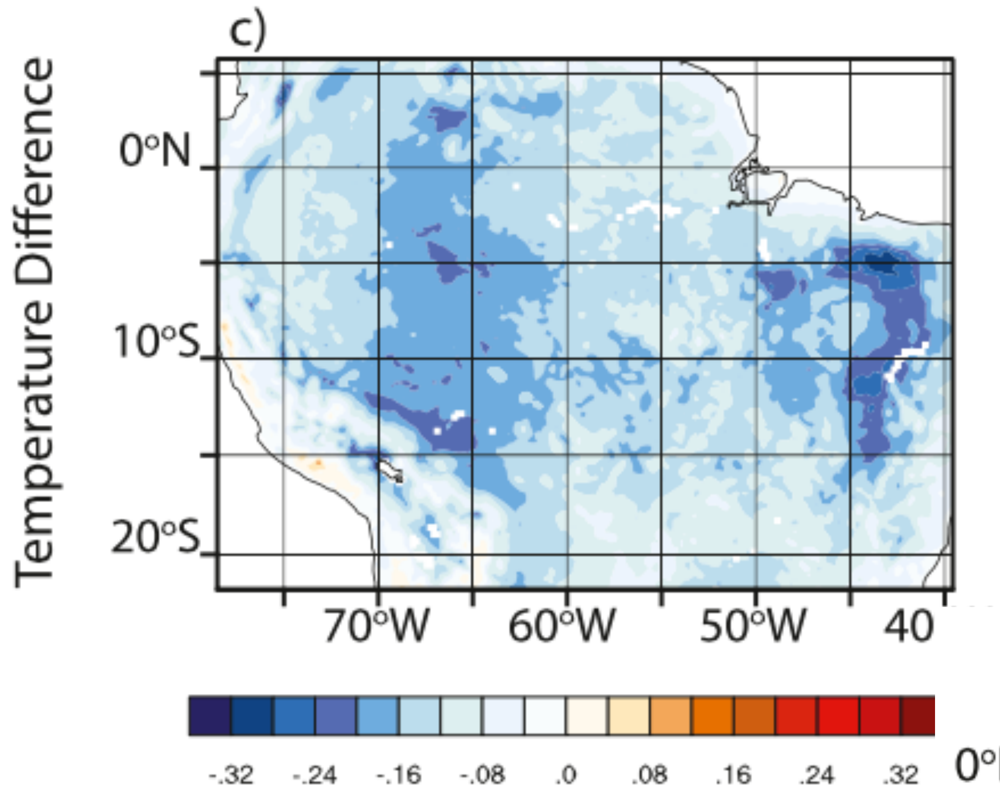
Potential Vegetation

Deforestation



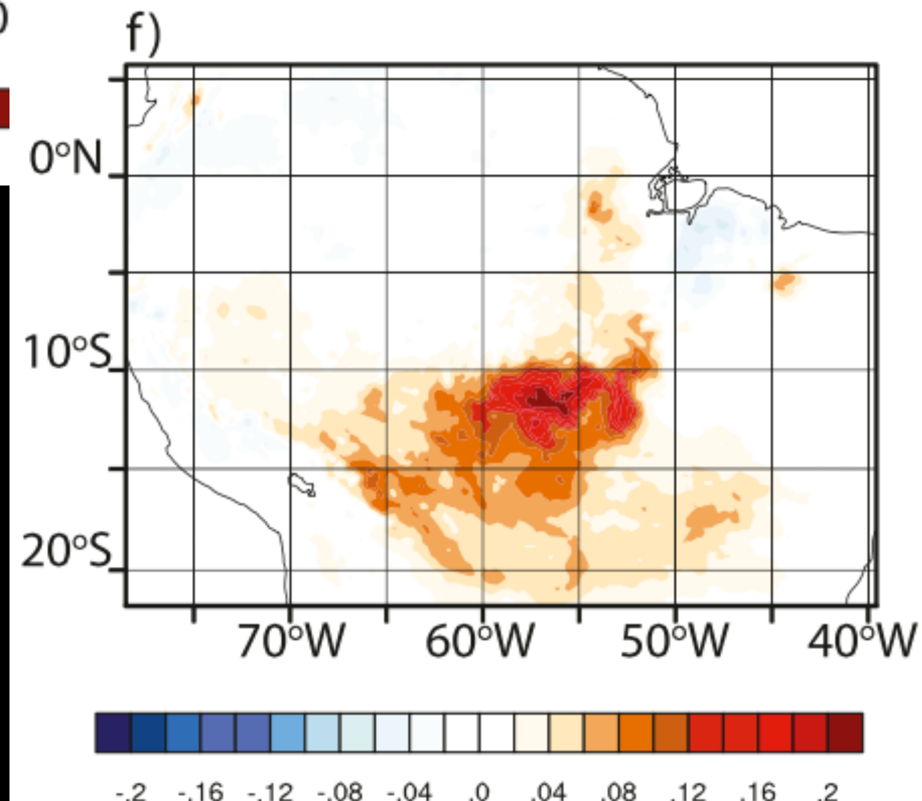
Impact

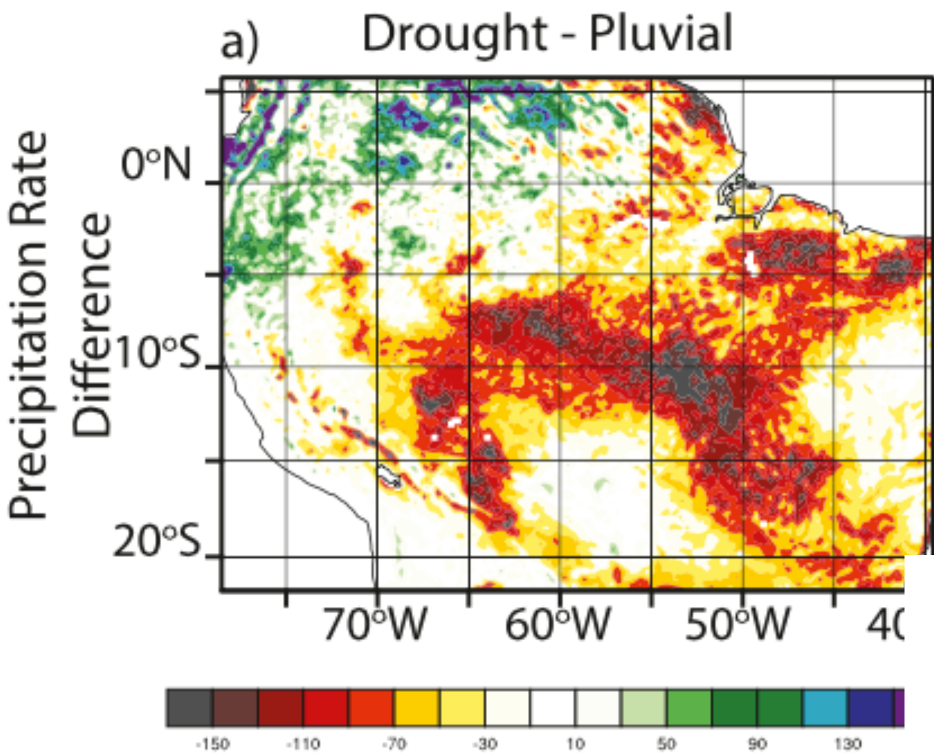




Drought-Pluvial

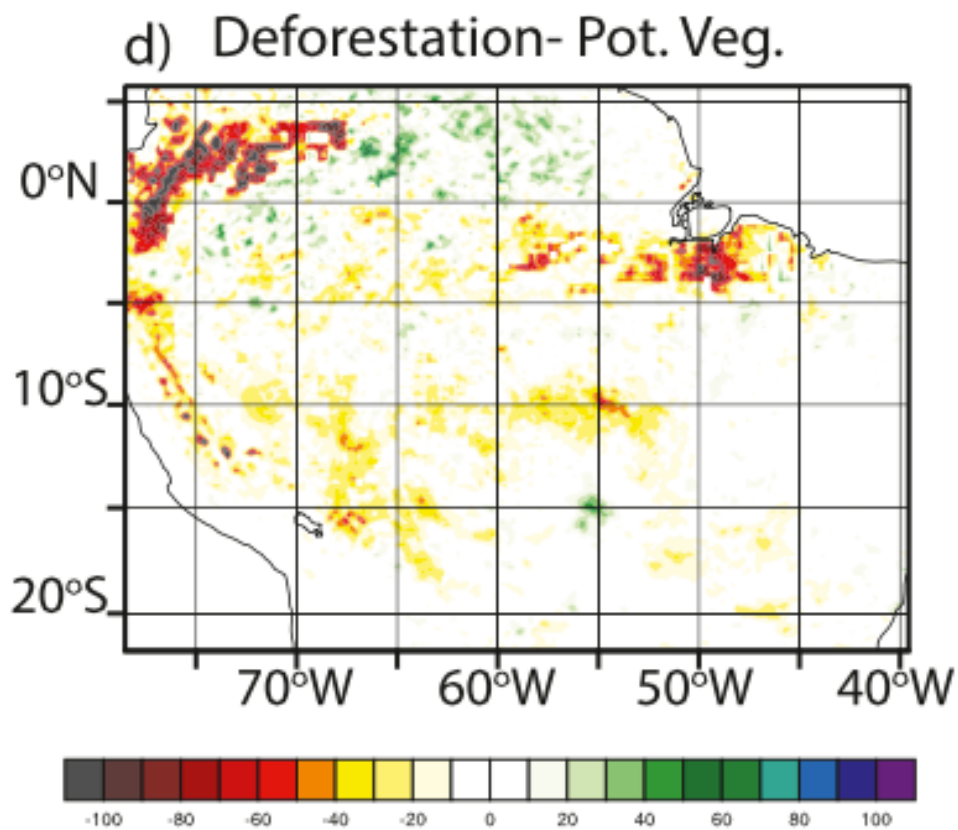
Deforested-Forested





[redacted]

[redacted]



[redacted]

	Full Amazon rain forest region		Region converted to pasture	
	April–June	July–September	April–June	July–September
Precipitation rate (mm month^{-1})	−9.36 (−3.16%)	−9.47 (−5.45%)	−32.51 (−16.27%)	−25.72 (−18.53%)
Sensible heat flux (W m^{-2})	−0.758 (−2.75%)	1.04 (+2.30%)	−0.14 (−0.65%)	6.26 (+11.44%)
ET (mm month^{-1})	−2.68 (−1.94%)	−5.95 (−4.61%)	−15.89 (−13.42%)	−28.37 (−29.55%)
Net surface radiation (W m^{-2})	−4.39 (−2.45%)	−4.82 (−2.50%)	−4.02 (−2.48%)	−10.11 (−6.04%)
Boundary layer height (m)	−6.21 (−1.27%)	3.90 (+.62%)	−5.95 (−1.28%)	28.29 (+4.25%)
2-m temperature (K)	−0.10	+0.036	−0.033	+0.32
2-m specific humidity (kg kg^{-1})	−5.74E-5 (−0.41%)	−1.50E-4 (−1.04%)	−1.84E-4 (−1.30%)	−4.67E-4 (−4.10%)
Lifting condensation level (m)	−4.49 (−0.56%)	31.31 (+2.31%)	7.08 (+.58%)	105.38 (+5.66%)

[redacted]

Back Trajectory Analysis Description

Precipitation, Recycling, and Land Memory: An Integrated Analysis (Dirmeryer 2009)

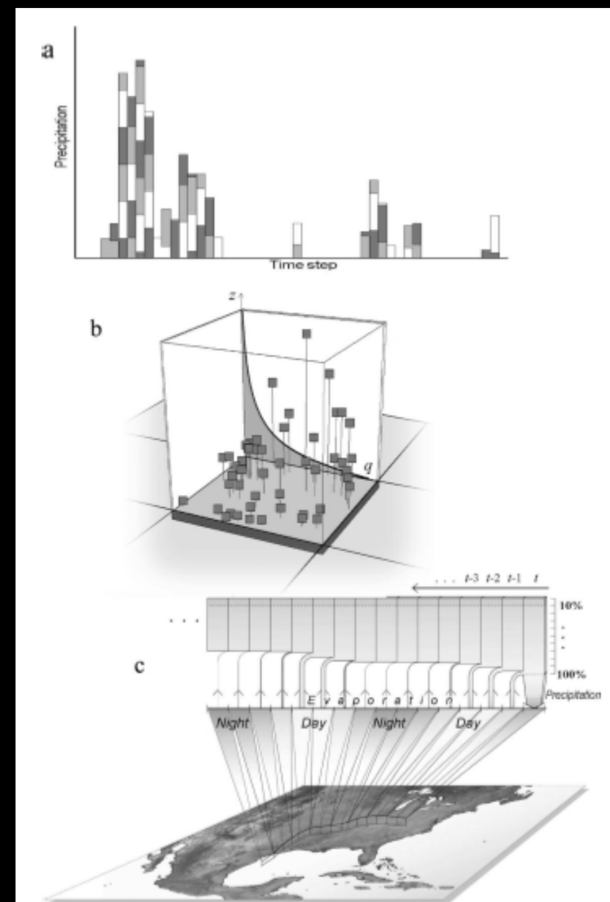
1. Identify precipitation event

2. Initialize 100 parcels at grid cell of precipitation at pseudo-random heights

3. Generally following isentropic lines follow parcels 14 days backward in time or until the parcel intersects the surface

4. As it passes over adjacent gridpoints assume the a portion of its moisture is given to it by the evapotranspiration occurring at that point

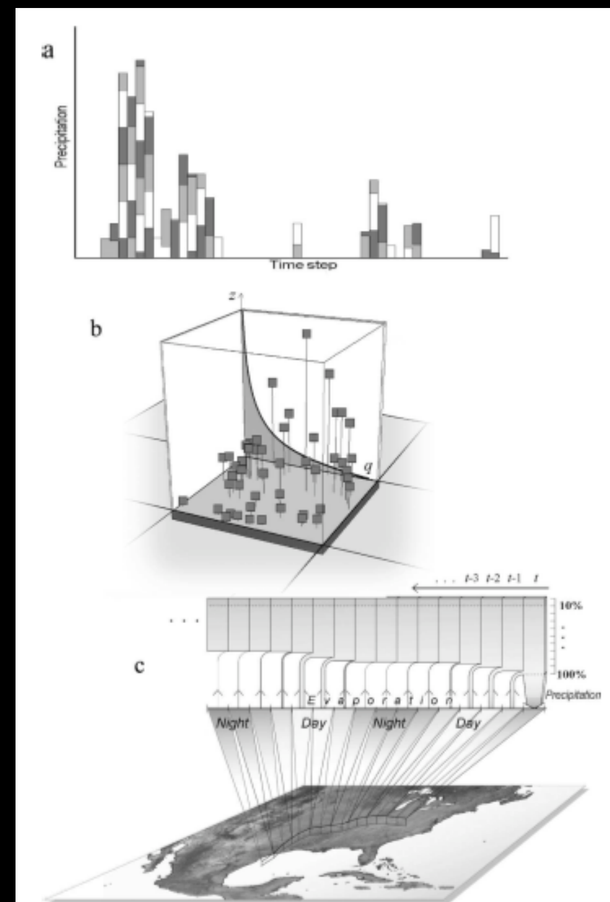
5. Aggregate parcels to get evaporative source of precipitation event



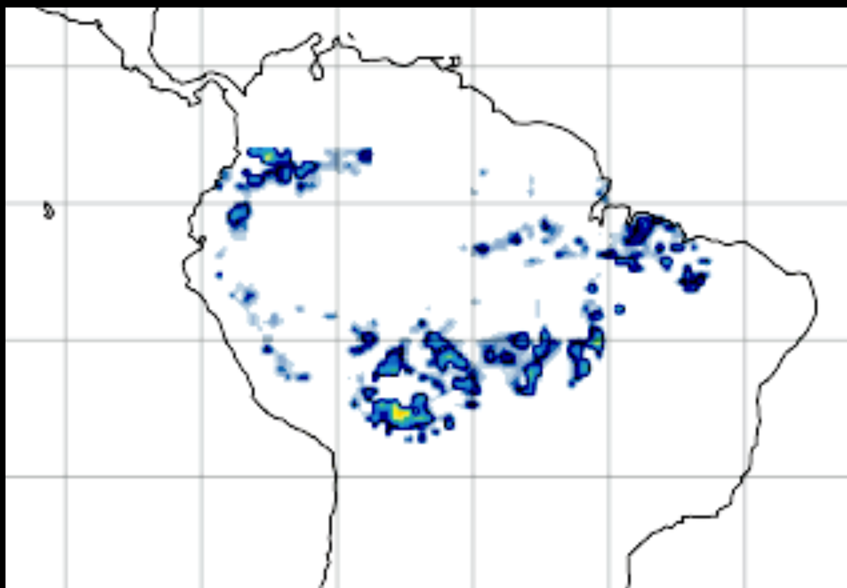
Back Trajectory
Analysis Description

Precipitation, Recycling, and Land Memory: An Integrated Analysis (Dirmeryer 2009)

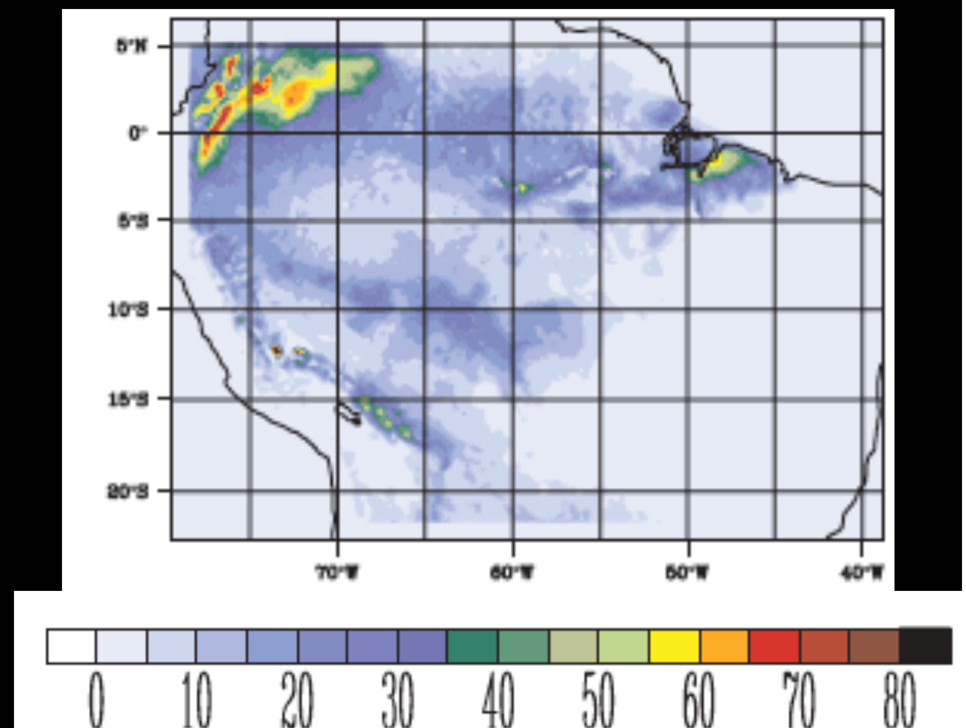
By compiling this information across all the precipitation events, we can invert the backtrajectories to determine where moisture evaporated from a given point tends to rain out of the atmosphere



Moisture Trajectory Analysis

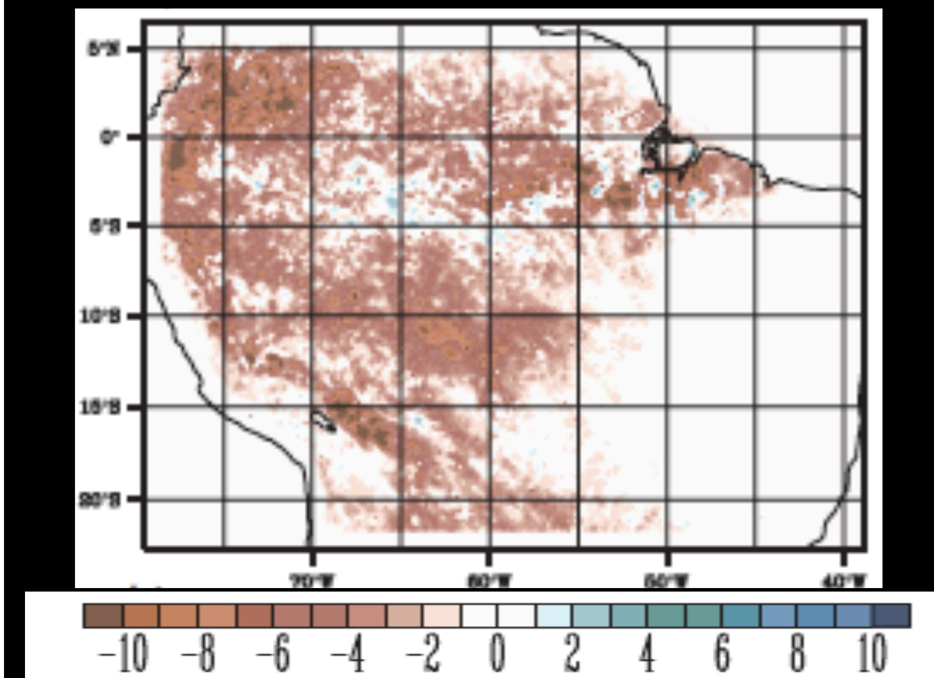


Deforested Regions

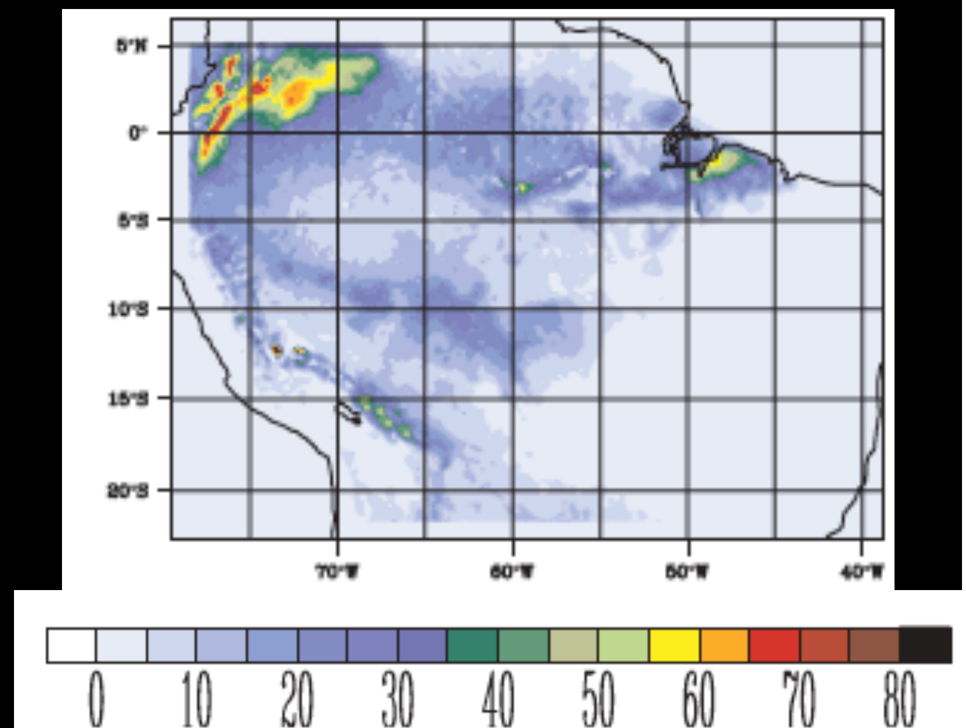


Mean forward trajectory precipitation rate from deforested points

Moisture Trajectory Analysis

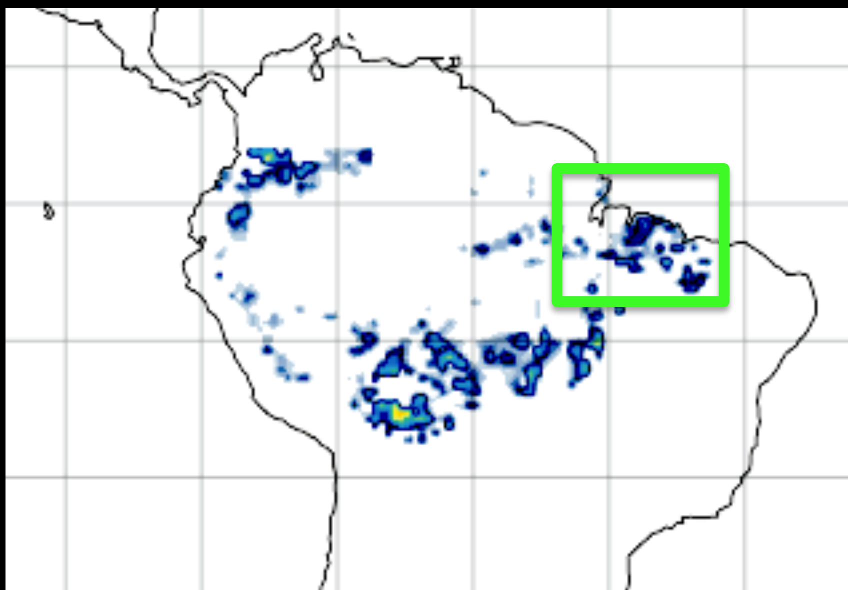


Impact of deforestation on precipitation rate from deforested points

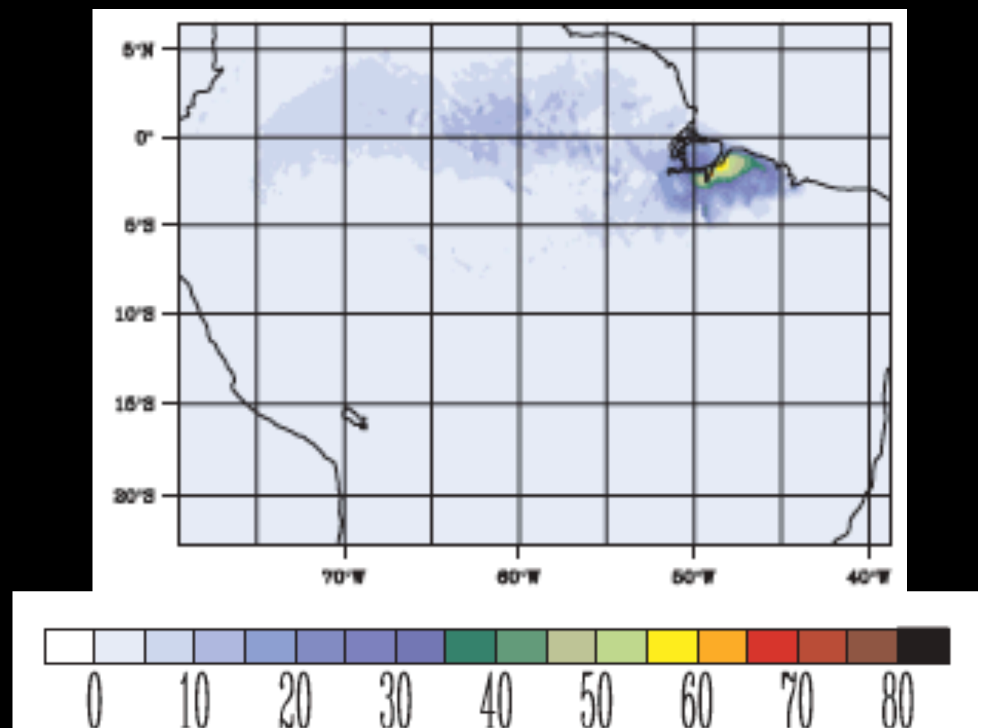


Mean forward trajectory precipitation rate from deforested points

Moisture Trajectory Analysis

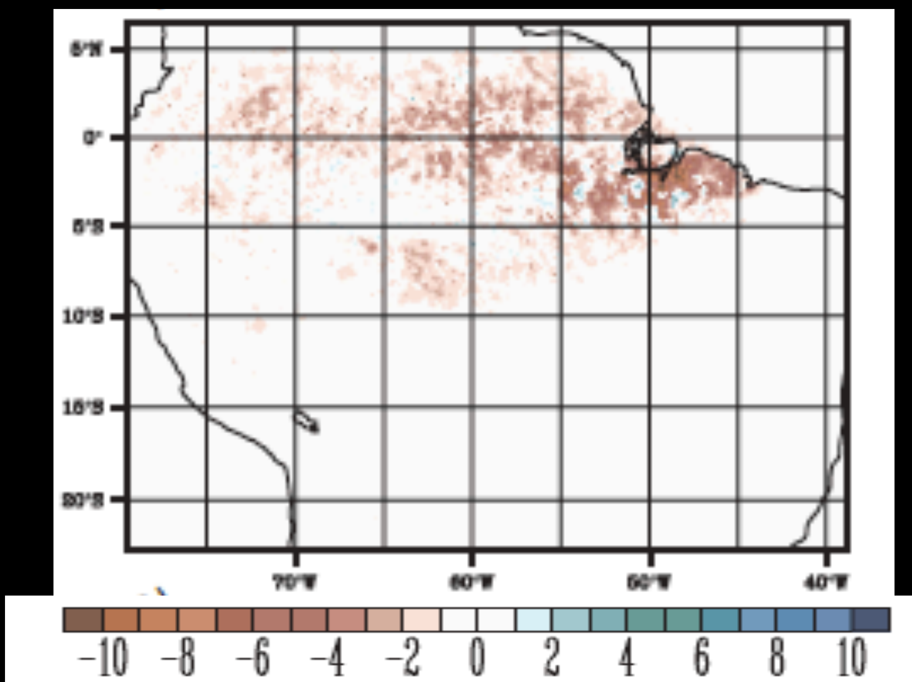


Source Region

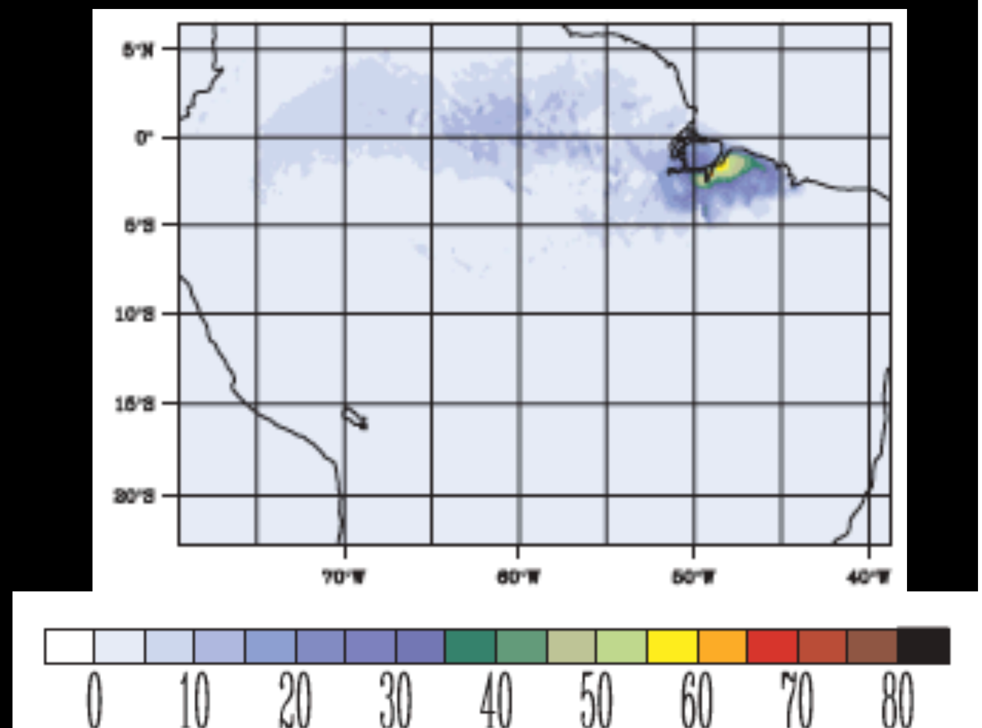


Mean forward trajectory precipitation rate from deforested points

Moisture Trajectory Analysis

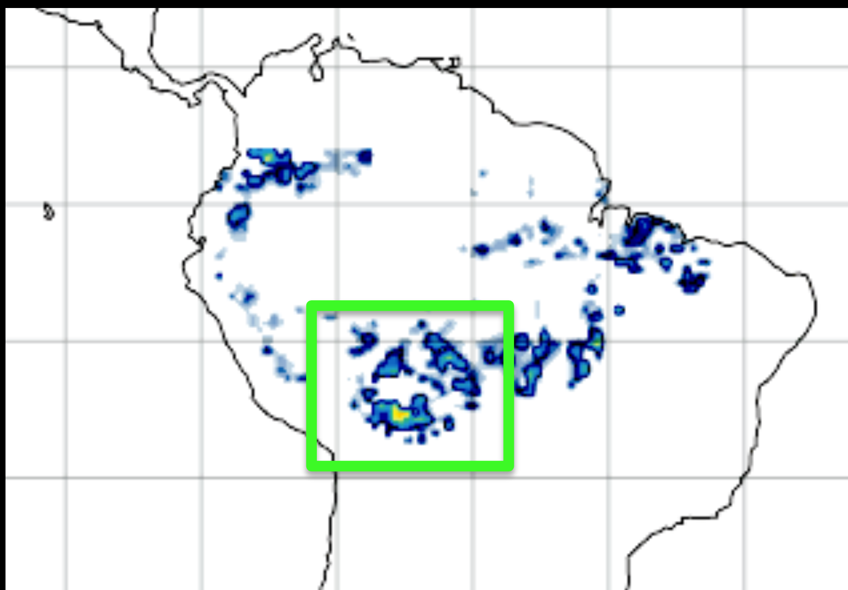


Impact of deforestation on precipitation rate from deforested points

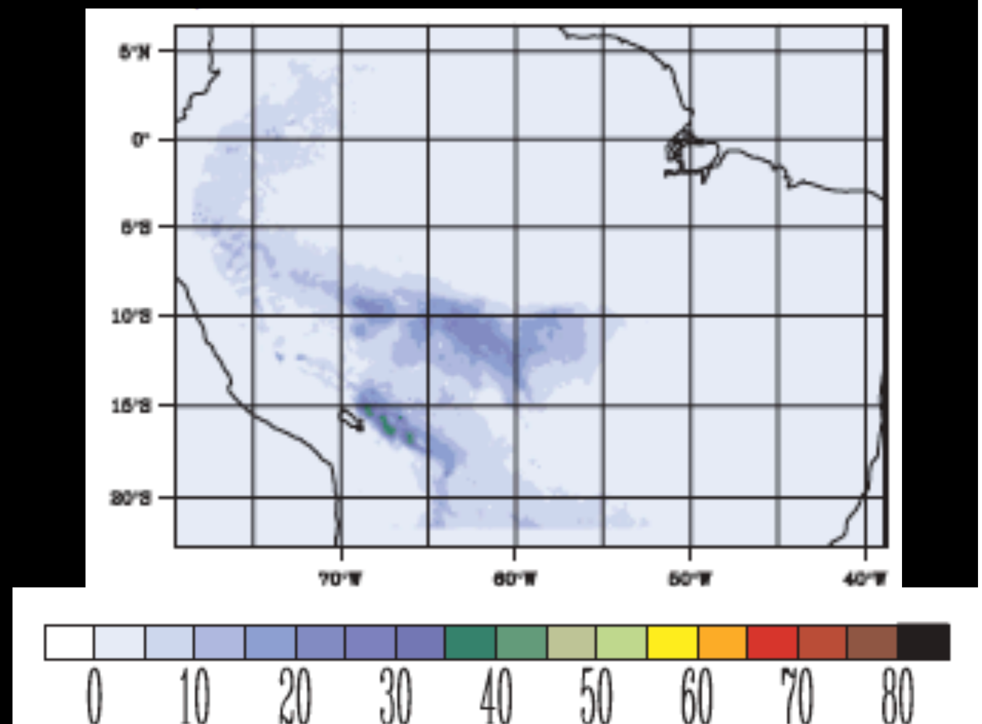


Mean forward trajectory precipitation rate from deforested points

Moisture Trajectory Analysis

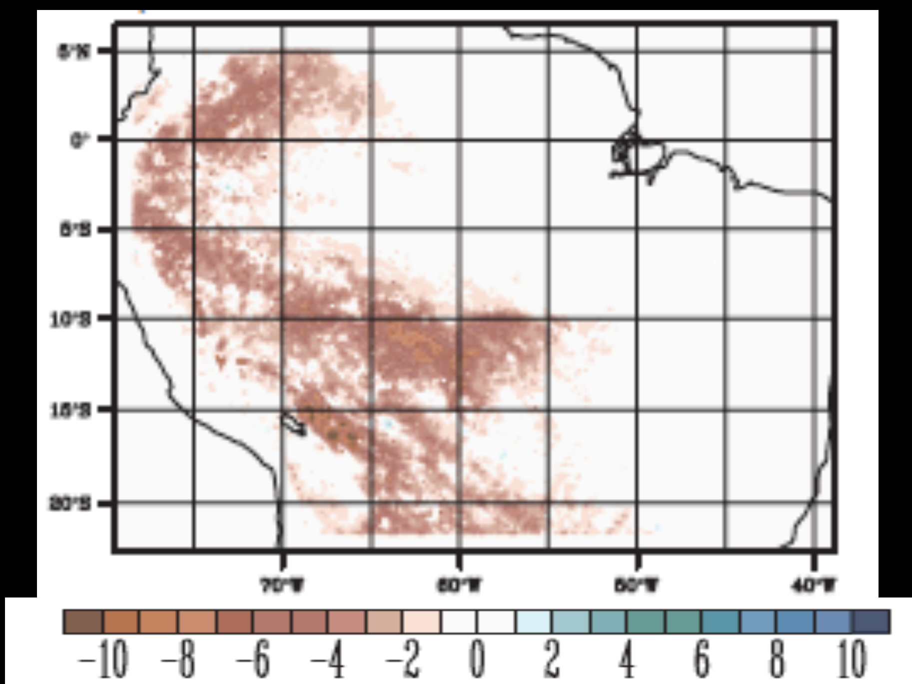


Source Region

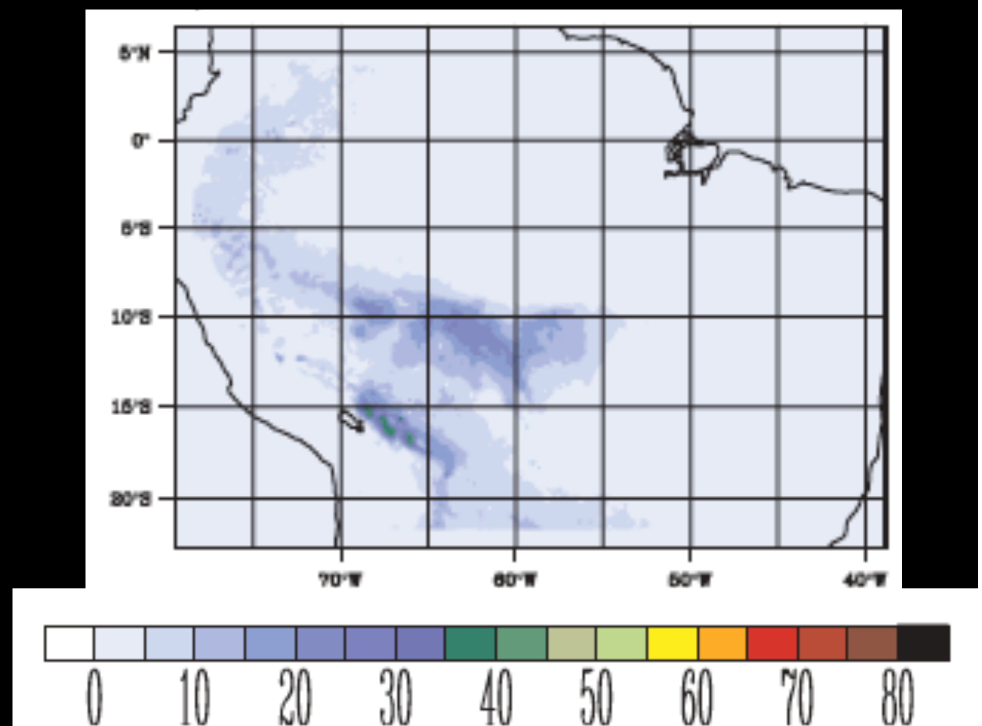


Mean forward trajectory precipitation rate from deforested points

Moisture Trajectory Analysis

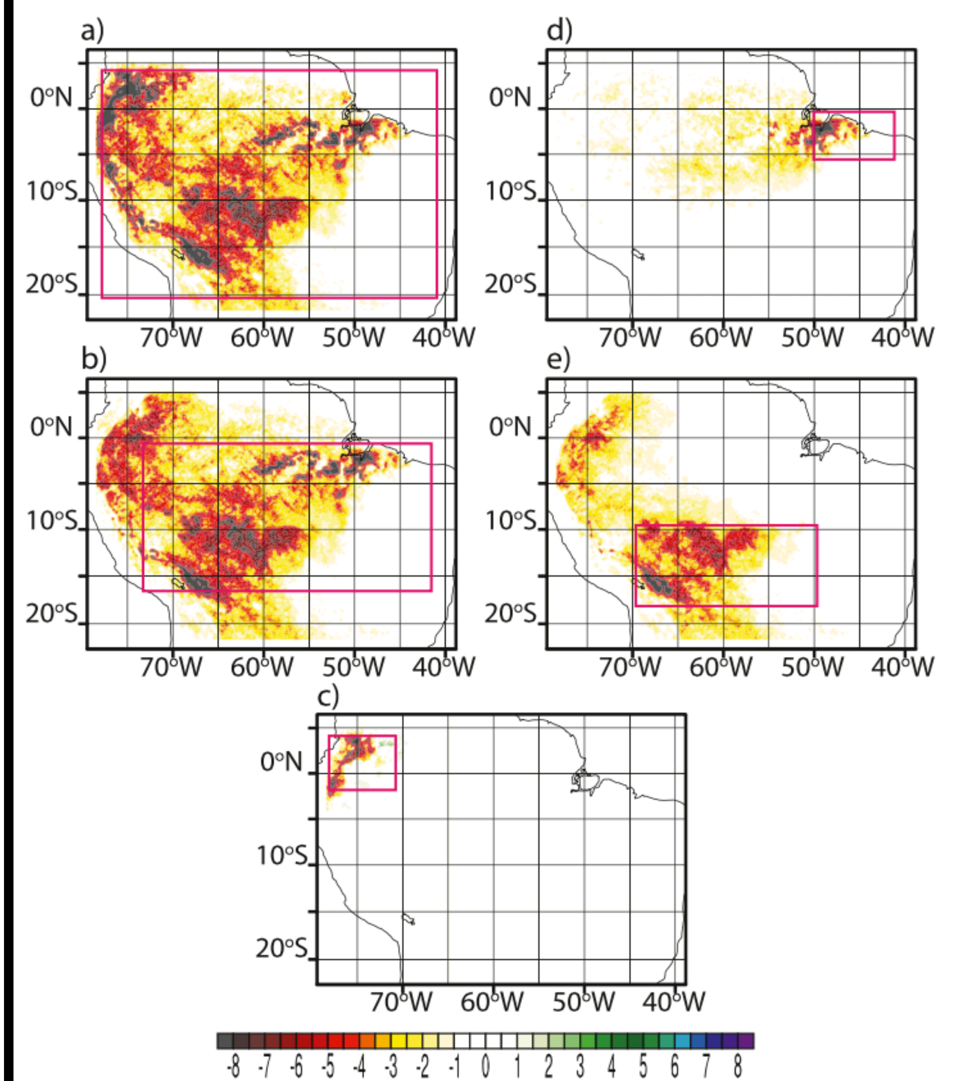


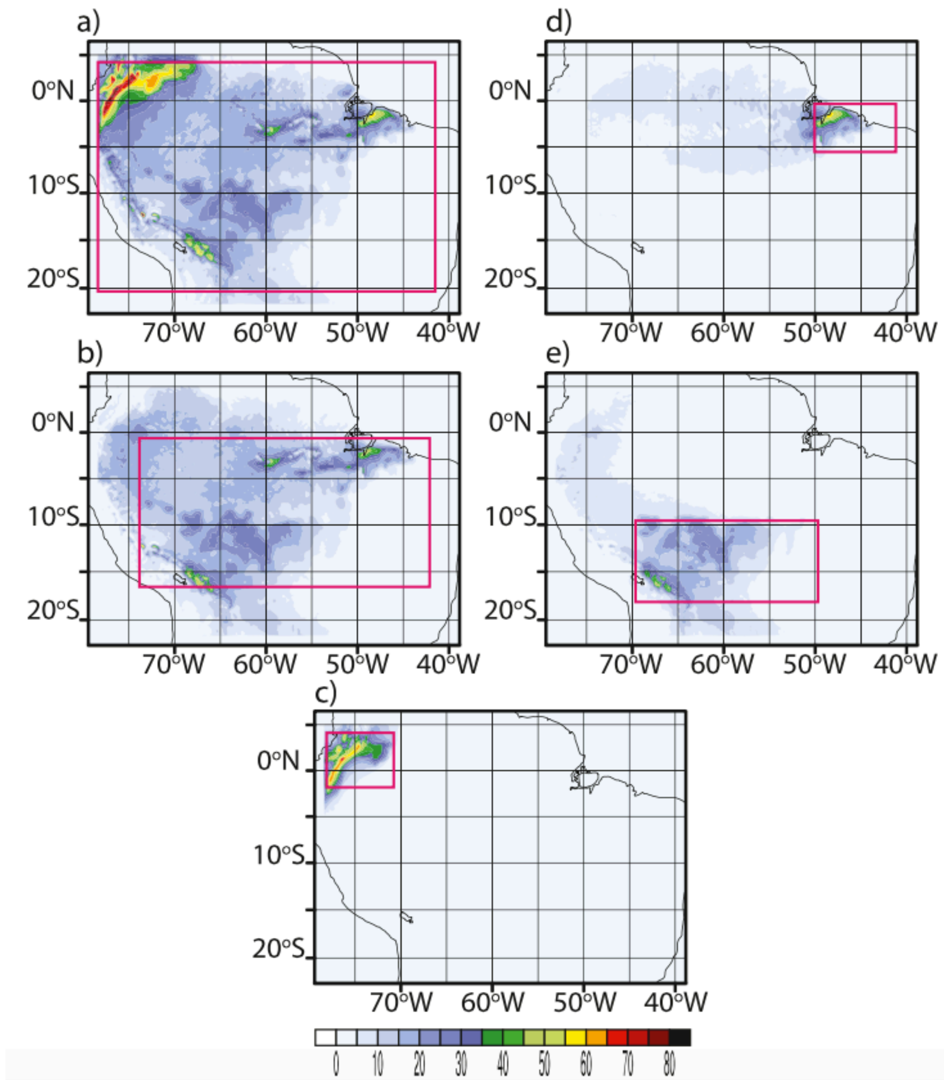
Impact of deforestation on precipitation rate from deforested points



Mean forward trajectory precipitation rate from deforested points

[redacted]





[redacted]

Recycling Ratio
Description

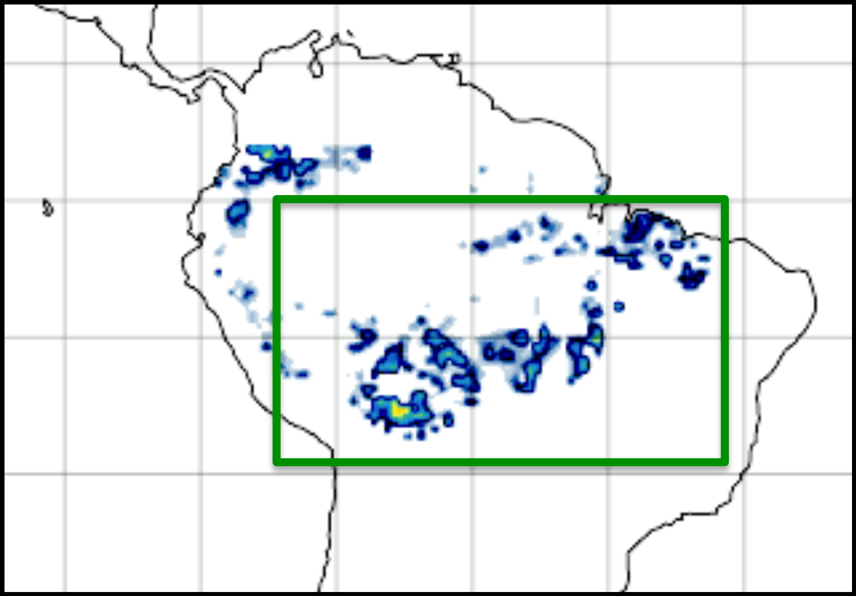
Recycling ratio is the fraction of precipitation in a given region that last evapotranspired from the region itself.

Using backtrajectory analysis this is trivially calculated.

The recycling ratio is an important estimate of land atmosphere coupling.

$$R = \frac{P_{rec}}{P_{tot}}$$

July Regional Recycling

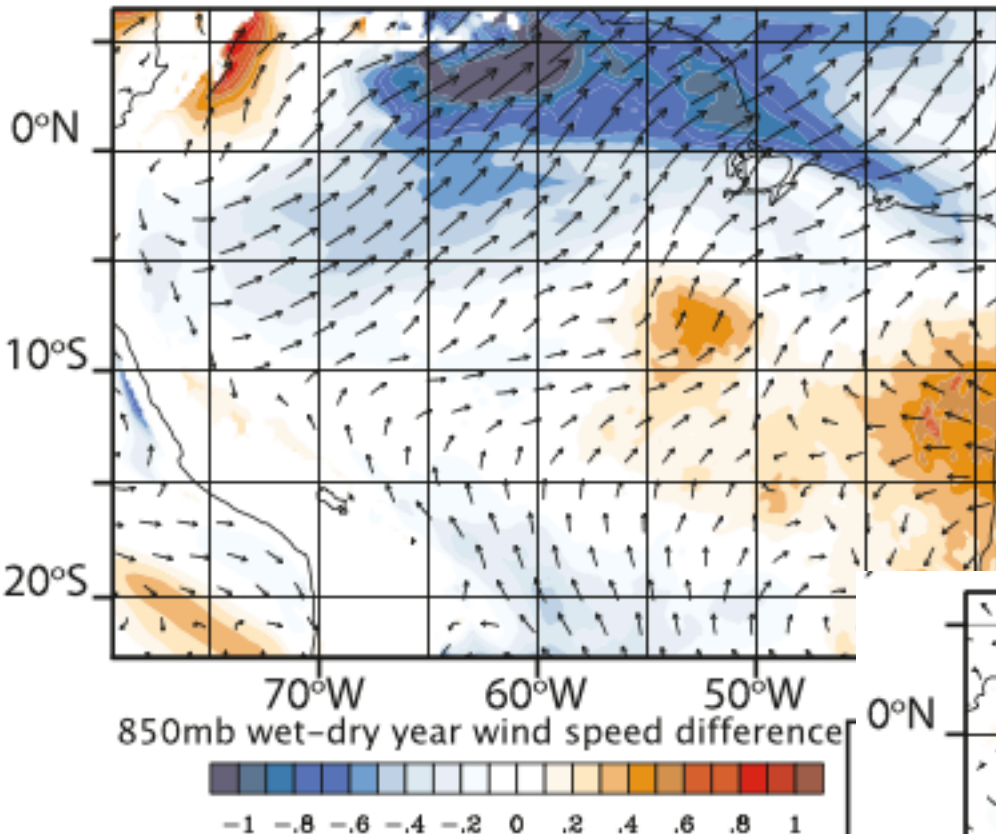


Pluvial Year
Recycling Ratio

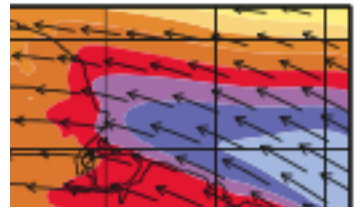
.694

Drought Year
Recycling Ratio

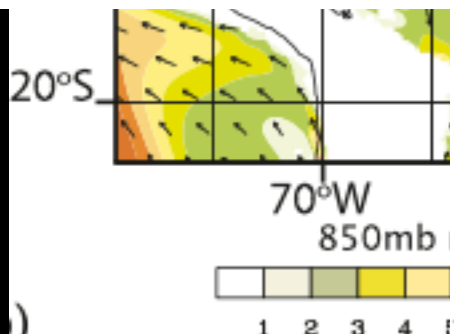
.850



[redacted]

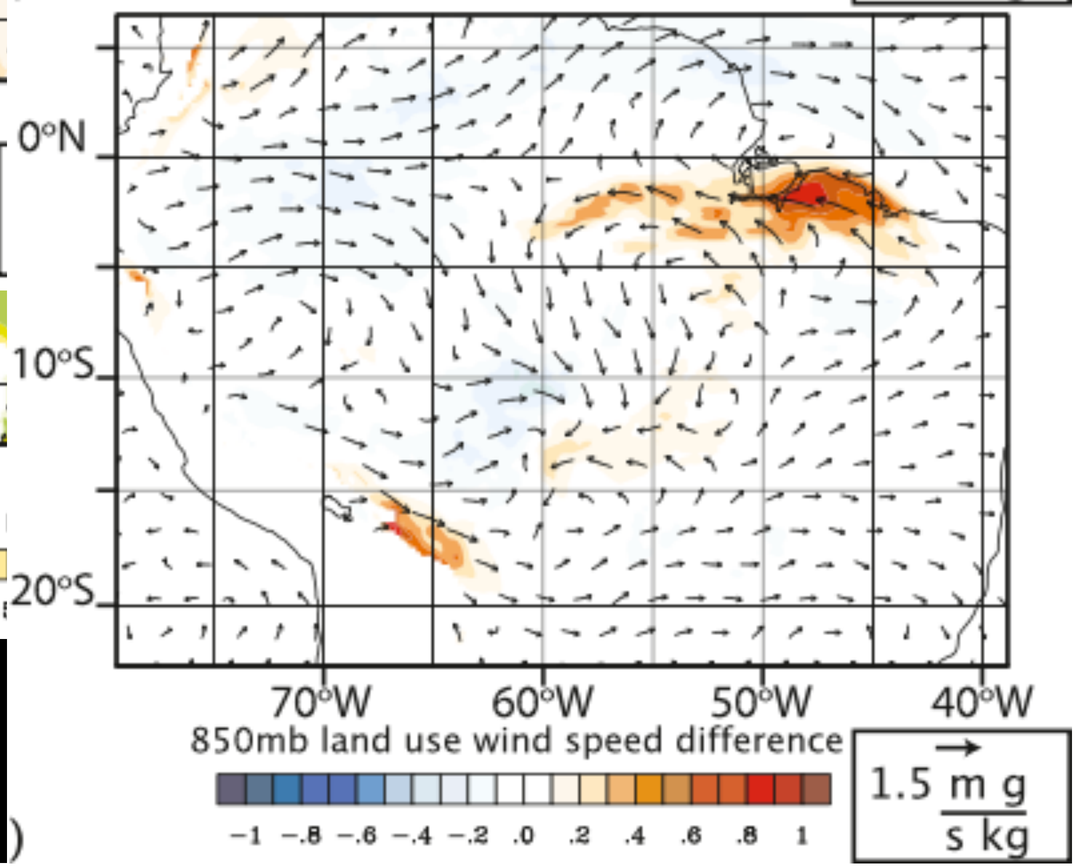


[redacted]



[redacted])

[redacted])

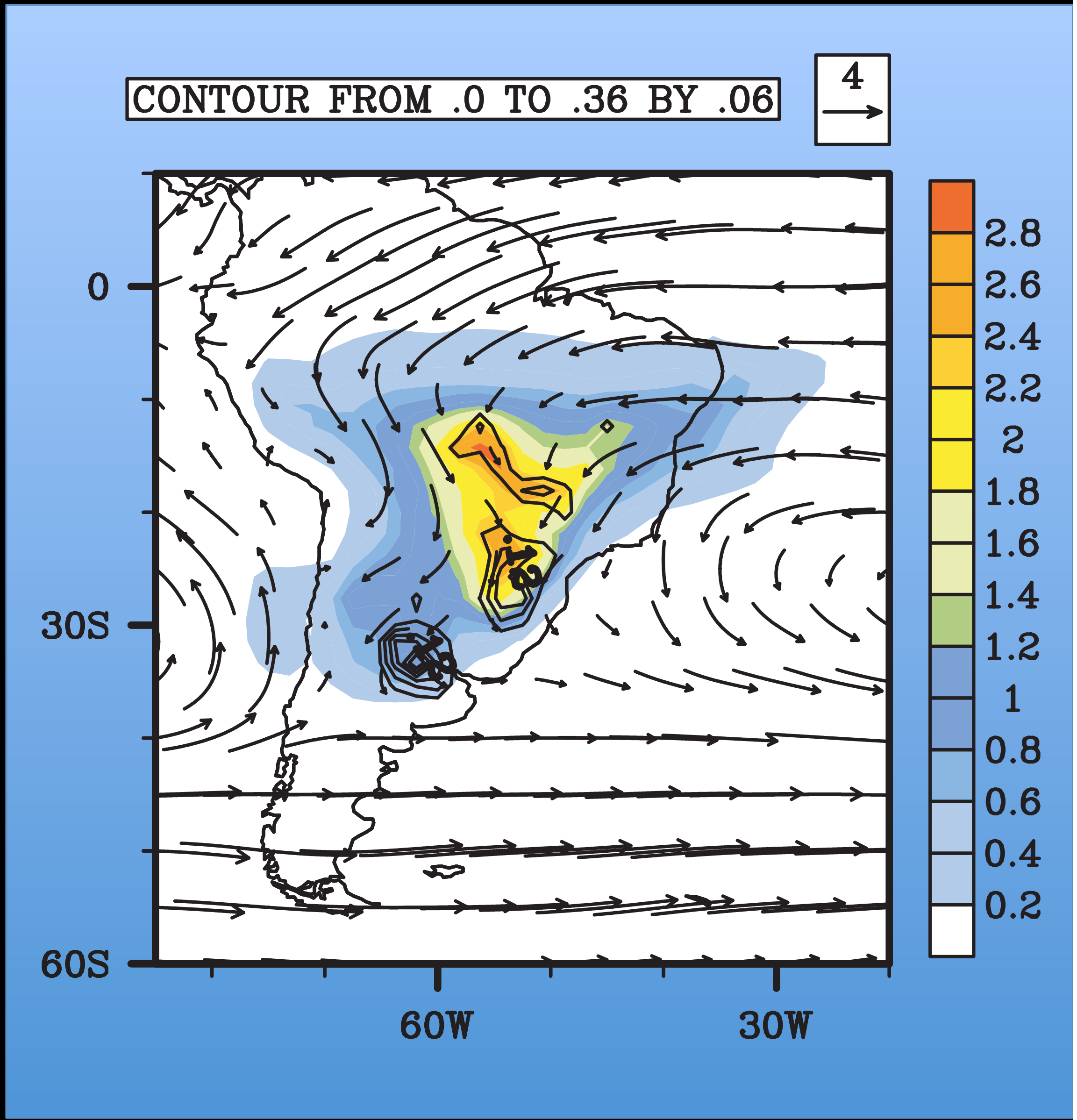


Amazon Rainforest Percent Changes with Deforestation

In nearly every measure the impact of deforestation is greater during drought years

	July - September	
	Pluvial Years	**Drought Years**
% Δ Precipitation Rate	-4.99%	-5.93%
% Δ Sensible Heat Flux	+.48%	+4.28%
% Δ Latent Heat Flux	-3.63%	-5.57%
% Δ Net Surface Radiation	-2.41%	-2.70%
% Δ Boundary Layer Height	-.11%	+1.36%
% Δ Rel. Soil Moisture Top Layer	-3.00%	-4.38%
% Δ Rel. Soil Moisture Bot. Layer	+3.50%	+5.09%
% Δ 2m Specific Humidity	-.77%	-1.31%
% Δ Level of free convection	+2.62%	+.52%
% Δ Lifting condensation level	+1.29%	+3.94%

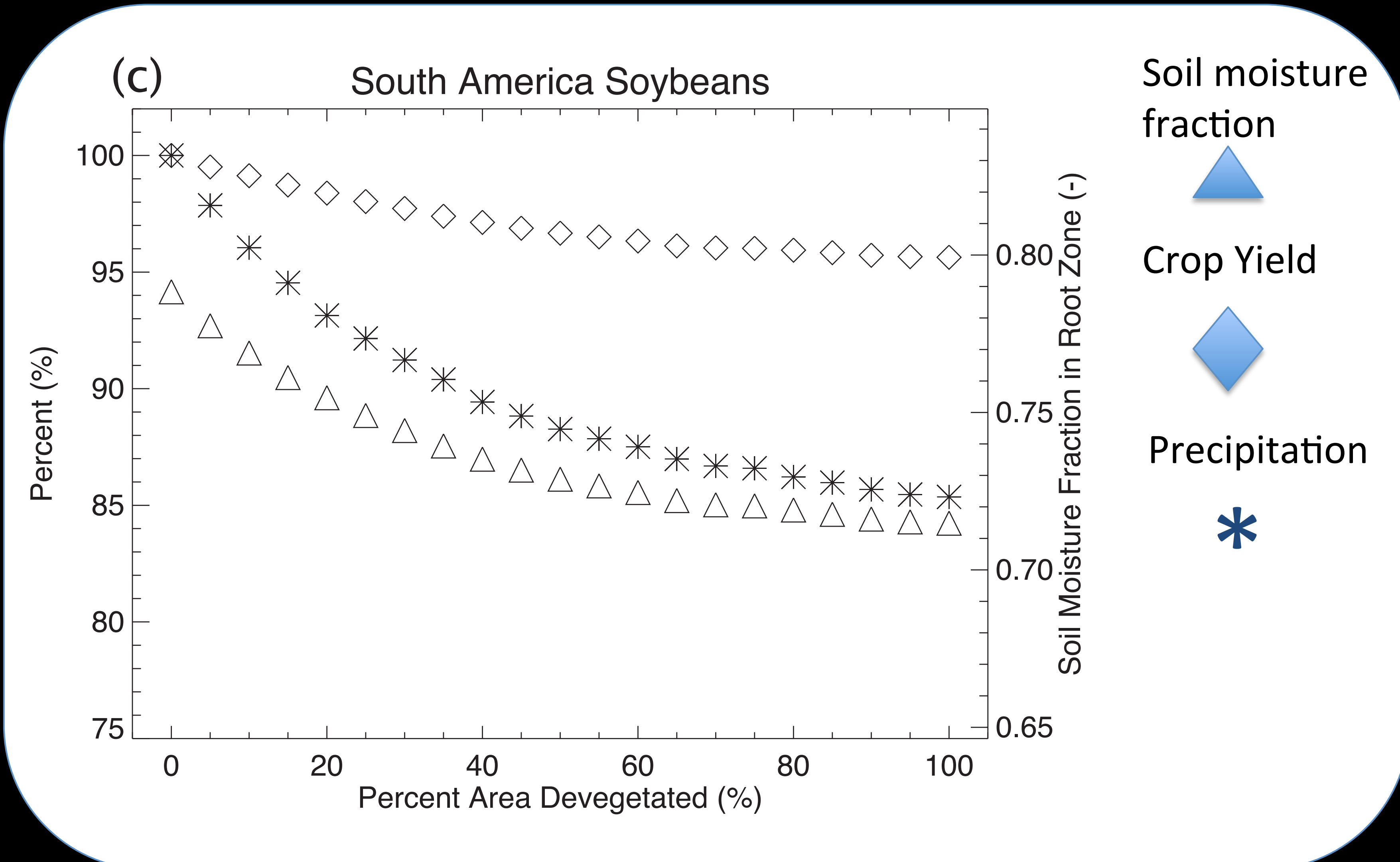
South American Soybeans
Evaporative Source



Bagley et al., ERL, 2012

Potential Impact of Land Cover Change on Crop Yield

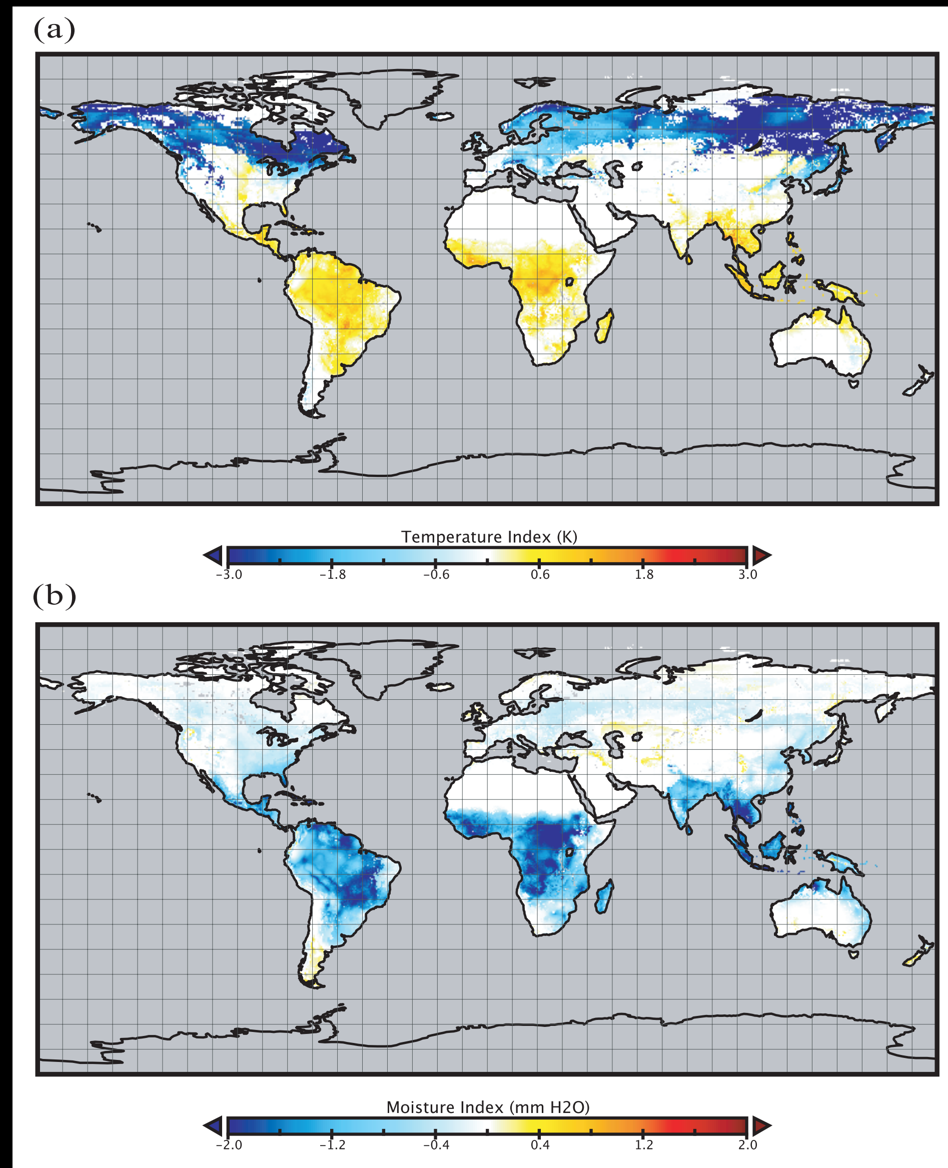
S. America Soybeans



Local regulation of surface climate by vegetation

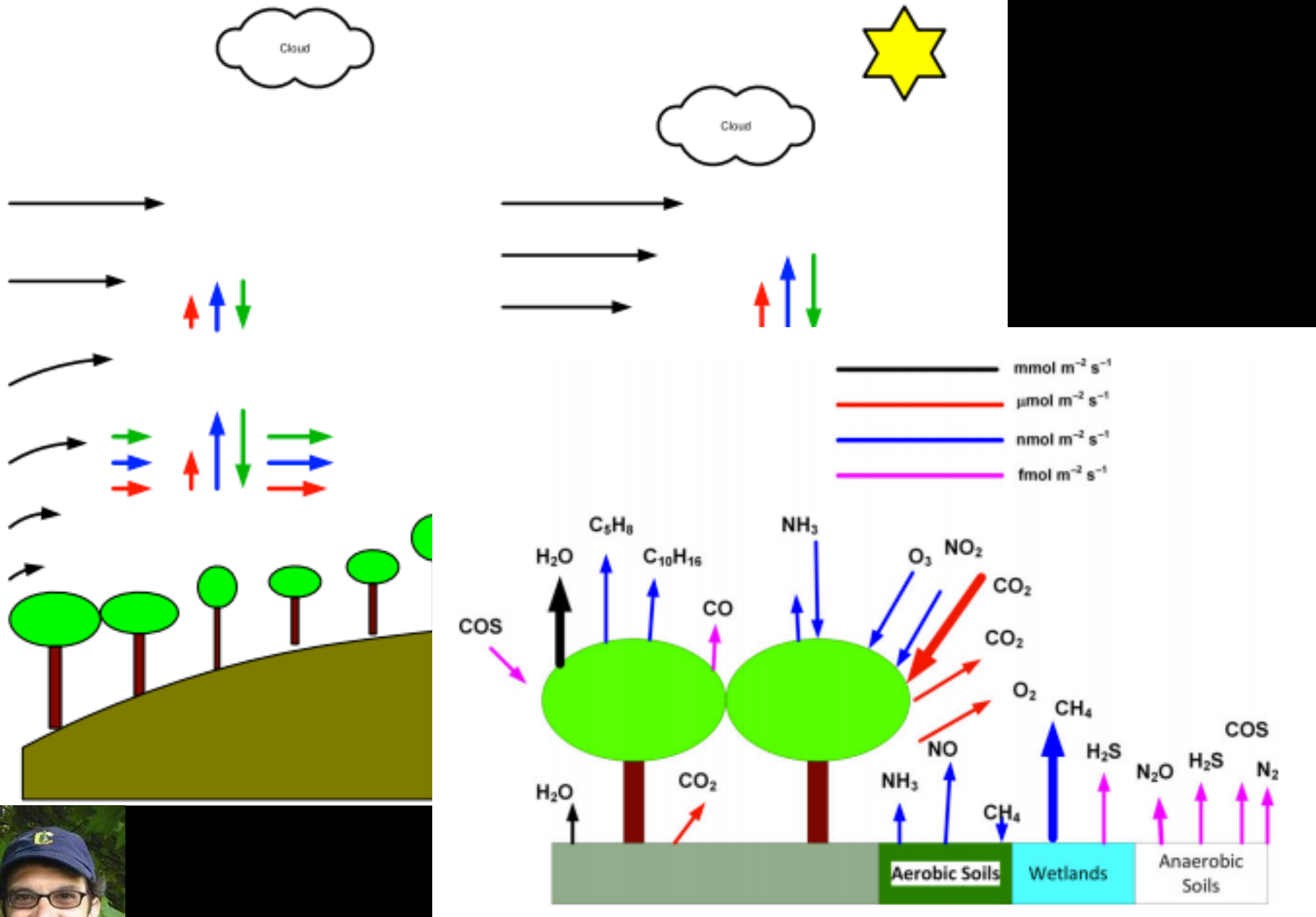
$$H\_reg\_index = \Delta H \frac{|\Delta H|}{|\Delta H| + |H_{adv}|}$$

$$Q\_reg\_index = \Delta Q \frac{|\Delta Q|}{|\Delta Q| + |Q_{adv}|}$$



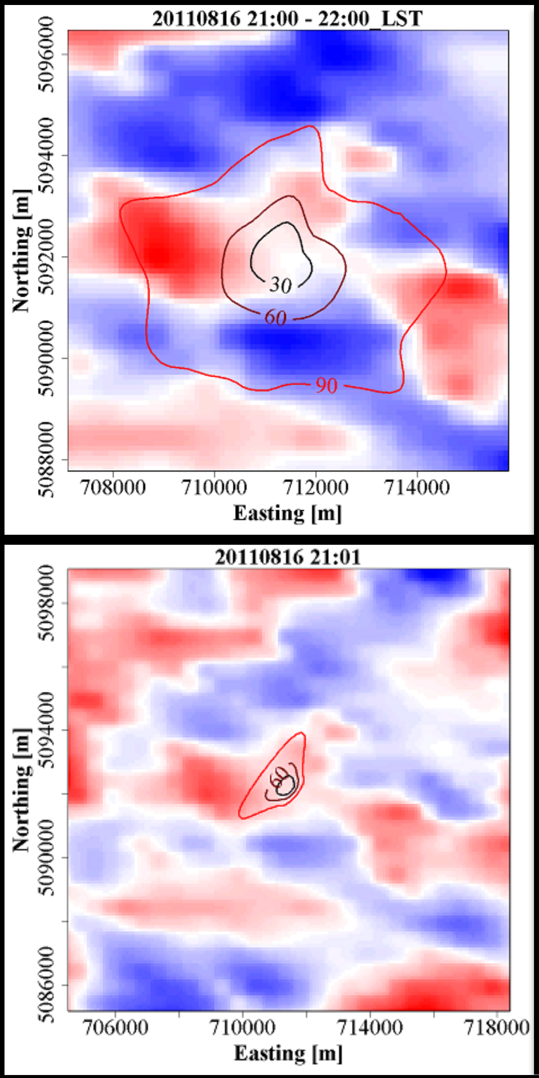
Let’s get a little smaller

Maybe a few kilometers


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
NH_3
H_2O
$C_{10}H_{16}$
O_3
NO_2
CO_2
CO
COS
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

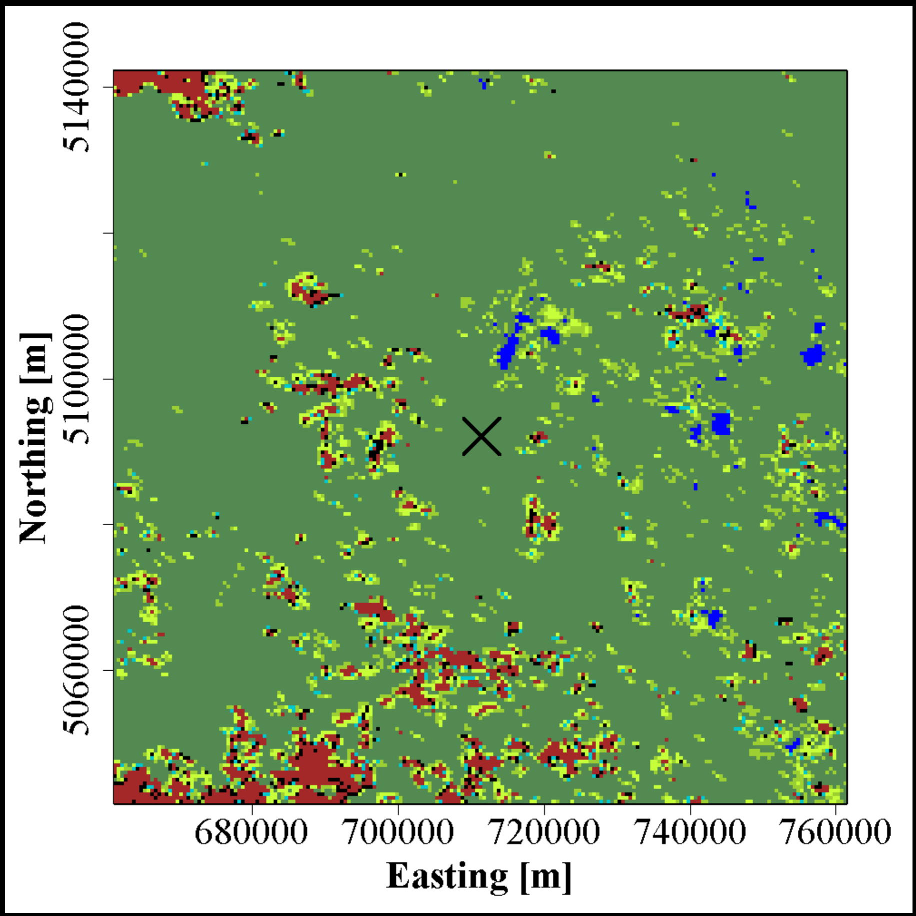
D. Baldocchi

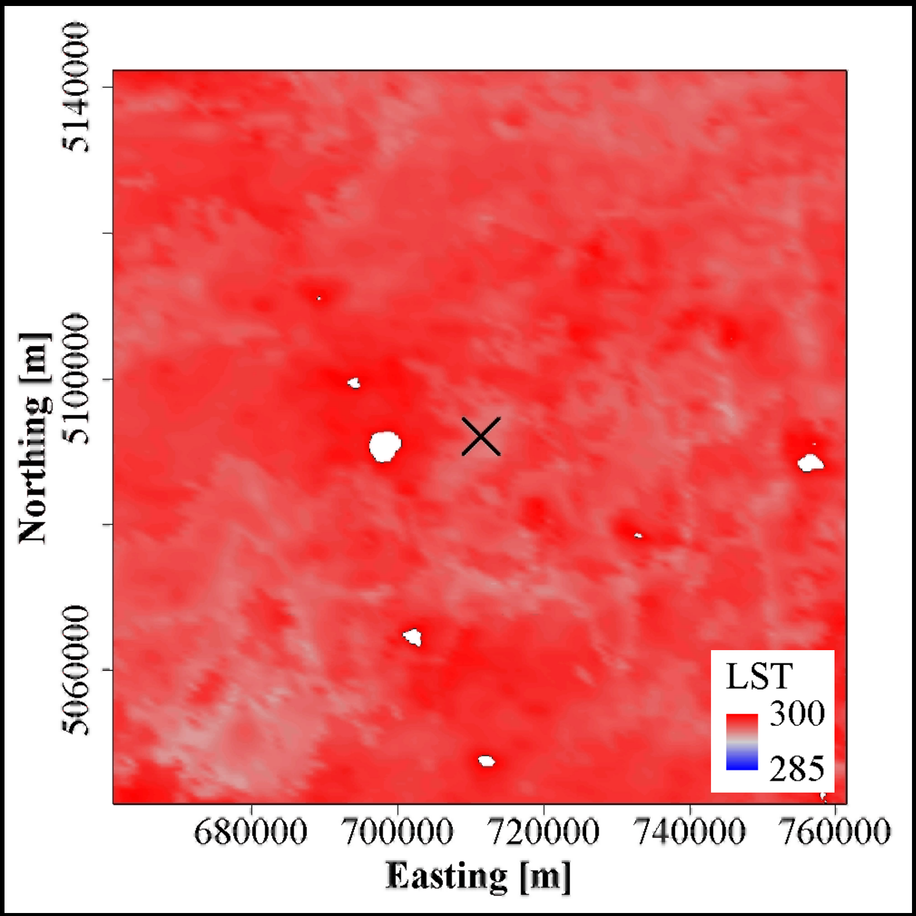
What does the tower flux measurement "see"?



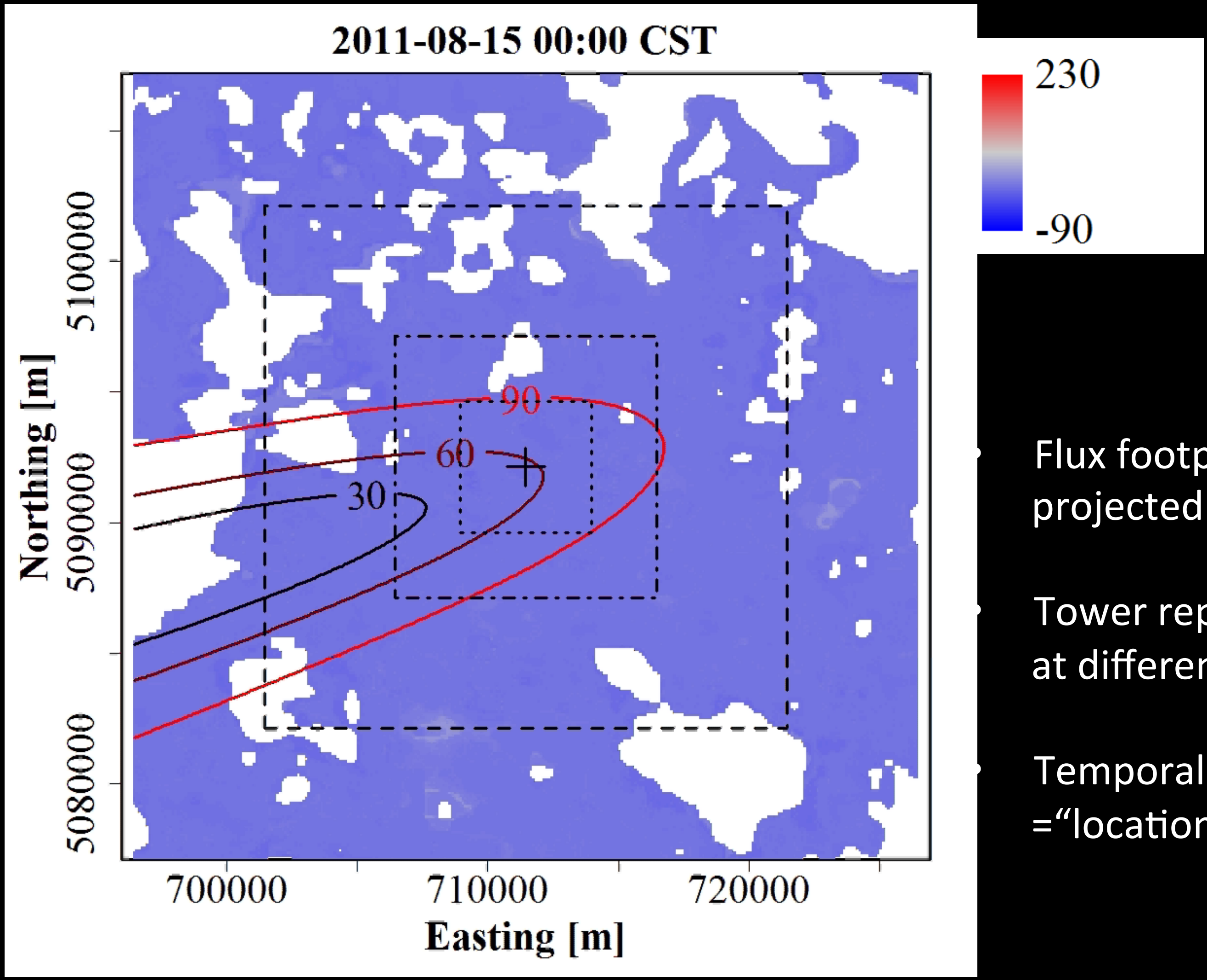
Park Falls/Chequamegon National Forest region

- Relative homogenous…
  - But biophysical properties transient in space and time!



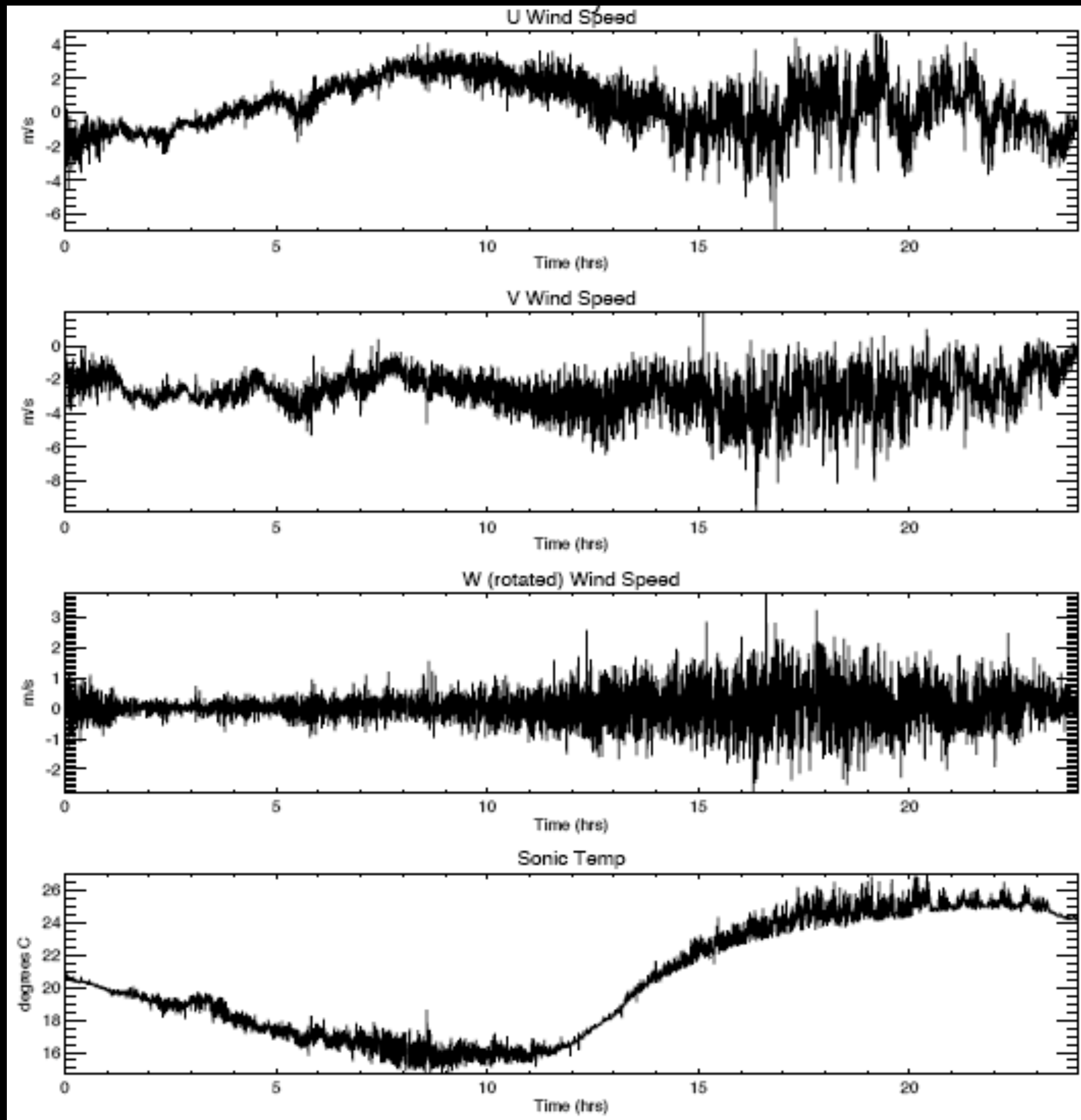


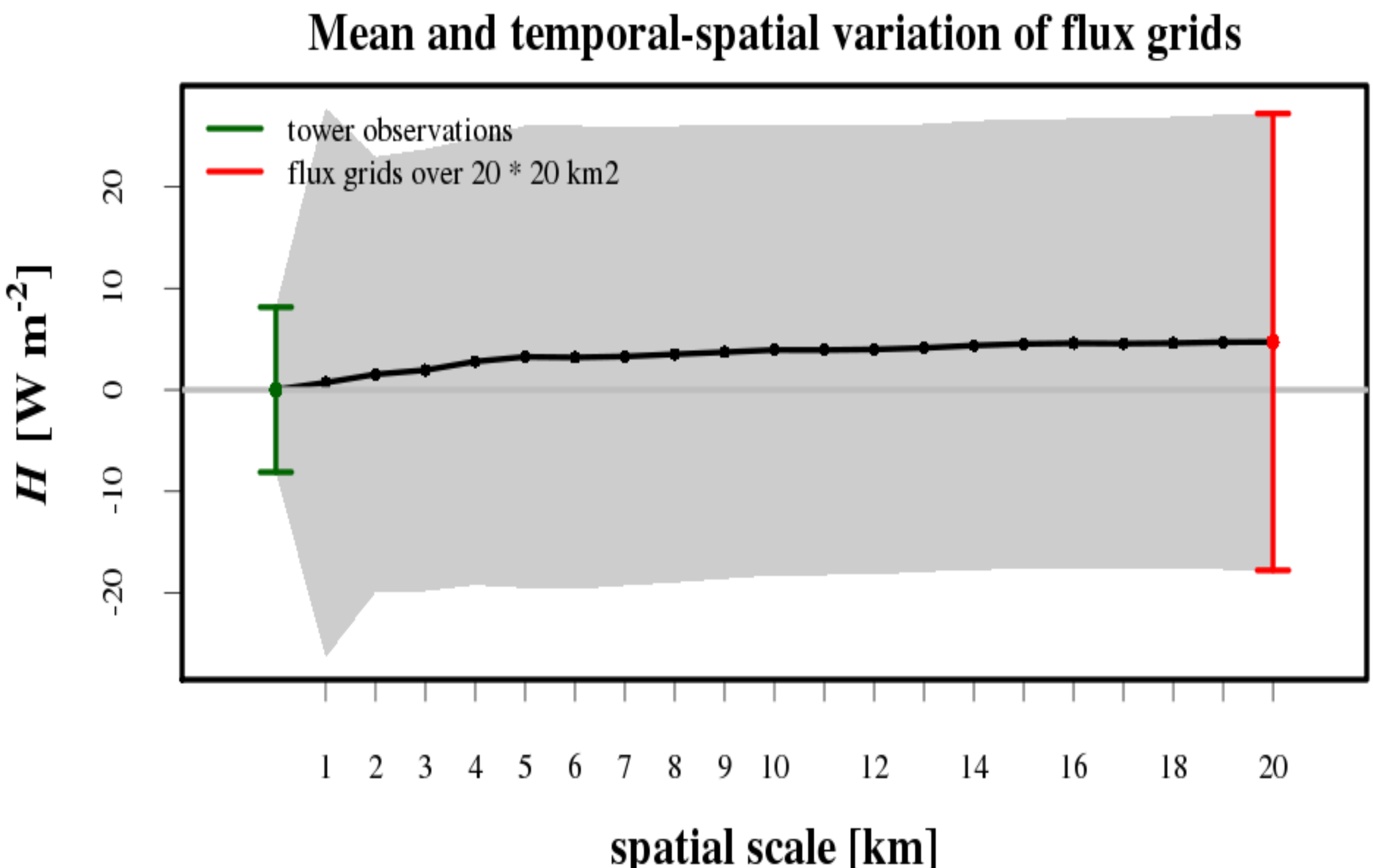
Sensible heat flux [W m^{-2}]



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


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)

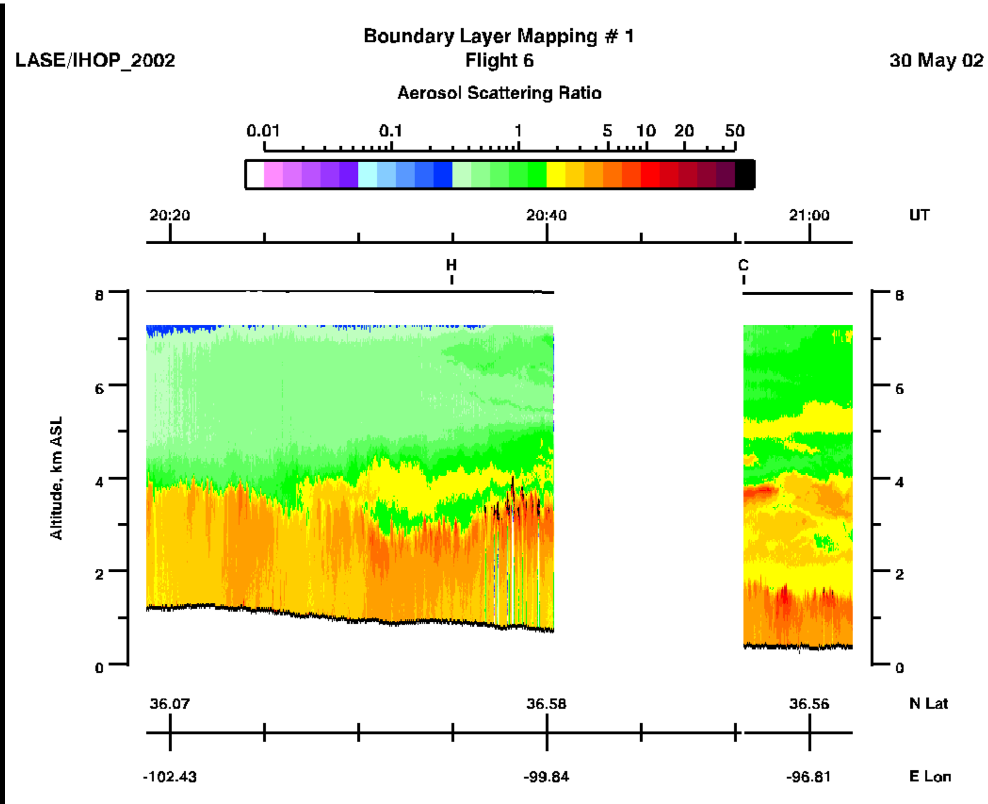


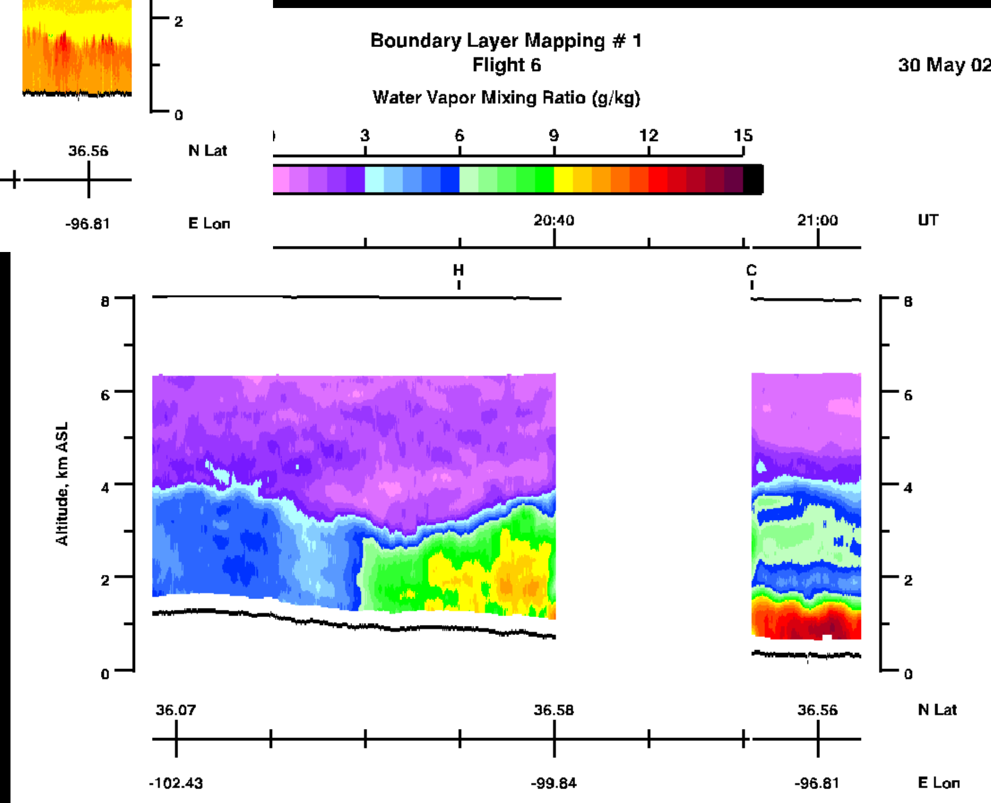
Mean and temporal-spatial variation of flux grids
tower observations
flux grids over 20 * 20 km2
H [W m-2]
20
10
0
-10
-20
1 2 3 4 5 6 7 8 9 10 12 14 16 18 20
spatial scale [km]


N2UW
U Wyoming
Photograph courtesy of Vanda Grubisic, Desert Research Institute


NASA DC-8 (Desai)


B.D. Cook

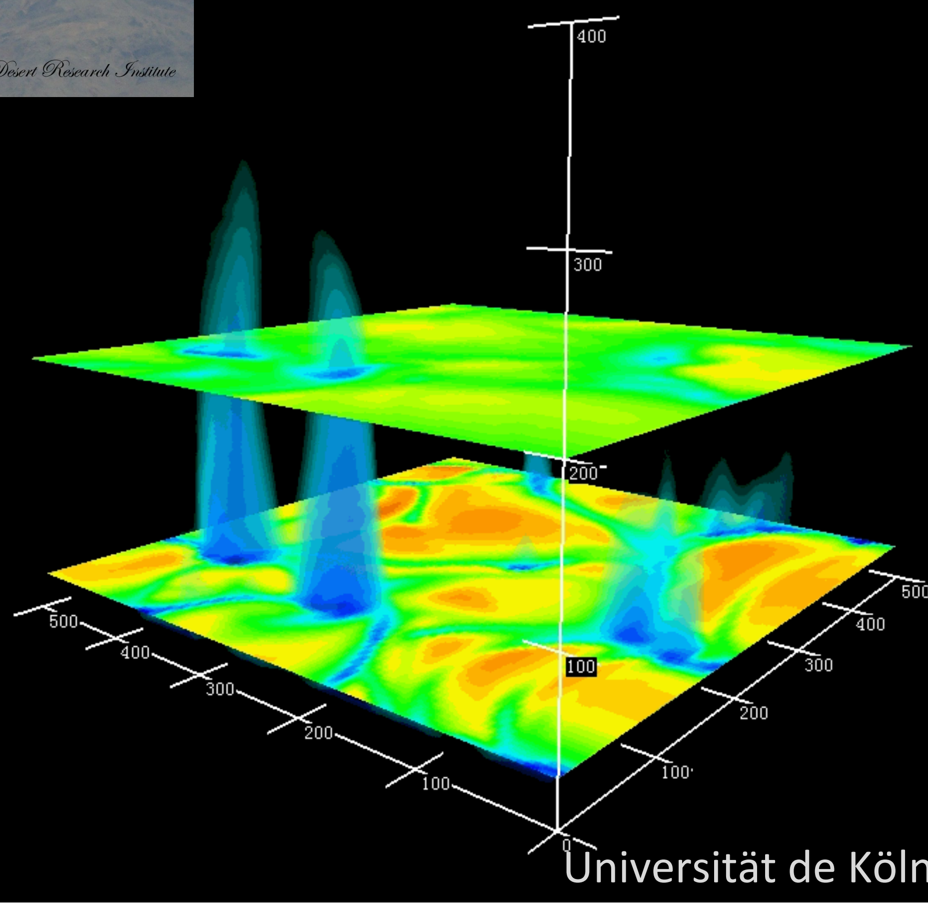

LASE/IHOP_2002
Boundary Layer Mapping # 1
Flight 6
30 May 02
Aerosol Scattering Ratio
0.01
0.1
1
5
10
20
50
20:20
20:40
21:00
UT
H
C
Altitude, km ASL
36.07
36.58
36.56
N Lat
-102.43
-99.84
-96.81
E Lon


Boundary Layer Mapping # 1
Flight 6
30 May 02
Water Vapor Mixing Ratio (g/kg)
3
6
9
12
15
20:40
21:00
UT
H
C
Altitude, km ASL
36.07
36.58
36.56
N Lat
-102.43
-99.84
-96.81
E Lon


N2UW
U Wyoming
Photograph courtesy of Vanda Grubisic, Desert Research Institute


NASA DC-8 (Desai)


B.D. Cook


400
300
200
100
500
400
300
200
100
500
400
300
200
100
0
Universität de Köln

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

$$TKE = \frac{1}{2}\overline{u_i'^2} = \int_0^\infty E(k)\,dk$$

- Can visualize energy spectrum at wavenumber k = eddies of size 2 pi / k

Energy Cascade

Garratt

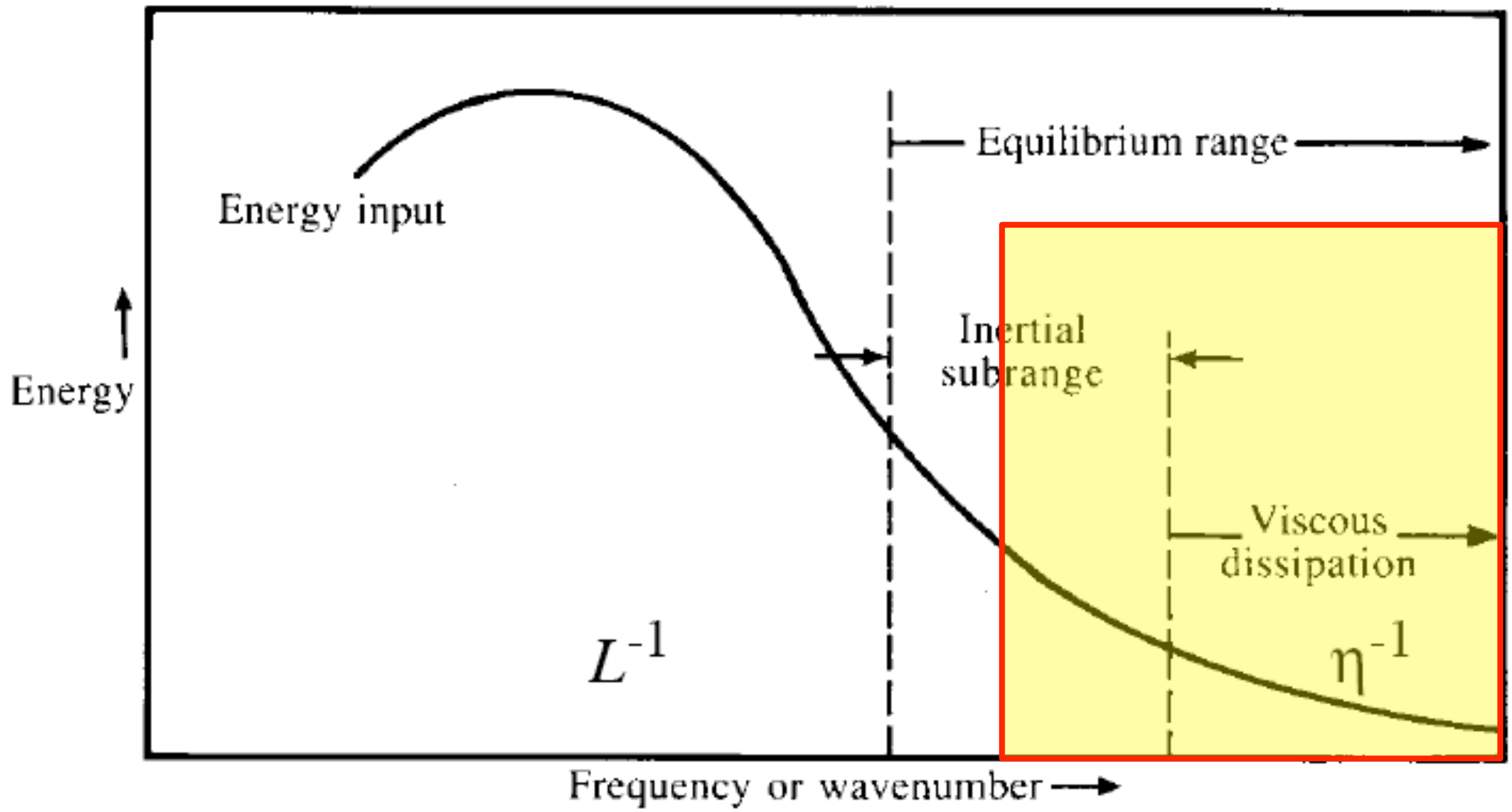


Fig. 2.1 Schematic representation of the energy spectrum of turbulence.

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

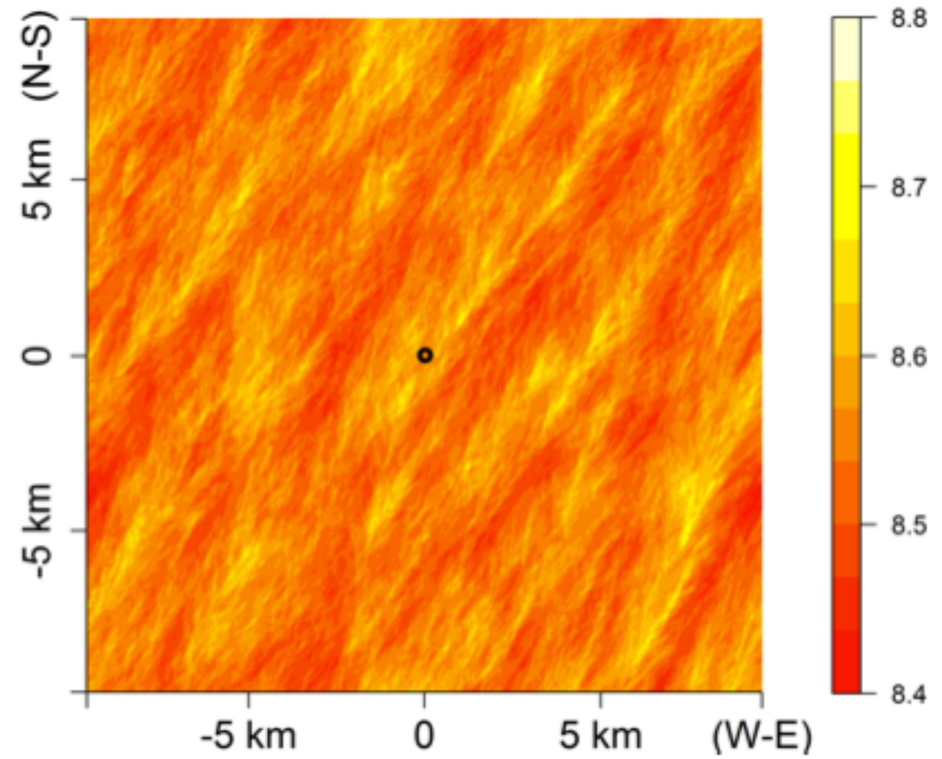
Boundary layer characteristics
$L = -1.4 \cdot 10^2\,\mathrm{m}$
$z_i = 1.3 \cdot 10^3\,\mathrm{m}$
$u_\star = 8.2 \cdot 10^{-1}\,\mathrm{m/s}$

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

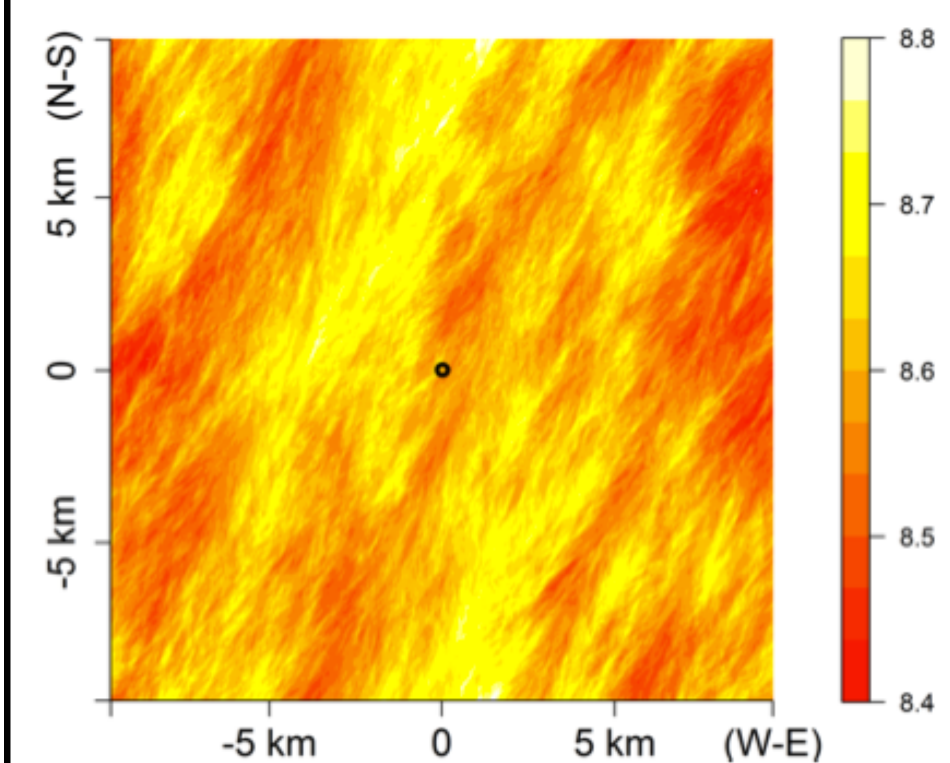
$\sigma_{xy}(\cdot)_{het} - \sigma_{xy}(\cdot)_{hom}$	$30\,\mathrm{m}$	$122\,\mathrm{m}$	$396\,\mathrm{m}$
T [K]	$+8.7 \cdot 10^{-3}$	$+9.6 \cdot 10^{-3}$	$+1.1 \cdot 10^{-2}$
q [g/kg]	$+2.2 \cdot 10^{-2}$	$+2.3 \cdot 10^{-2}$	$+2.3 \cdot 10^{-2}$
w [m/s]	$-5.6 \cdot 10^{-3}$	$-2.2 \cdot 10^{-2}$	$-3.8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

Frederick deRoo (KIT IMK-IFU), TERRENO

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

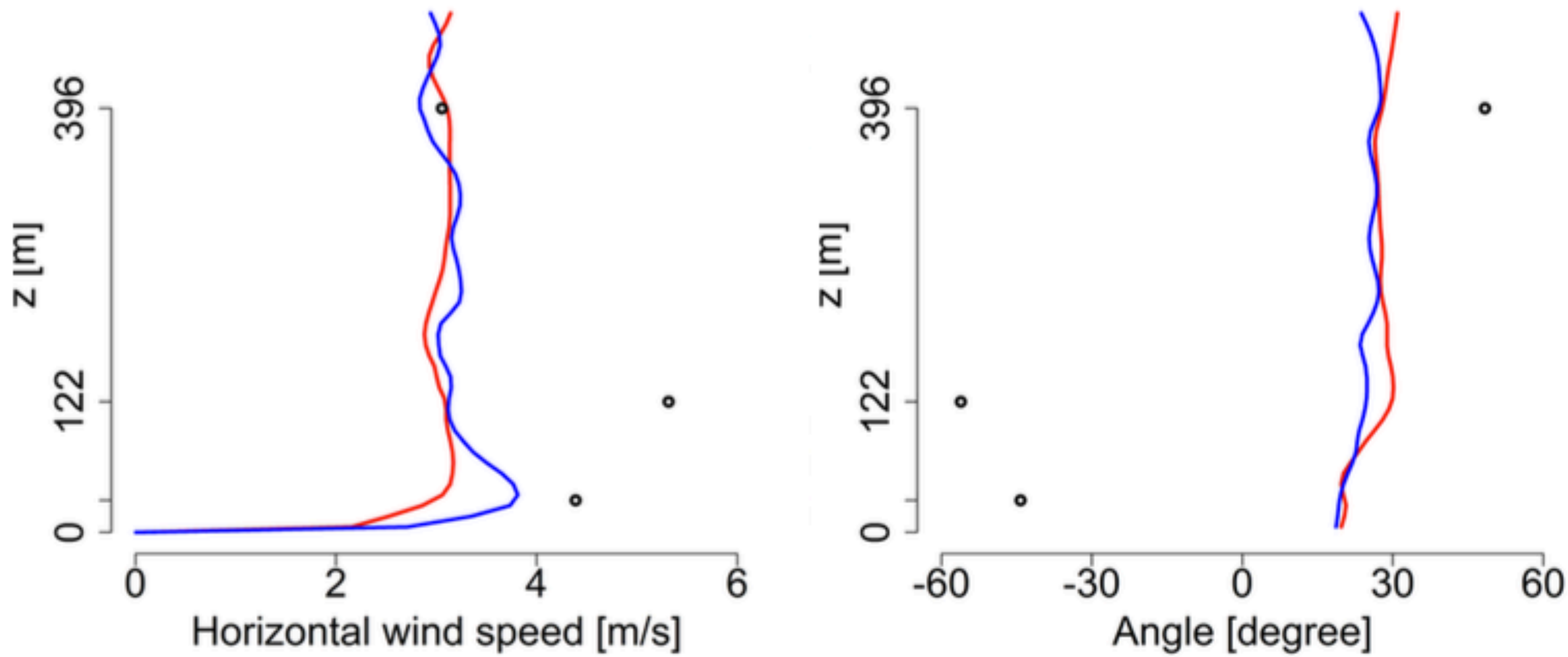


Homogeneous $\bar{q}(xy)$ at 122 m [g/kg]



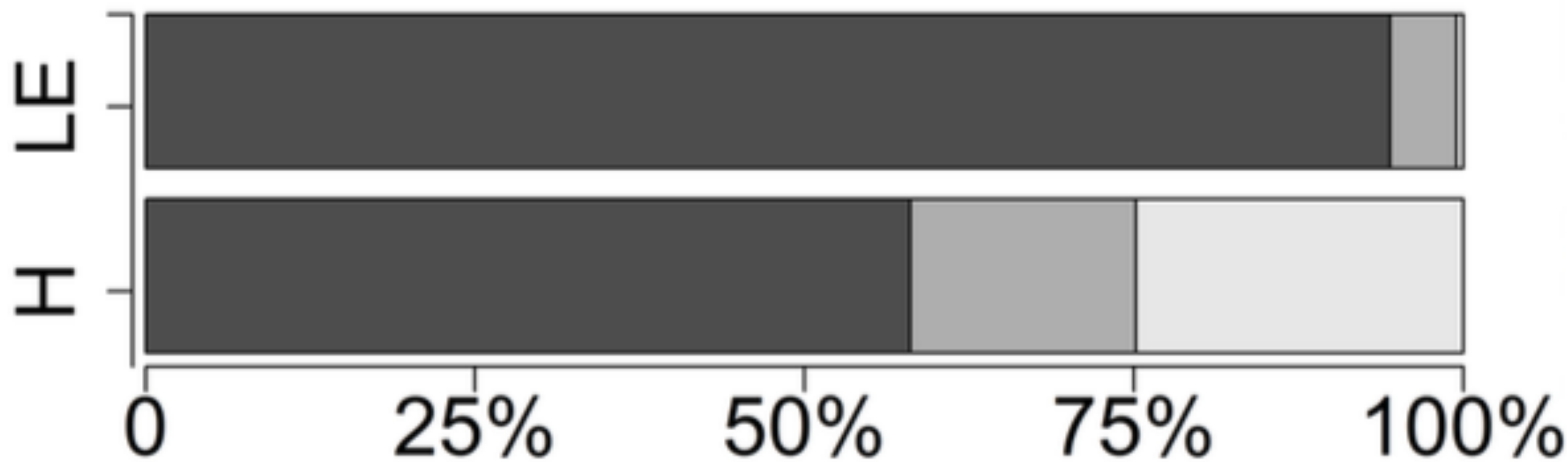
Heterogeneous $\bar{q}(xy)$ at 122 m [g/kg]

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

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!