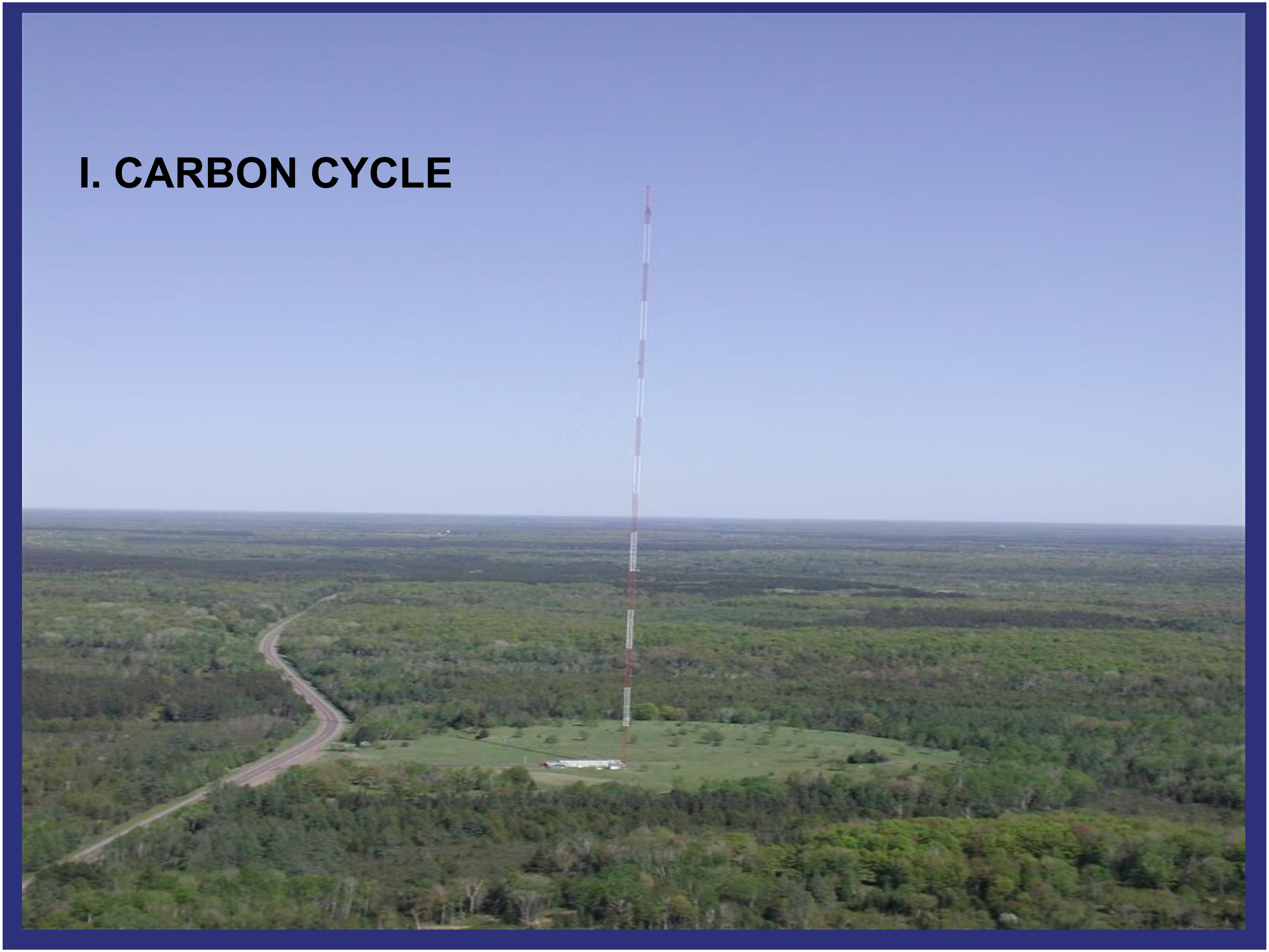
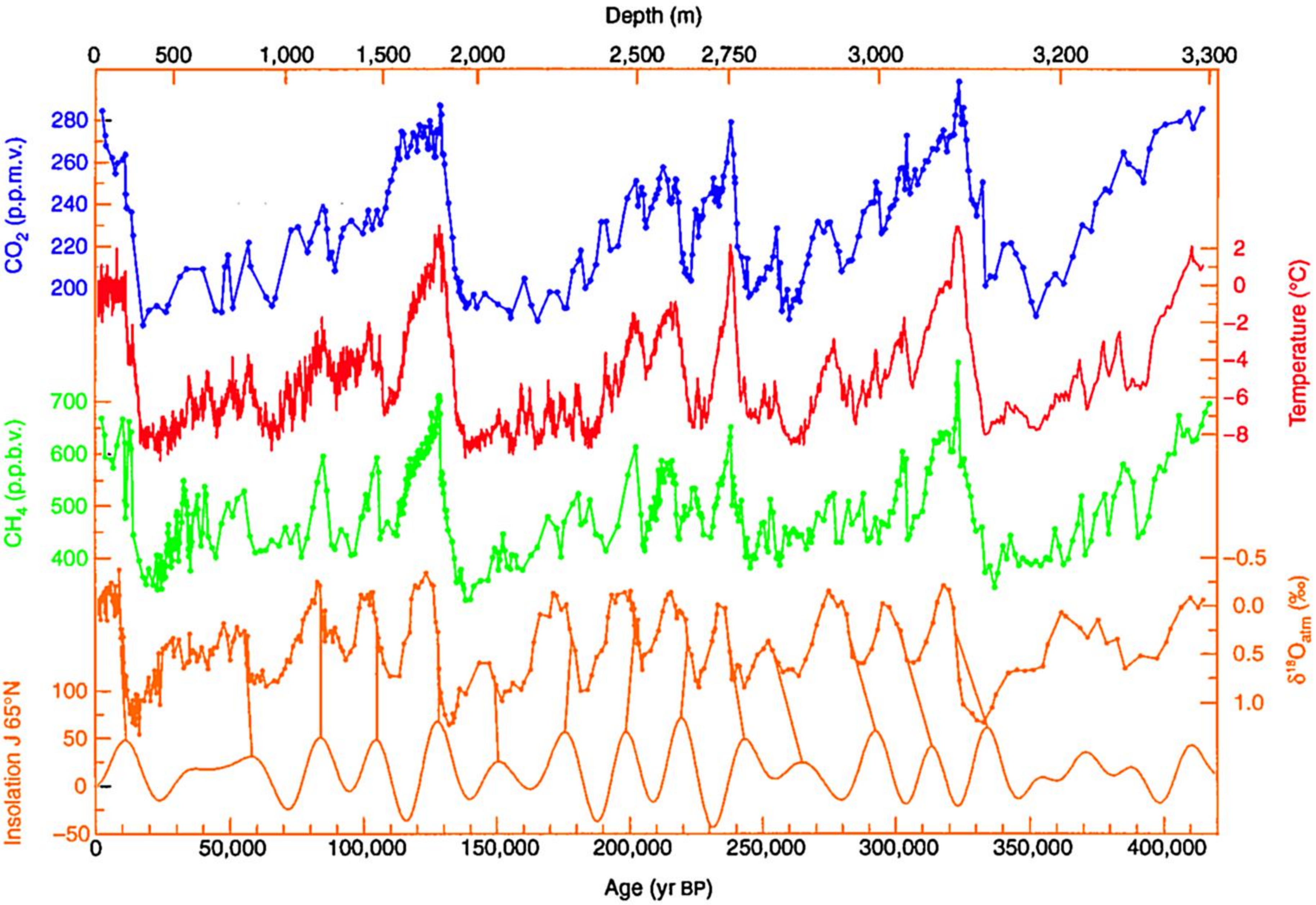
Why a meteorologist studies forests:

The atmospheric carbon cycle,
turbulent eddies,
pessimistic trees,
and you!

Ankur Desai
University of Wisconsin-Madison

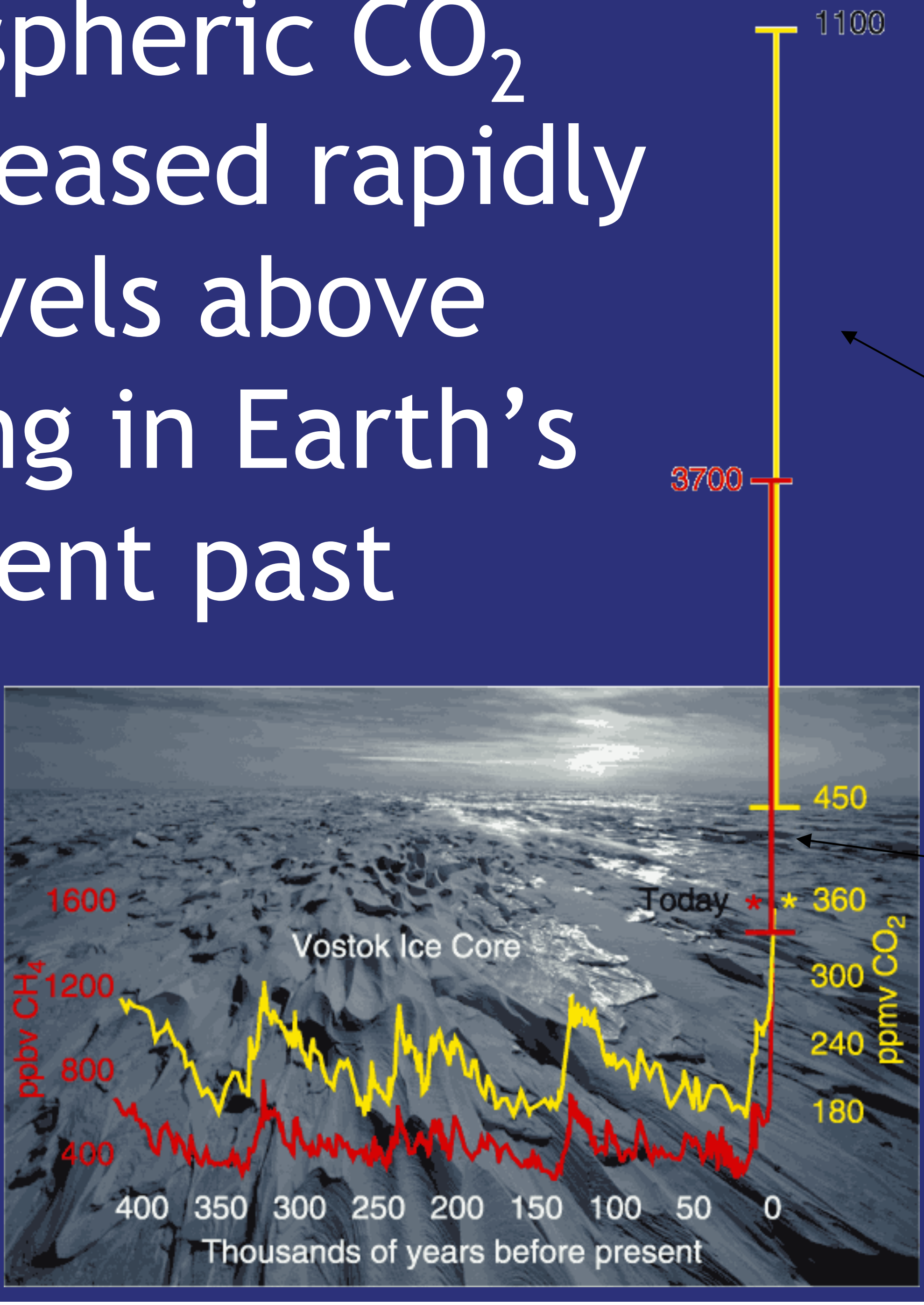
I. CARBON CYCLE





Depth (m)
0
500
1,000
1,500
2,000
2,500
2,750
3,000
3,200
3,300
CO$_2$ (p.p.m.v.)
280
260
240
220
200
Temperature (°C)
2
0
−2
−4
−6
−8
CH$_4$ (p.p.b.v.)
700
600
500
400
δ^{18}O$_{atm}$ (‰)
−0.5
0.0
0.5
1.0
Insolation J 65°N
100
50
0
−50
0
50,000
100,000
150,000
200,000
250,000
300,000
350,000
400,000
Age (yr BP)

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



2100?

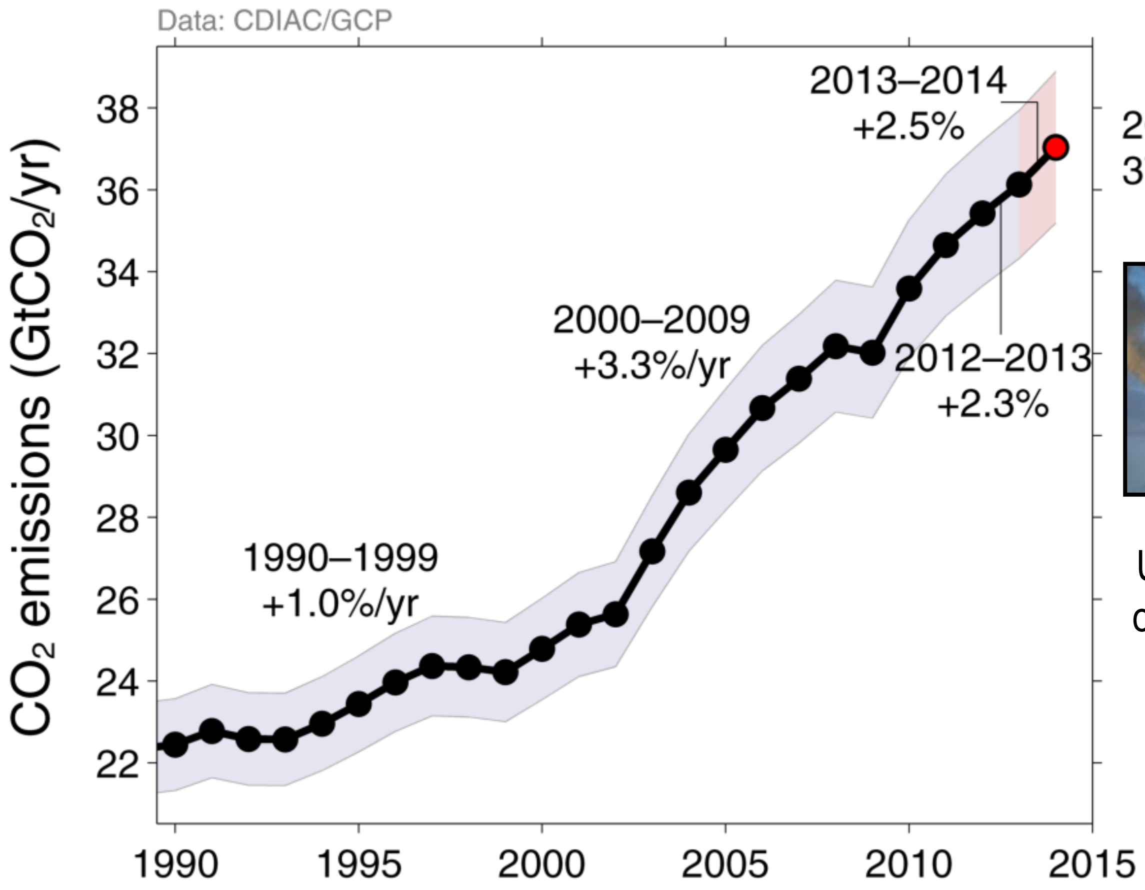
Today

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

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)

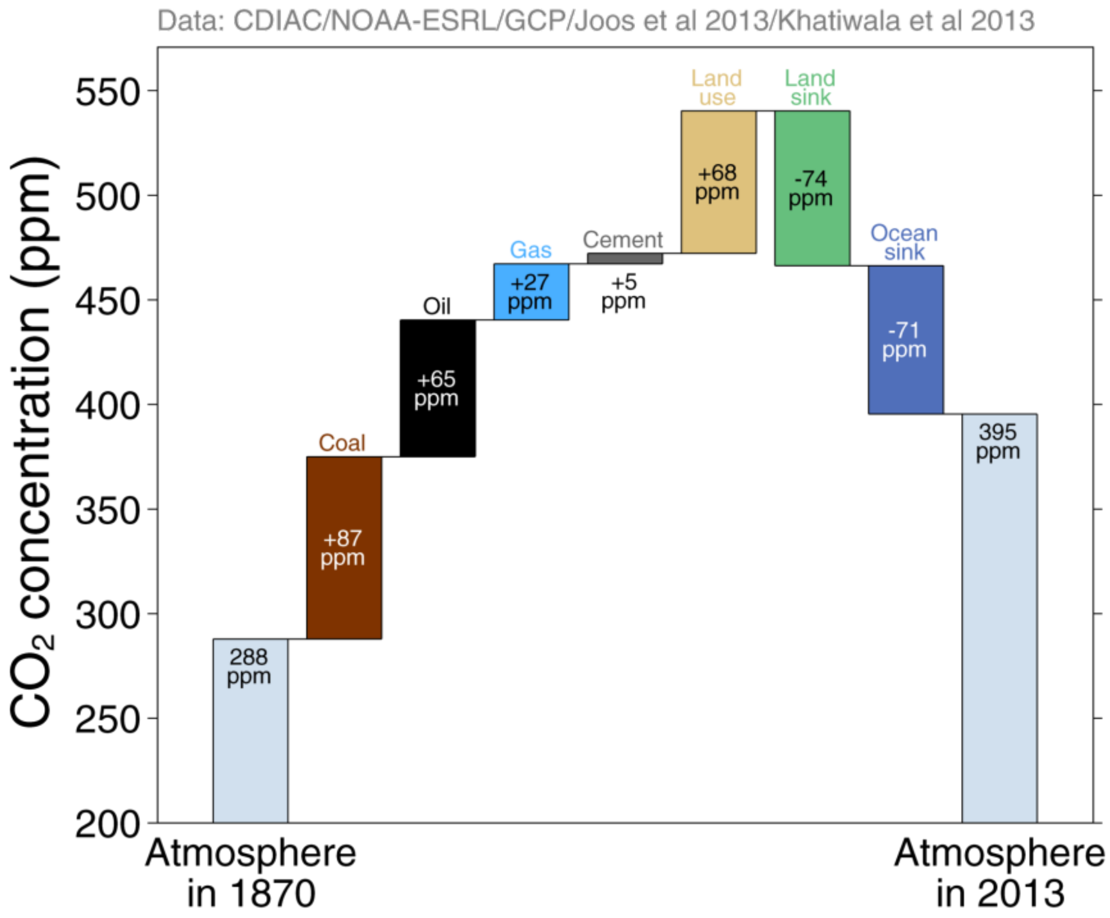


Figure concept from Shrink That Footprint

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

Fate of Anthropogenic CO$_2$ Emissions (2004-2013 average)

32.4±1.6 GtCO$_2$/yr 91%

3.3±1.8 GtCO$_2$/yr 9%

+

15.8±0.4 GtCO$_2$/yr
44%

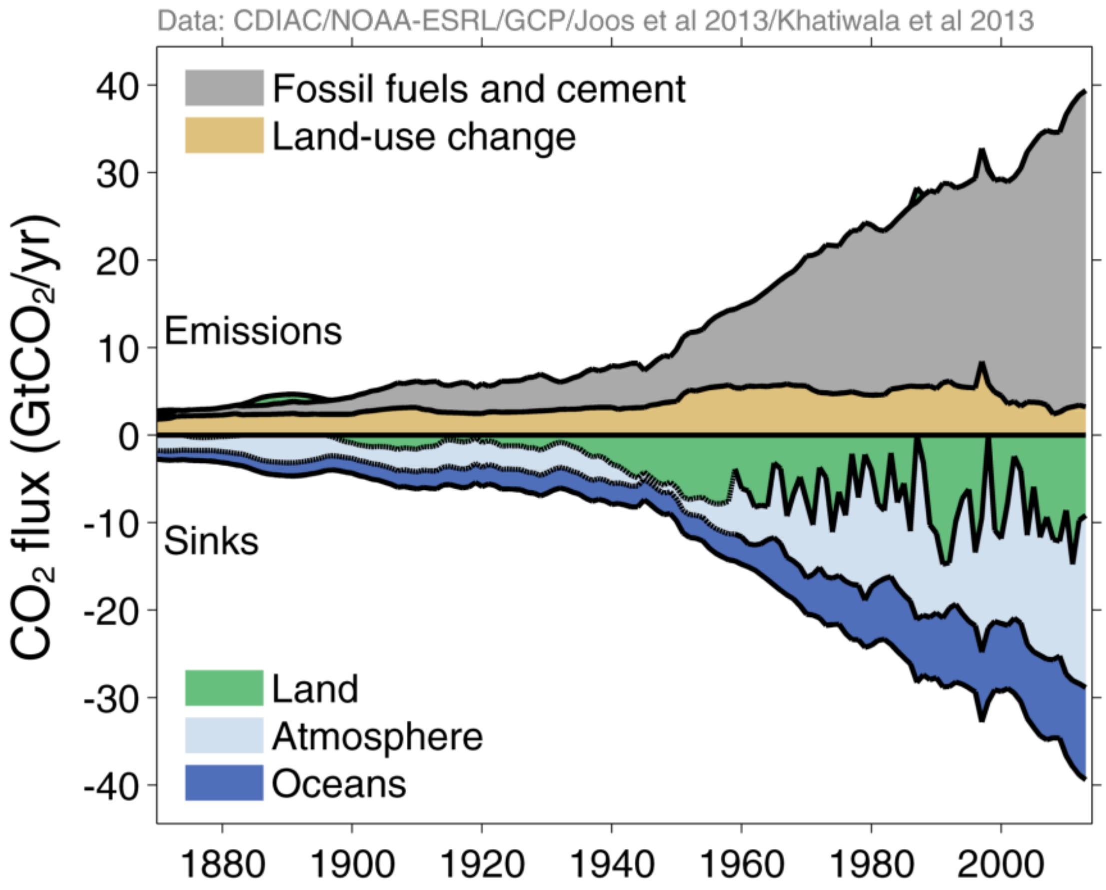
10.5±1.8 GtCO$_2$/yr
29%
Calculated as the residual
of all other flux components

26%
9.4±1.8 GtCO$_2$/yr

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

Global Carbon Budget

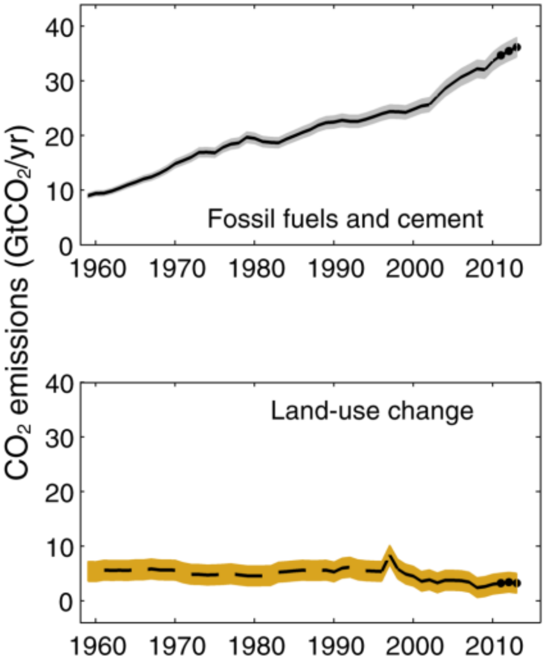
Emissions are partitioned between the atmosphere, land, and ocean

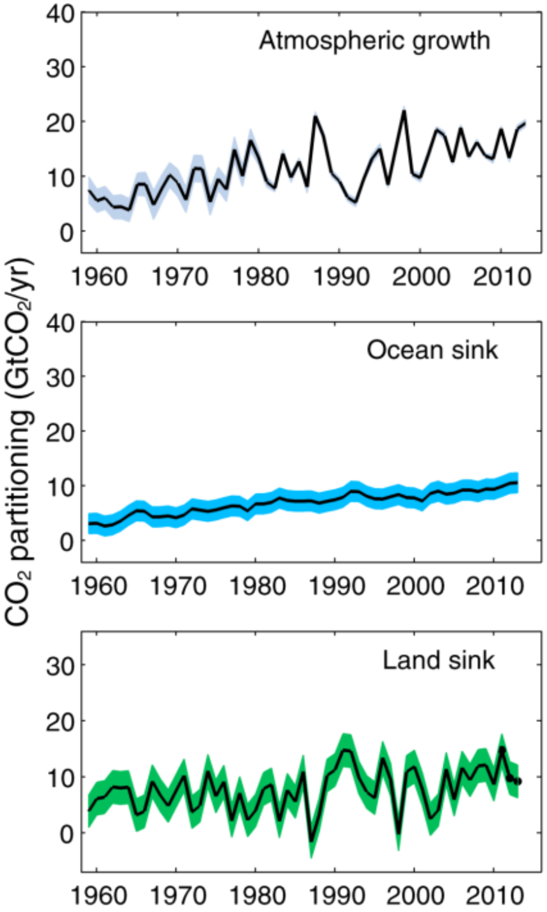


Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Joos et al 2013; Khatiwala et al 2013; Le Quéré et al 2014; Global Carbon Budget 2014

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



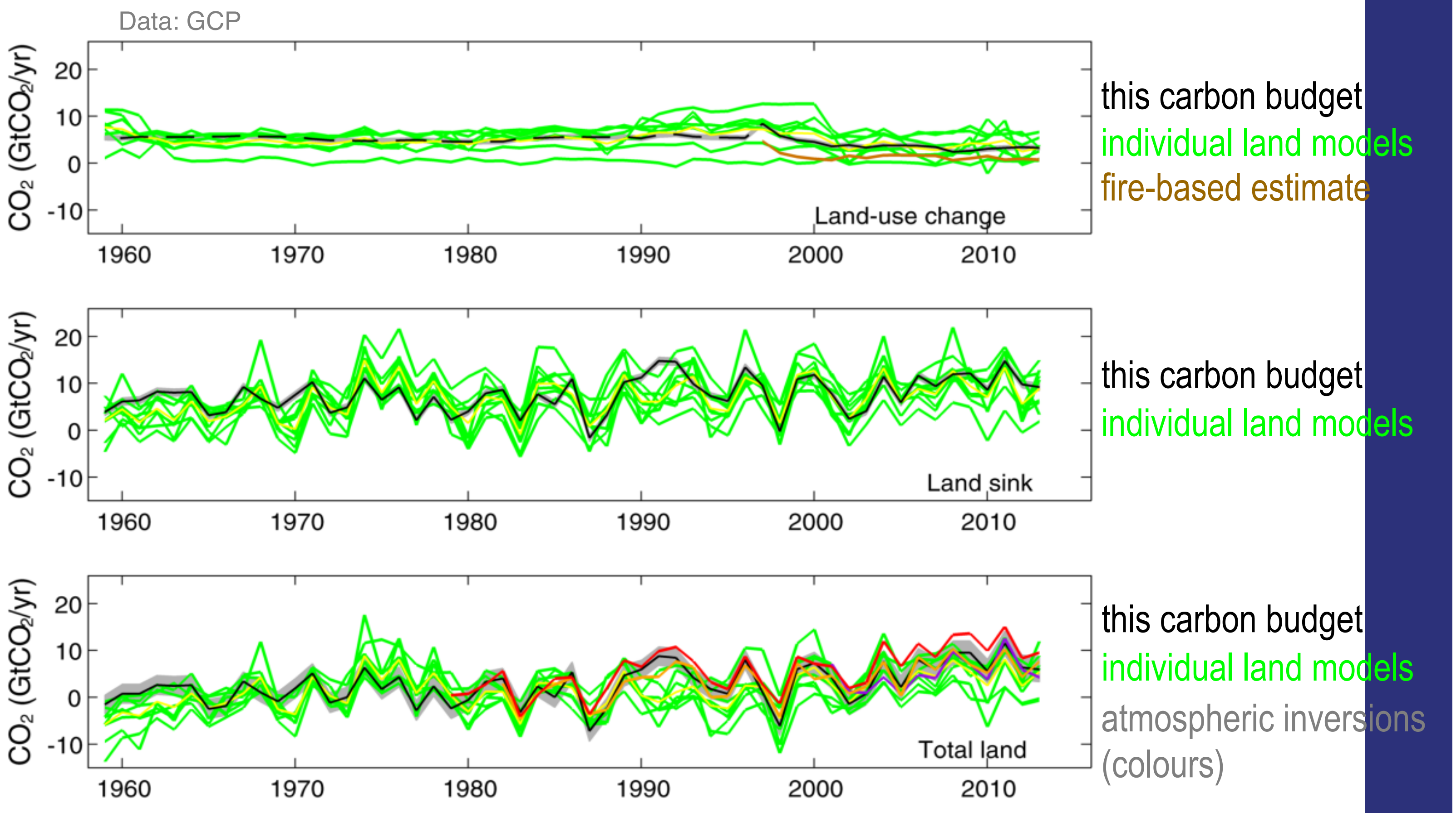


Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Le Quéré et al 2014; Global Carbon Budget 2014

GLOBAL CARBON PROJECT

Terrestrial Sink

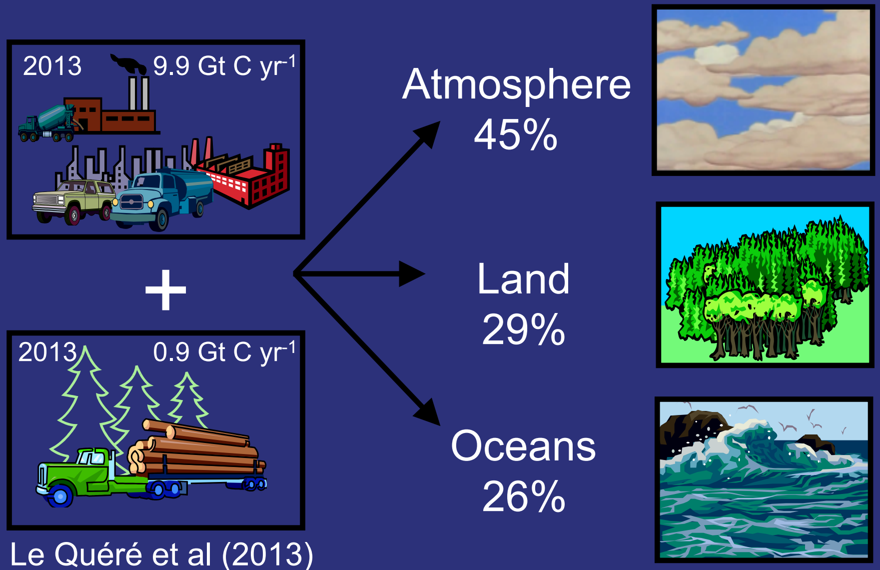
The residual land sink is increasing with time to 9.2±1.8 $GtCO_2$/yr in 2013, with large variability
Total CO_2 fluxes on land (including land-use change) are constrained by atmospheric inversions



Source: Le Quéré et al 2014; Global Carbon Project 2014

Individual estimates from Zhang et al. (2013); Oleson et al. (2013); Jain et al. (2013); Clarke et al. (2011); Smith et al. (2001); Sitch et al. (2003); Stocker et al. (2013); Krinner et al. (2005); Zeng et al. (2005); Kato et al. (2013); Peters et al. (2010); Rodenbeck et al. (2003); Chevallier et al. (2005). References provided in Le Quéré et al. (2014).

Terrestrial Biosphere CO_2 Flux Dominates Carbon Cycle Prediction Uncertainty



2013 9.9 Gt C yr^{-1}

\+

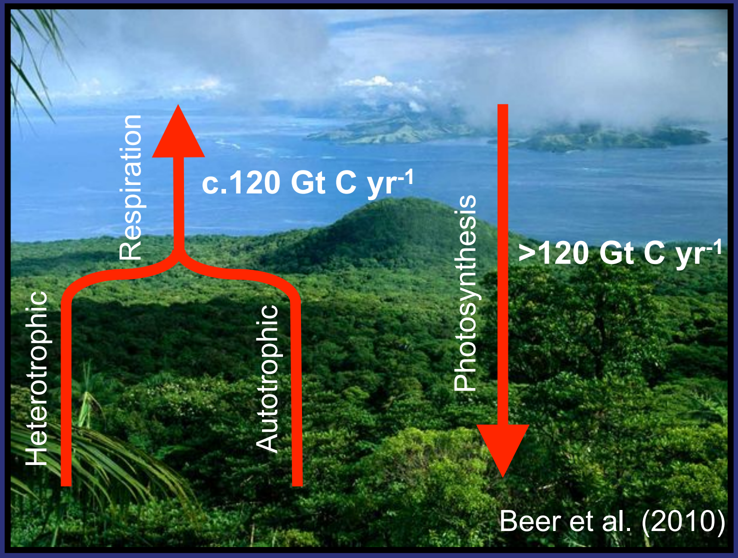
2013 0.9 Gt C yr^{-1}

Atmosphere 45%

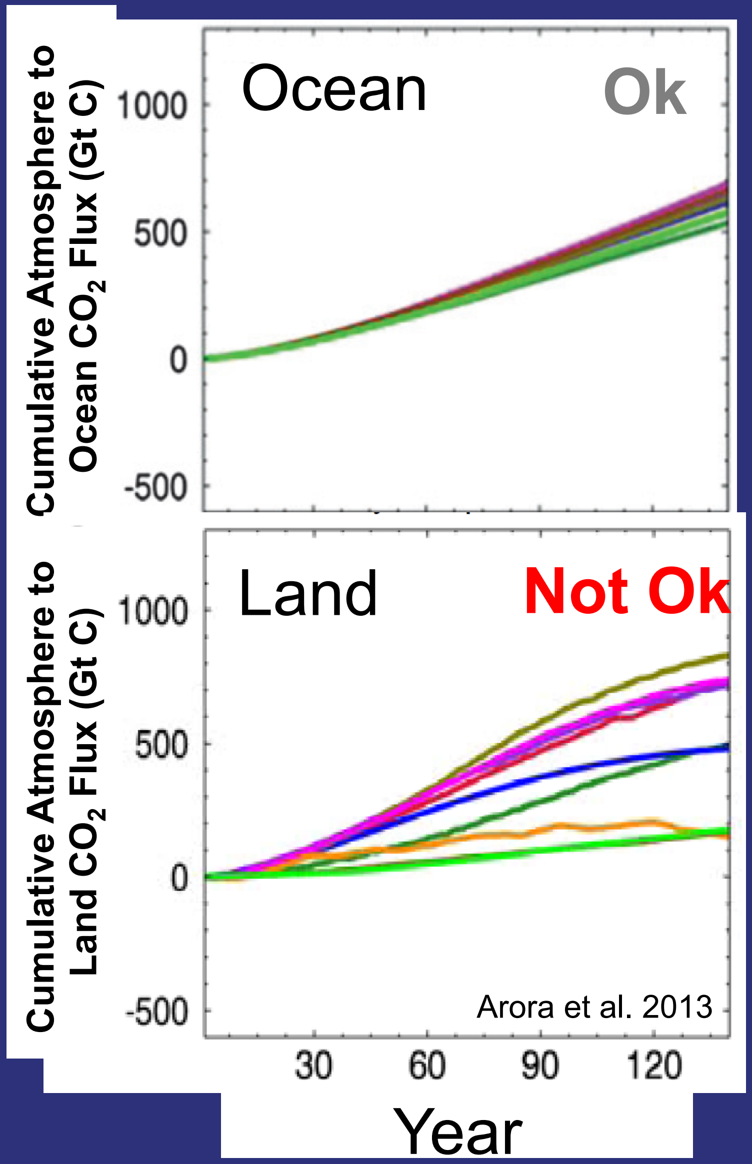
Land 29%

Oceans 26%

Le Quéré et al (2013)



Beer et al. (2010)

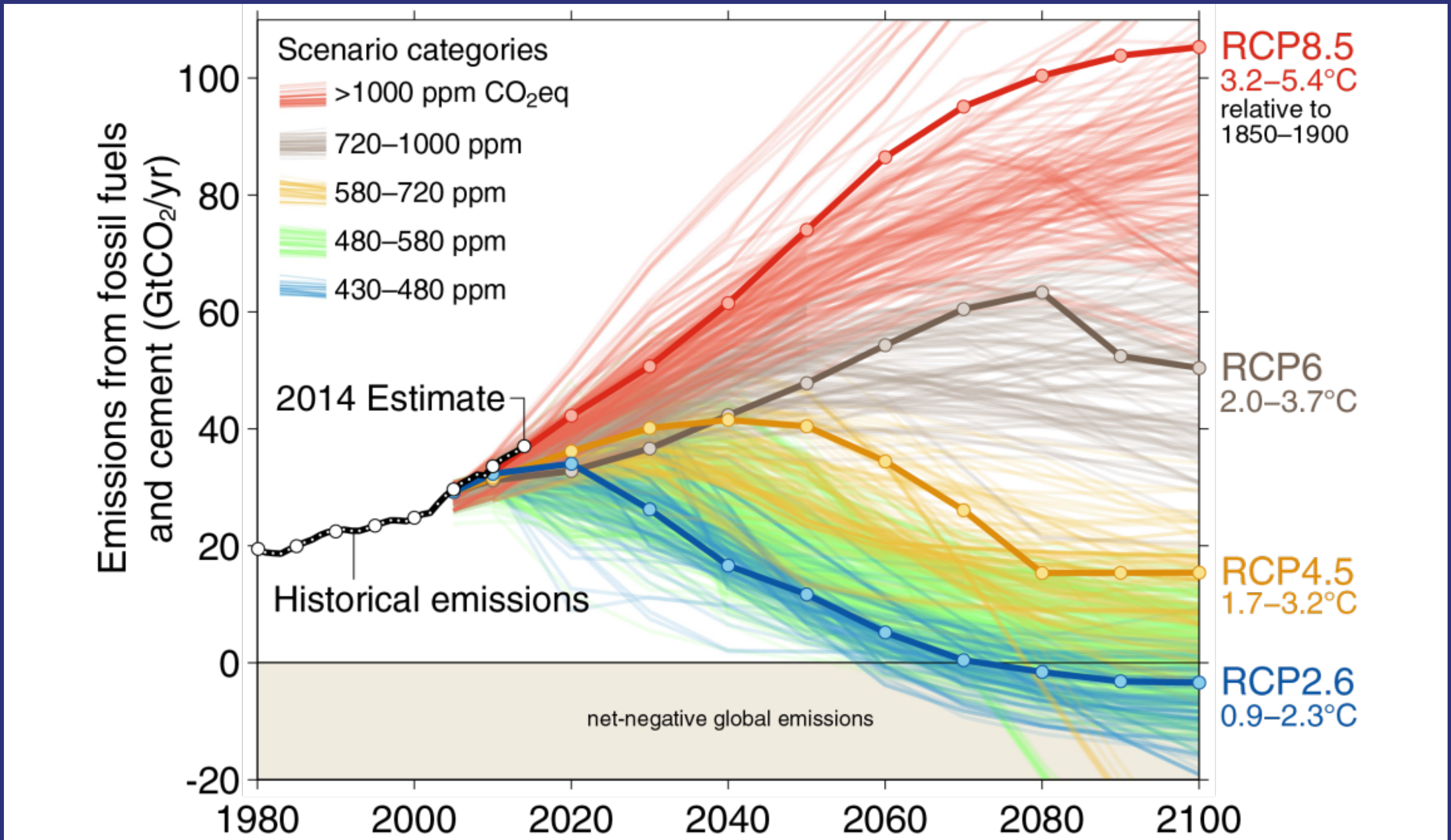


Arora et al. 2013

Observed Emissions and Emissions Scenarios

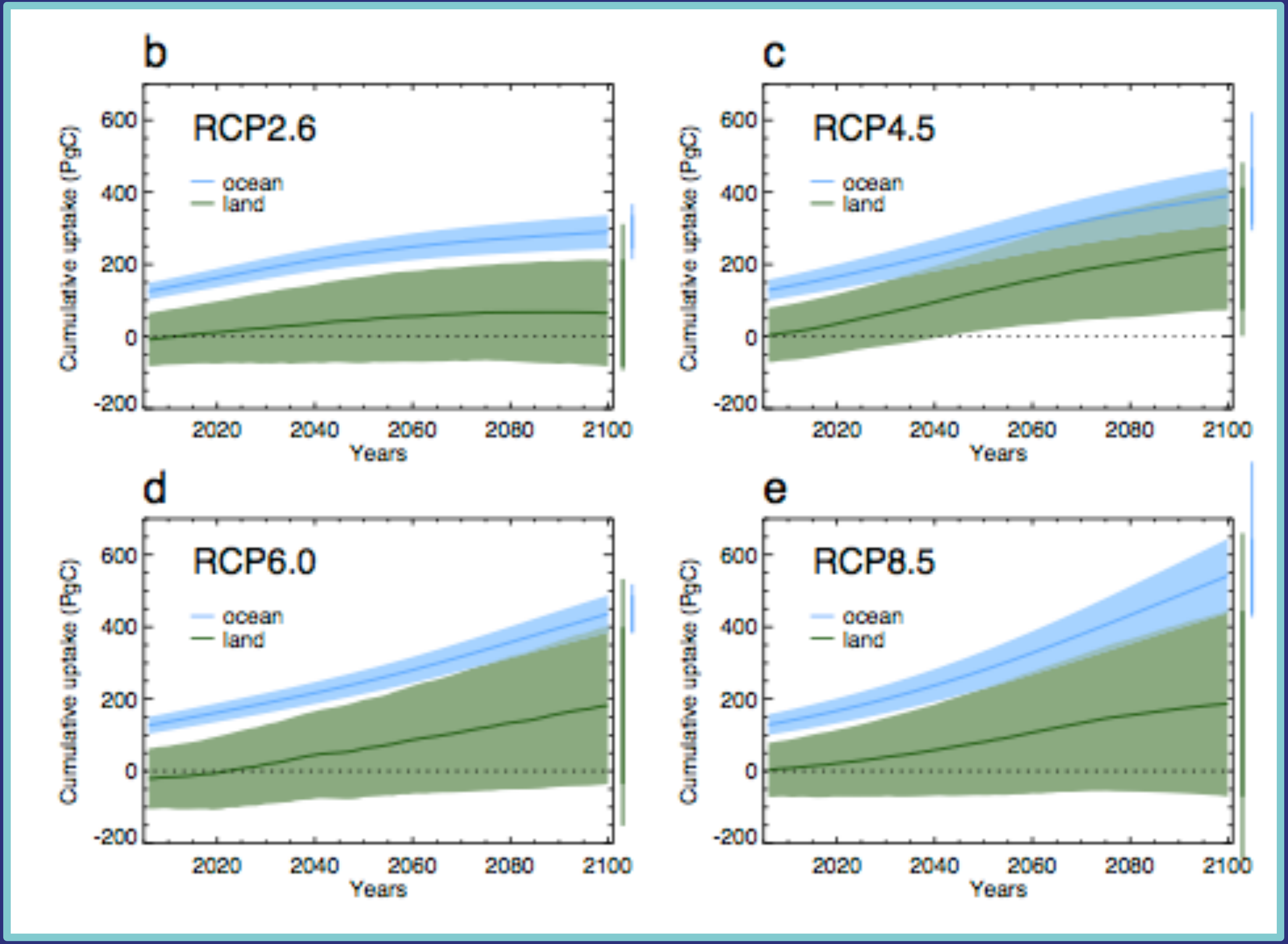
Emissions are on track for 3.2–5.4ºC “likely” increase in temperature above pre-industrial
Large and sustained mitigation is required to keep below 2ºC

Data: CDIAC/GCP/IPCC/Fuss et al 2014



Over 1000 scenarios from the IPCC Fifth Assessment Report are shown
Source: Fuss et al 2014; CDIAC; Global Carbon Budget 2014

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



IPCC AR5 WG1 CH6

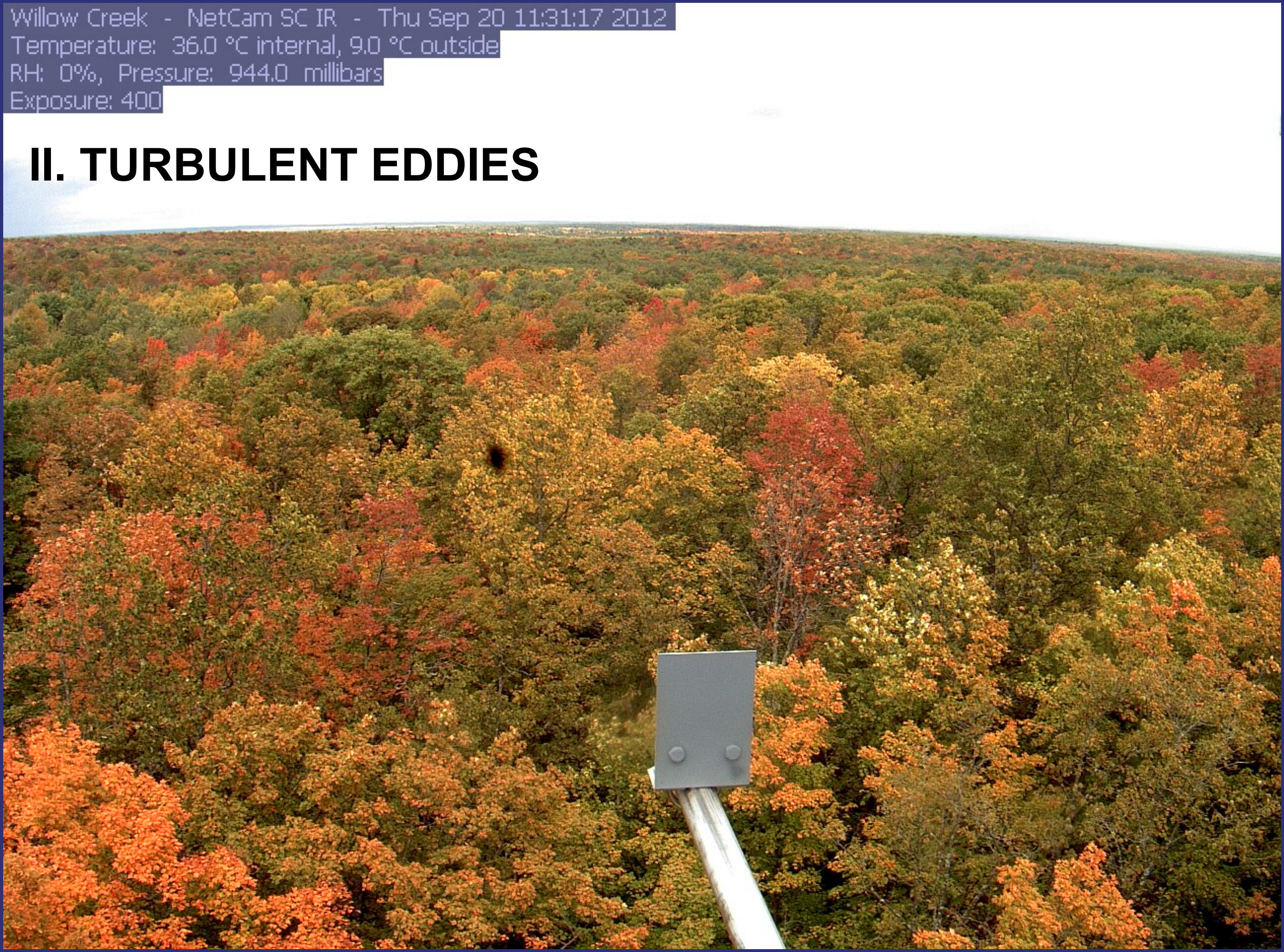
What do I (we) do?

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

II. TURBULENT EDDIES

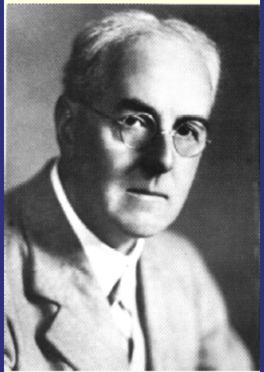


Eddy covariance is mature technology

B. Cook

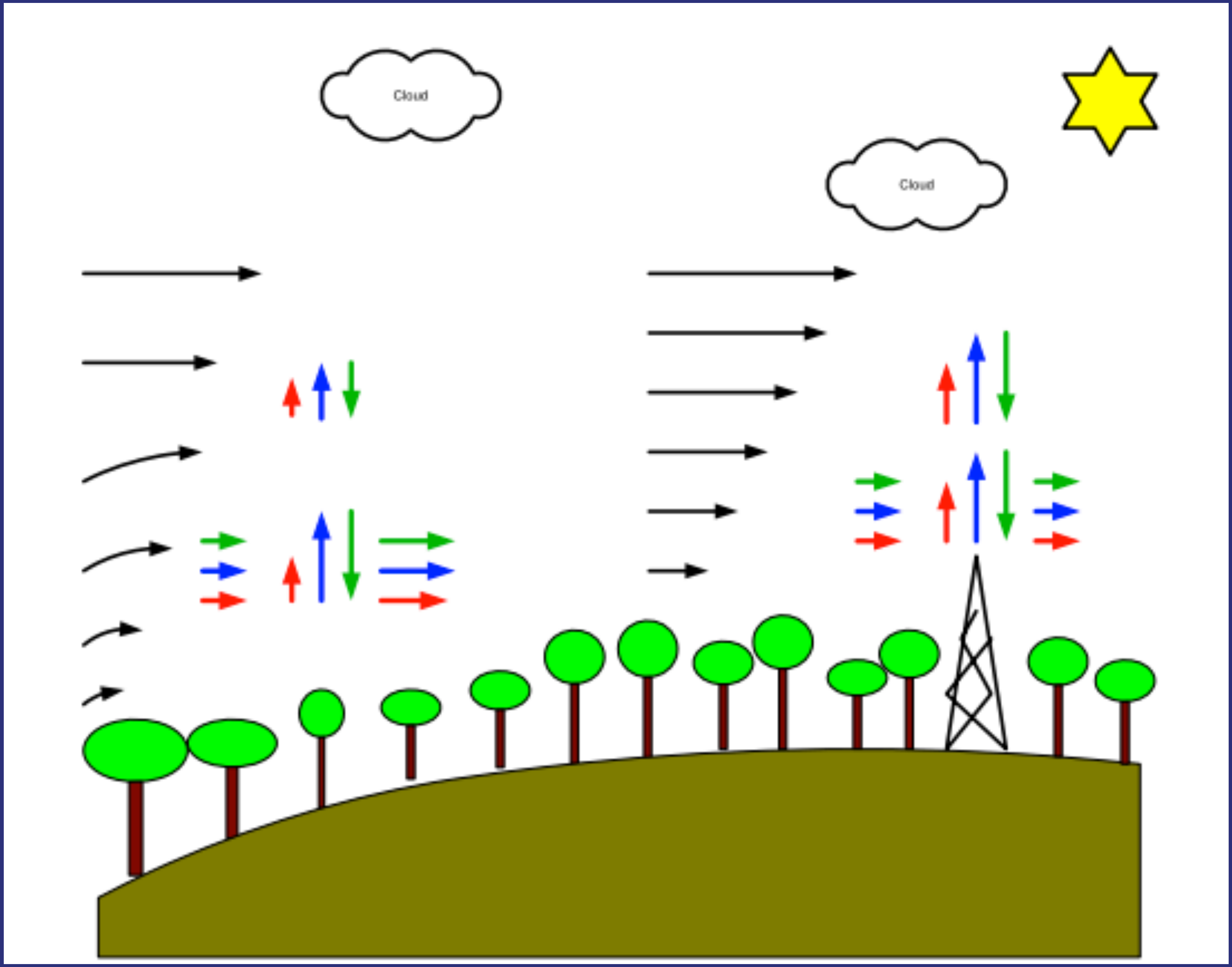


History


- 1880-1920s Turublence theory (Reynolds, Prandtl, Richardson, Taylor)
- 1940s-1950s Surface-layer theory (Monin-Obhukov, Kolmogorov), development of fast sensors for anemometry
- 1960s early measurements (Inoue, Wyngaard, Kaimal)
- 1970s forest fluxes (Raupach, Lenschow, Denmead)
- 1970s CO_2 fluxes (Desjardins, Leuning)
- 1980s Infrared gas analyzers (Verma, Anderson, Valentini)
- 1990s First long-term regional CO_2 flux networks (Wofsy, Baldocchi, Goulden, Law, Aubinet)
- 2000s Global syntheses (FLUXNET, Falge, Papale, Reichstein)
- 2010s Model-data integration, development of operational measurements (NEON, ICOS, you?)



D. Baldocchi

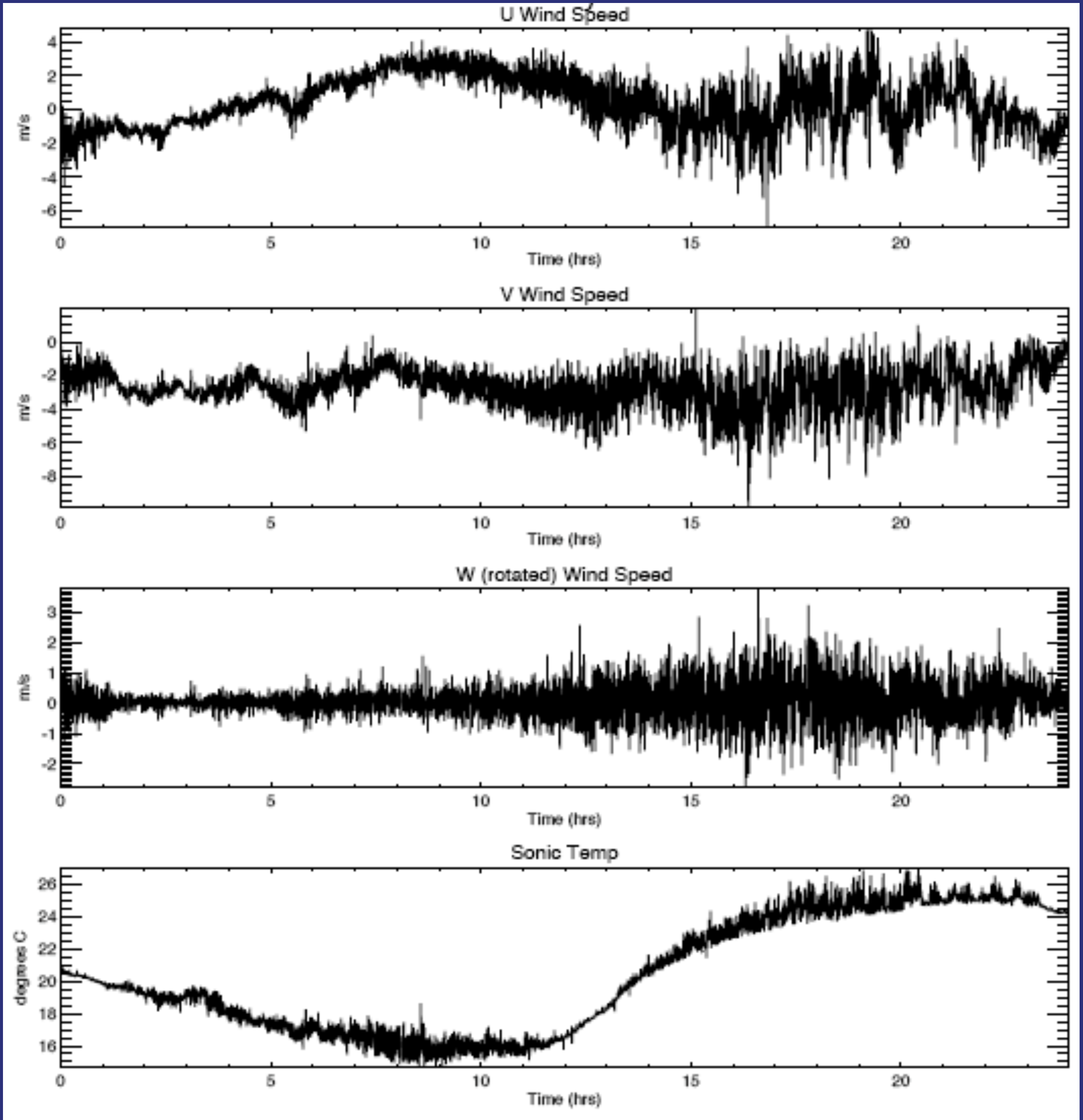
$$\overline{\frac{D\tilde{C}}{Dt}} = 0 \longrightarrow \overline{\frac{\partial \tilde{C}}{\partial t} + \tilde{U}_j \frac{\partial \tilde{C}}{\partial x}} = 0$$

STORAGE TURBULENT-FLUX

$$\begin{aligned} \mathrm{NEE} &\equiv \int_0^{z_r} s\,\mathrm{d}z + \left(\overline{w'c'}\right)\Big|_{z=0} \\ &= \int_0^{z_r} \frac{\partial \bar{c}}{\partial t}\,\mathrm{d}z + \left(\overline{w'c'}\right)_r + \cancel{\bar{w}_r\left(\bar{c}_r - \langle \bar{c} \rangle\right)} \end{aligned} \tag{4}$$

$$\frac{\partial \bar{C}}{\partial t} + \frac{\partial \overline{c'}}{\partial t} + \overline{\bar{U}_j \frac{\partial \bar{C}}{\partial x_j}} + \overline{u_j' \frac{\partial \bar{C}}{\partial x_j}} + \overline{\bar{U}_j \frac{\partial c'}{\partial x_j}} + \overline{u_j' \frac{\partial c'}{\partial x_j}} = 0$$

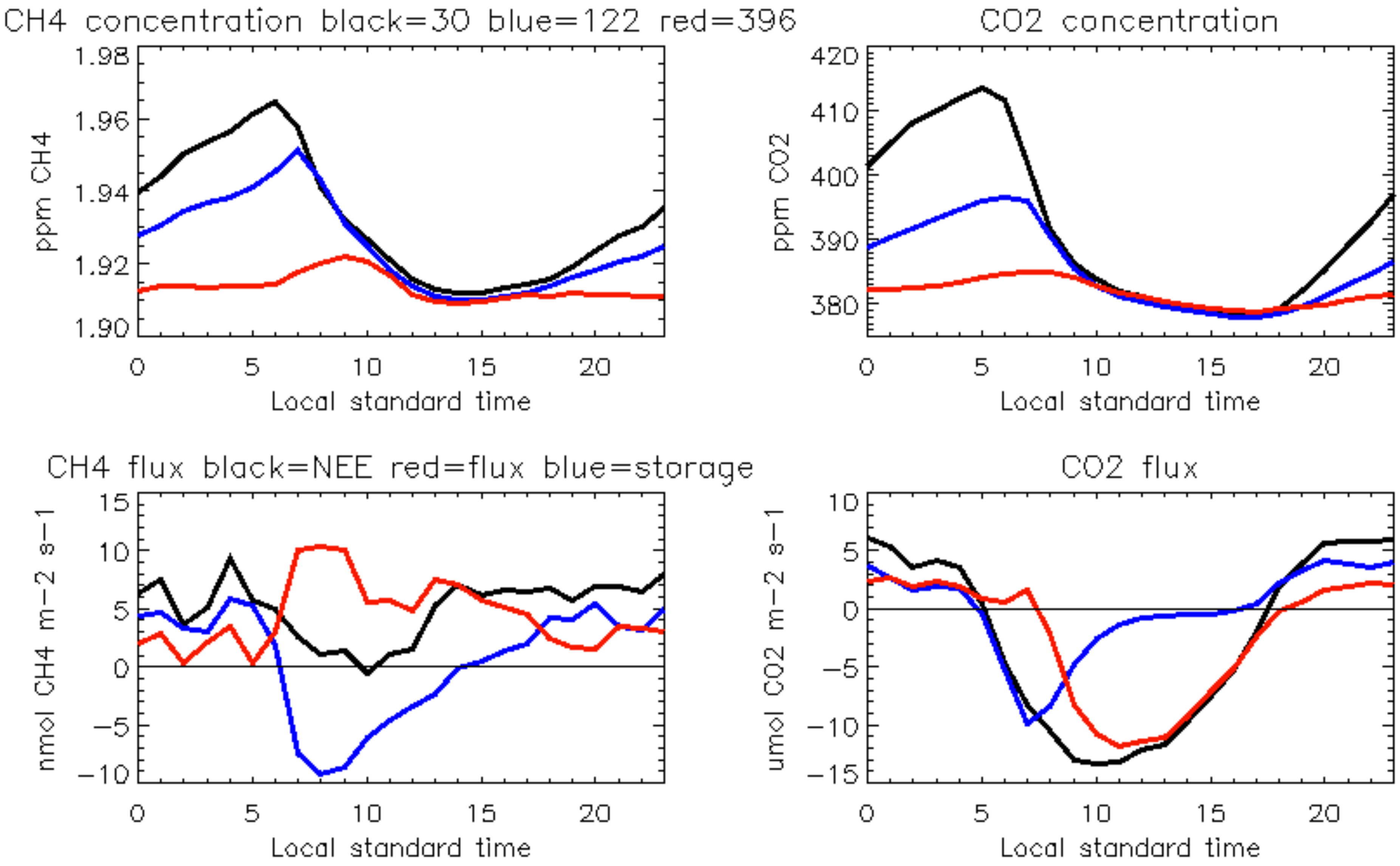
$$\frac{\partial \bar{C}}{\partial t} + \bar{U}_j \frac{\partial \bar{C}}{\partial x_j} + \overline{u_j' \frac{\partial c'}{\partial x_j}} = \boxed{\frac{\partial \bar{C}}{\partial t} + \frac{\partial \overline{U_j C}}{\partial x_j} + \frac{\partial \overline{u_j' c'}}{\partial x_j} = 0}$$

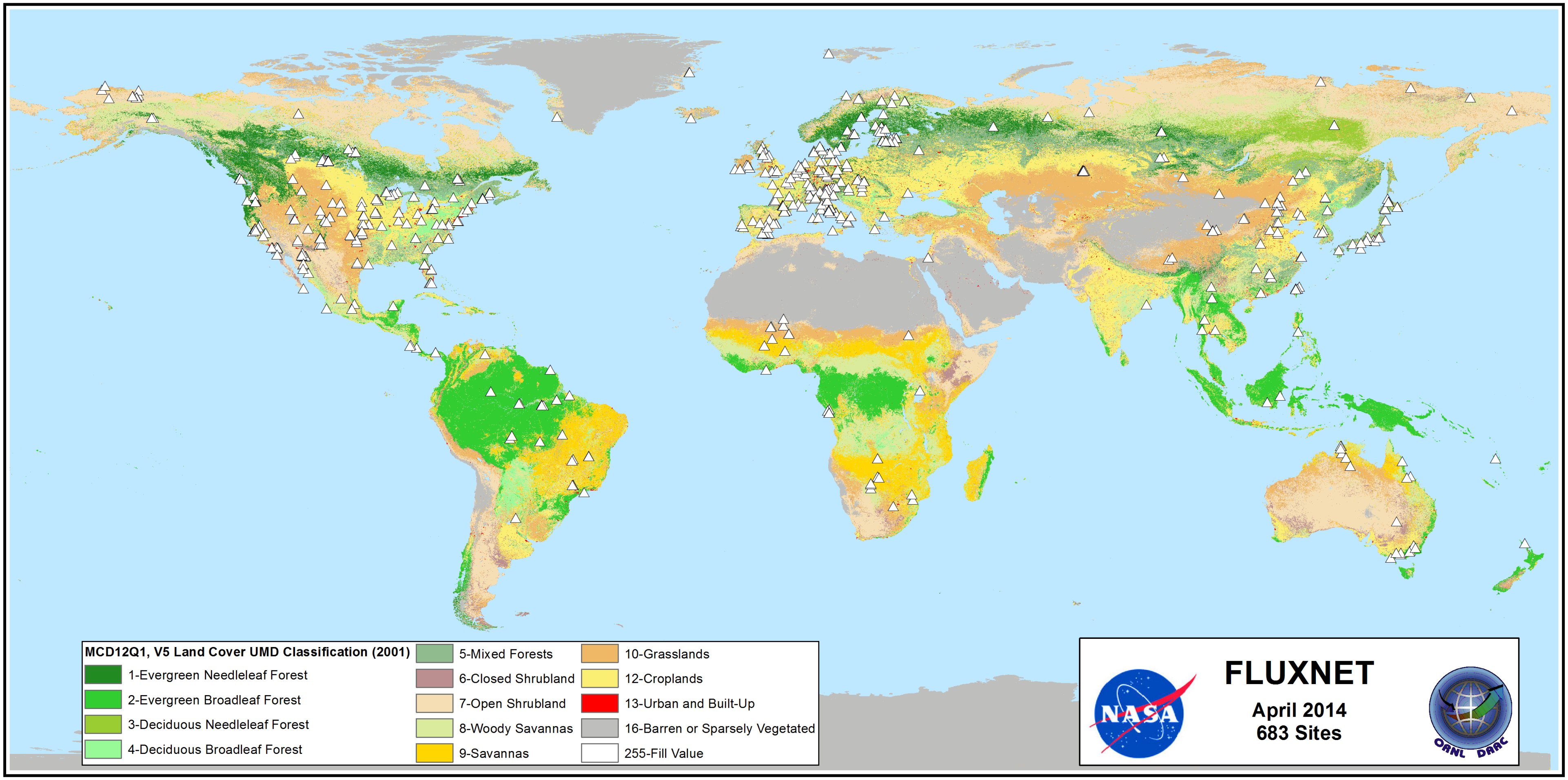

U Wind Speed

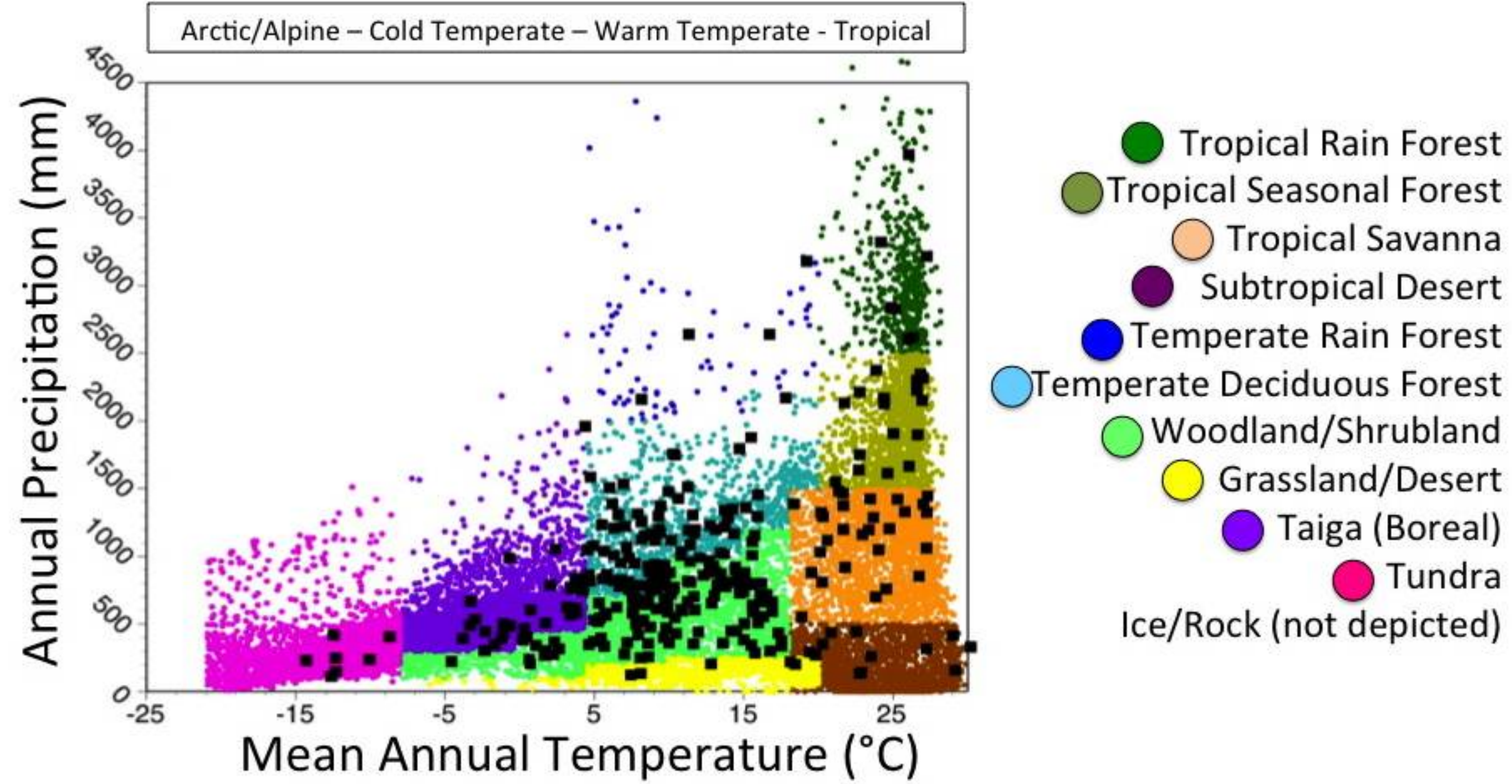
V Wind Speed

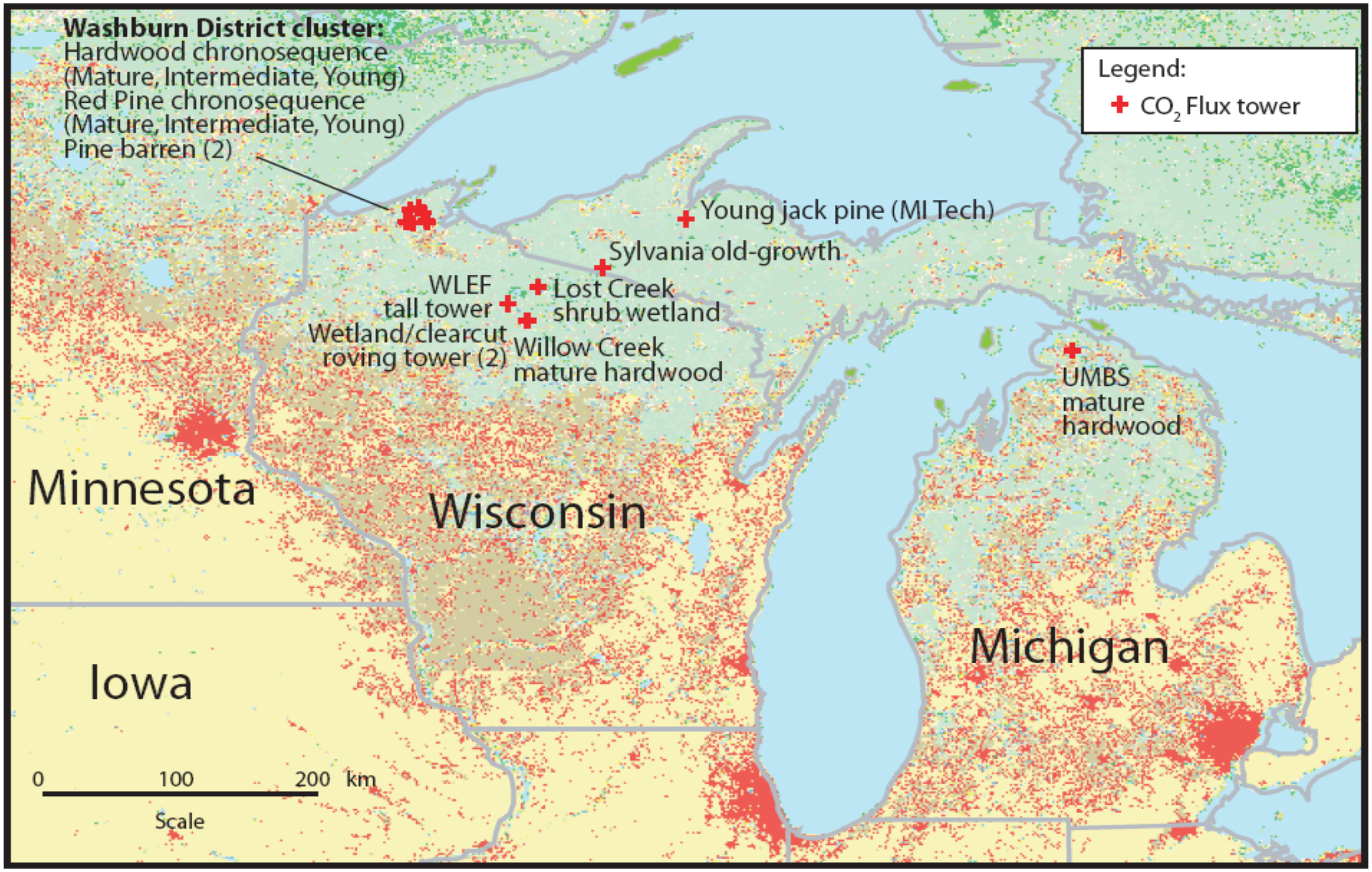
W (rotated) Wind Speed

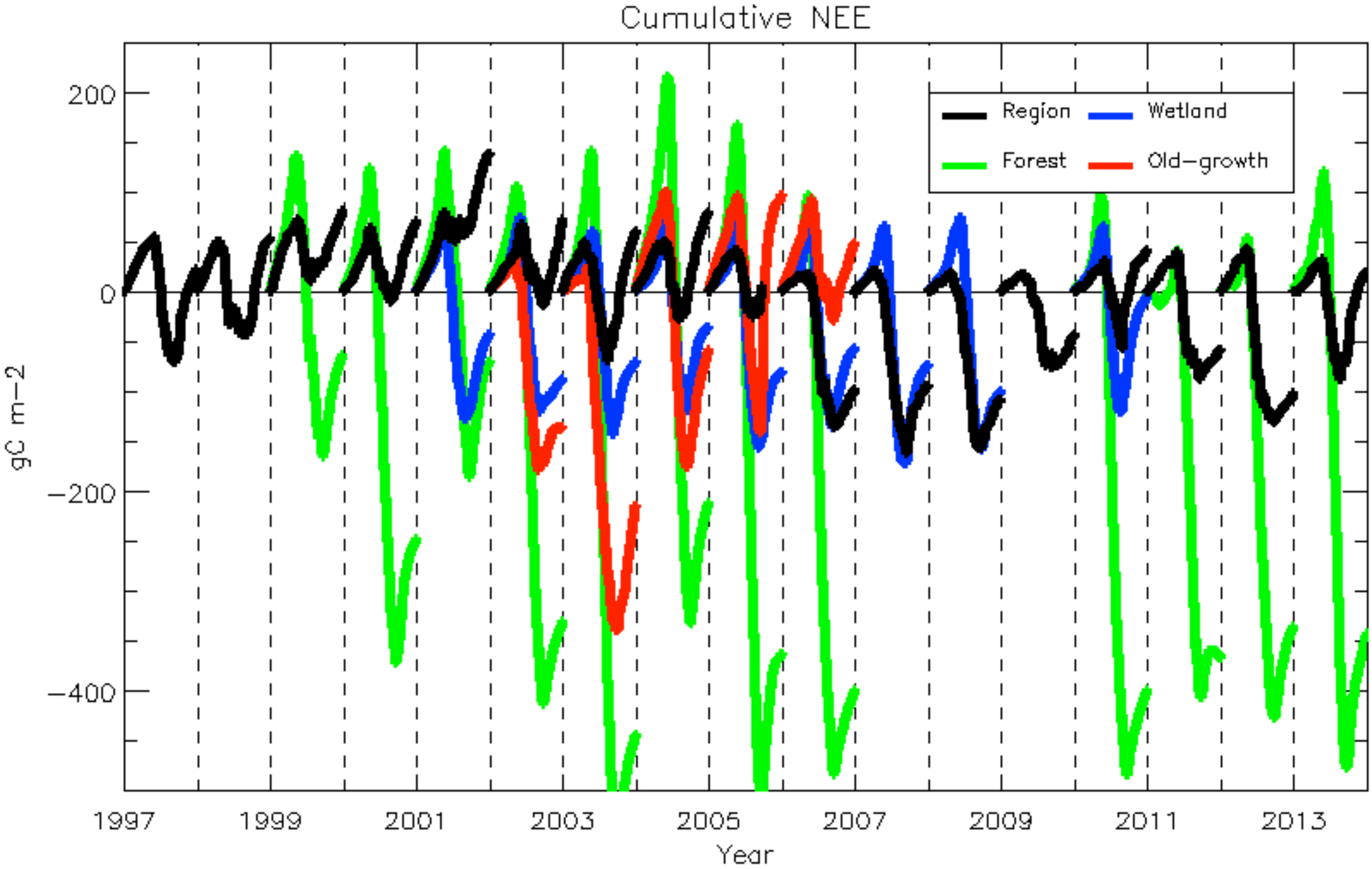
Sonic Temp


CH4 concentration black=30 blue=122 red=396
ppm CH4
1.98
1.96
1.94
1.92
1.90
0
5
10
15
20
Local standard time
CO2 concentration
ppm CO2
420
410
400
390
380
0
5
10
15
20
Local standard time
CH4 flux black=NEE red=flux blue=storage
nmol CH4 m−2 s−1
15
10
5
0
−5
−10
0
5
10
15
20
Local standard time
CO2 flux
umol CO2 m−2 s−1
10
5
0
−5
−10
−15
0
5
10
15
20
Local standard time

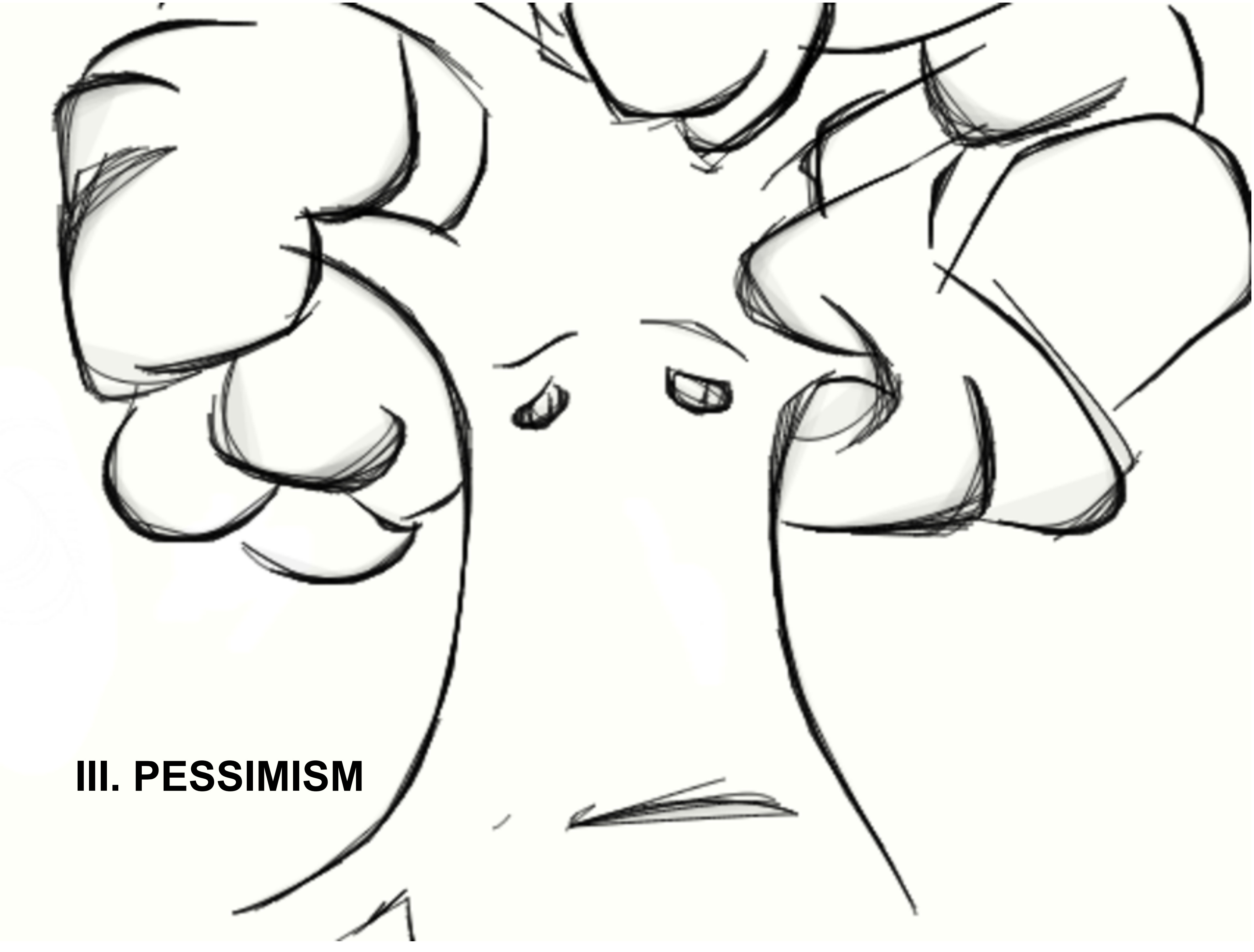

MCD12Q1, V5 Land Cover UMD Classification (2001)
1-Evergreen Needleleaf Forest
2-Evergreen Broadleaf Forest
3-Deciduous Needleleaf Forest
4-Deciduous Broadleaf Forest
5-Mixed Forests
6-Closed Shrubland
7-Open Shrubland
8-Woody Savannas
9-Savannas
10-Grasslands
12-Croplands
13-Urban and Built-Up
16-Barren or Sparsely Vegetated
255-Fill Value
NASA
FLUXNET
April 2014
683 Sites
ORNL DAAC

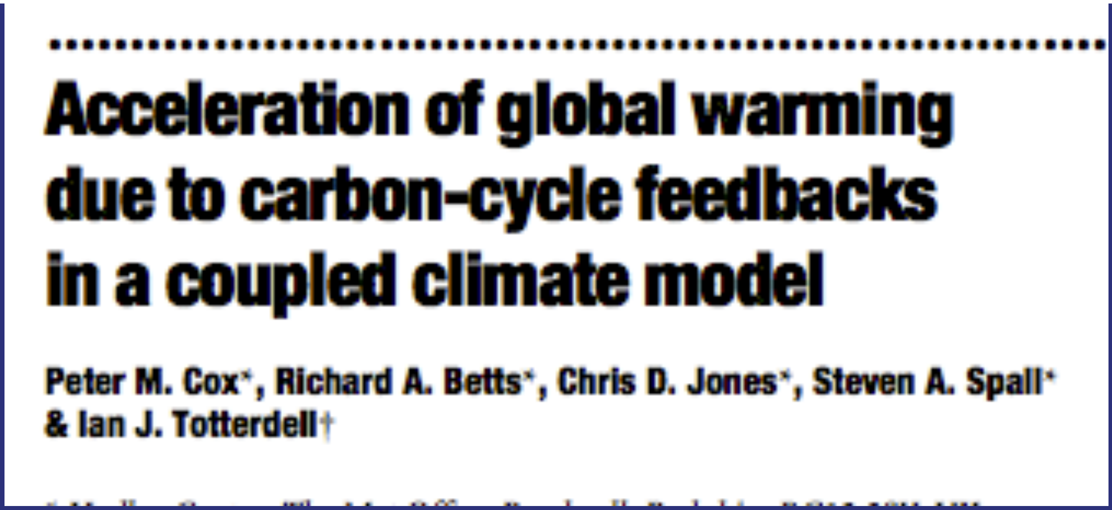

Arctic/Alpine – Cold Temperate – Warm Temperate - Tropical
Annual Precipitation (mm)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-25
-15
-5
5
15
25
Mean Annual Temperature (°C)
Tropical Rain Forest
Tropical Seasonal Forest
Tropical Savanna
Subtropical Desert
Temperate Rain Forest
Temperate Deciduous 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


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

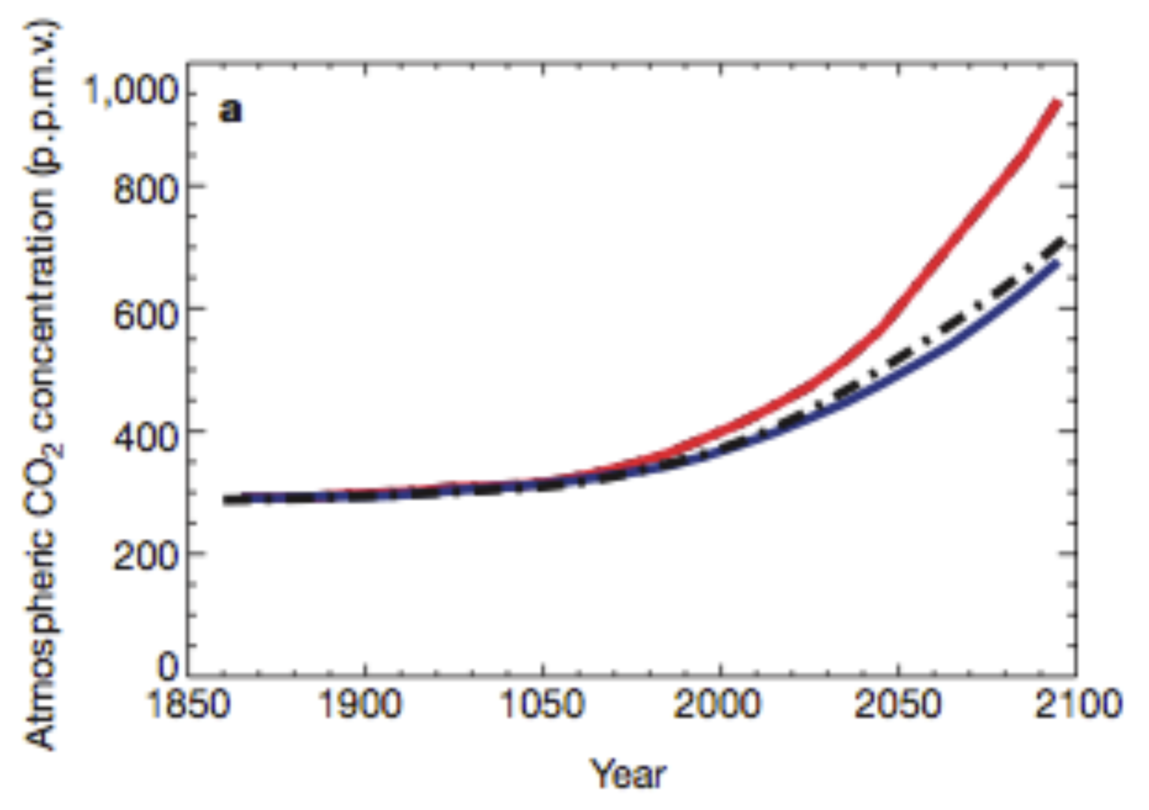
III. PESSIMISM



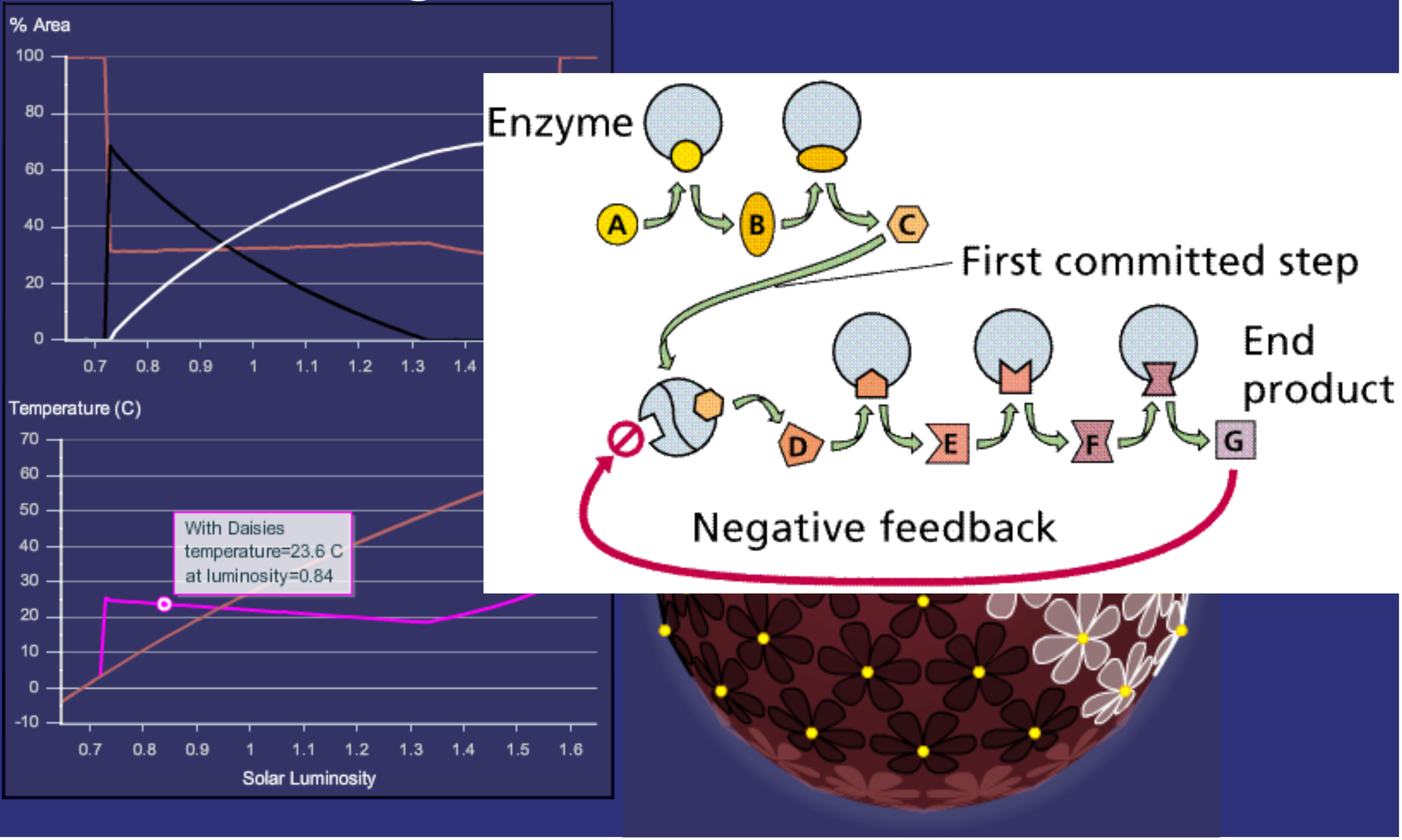


Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model

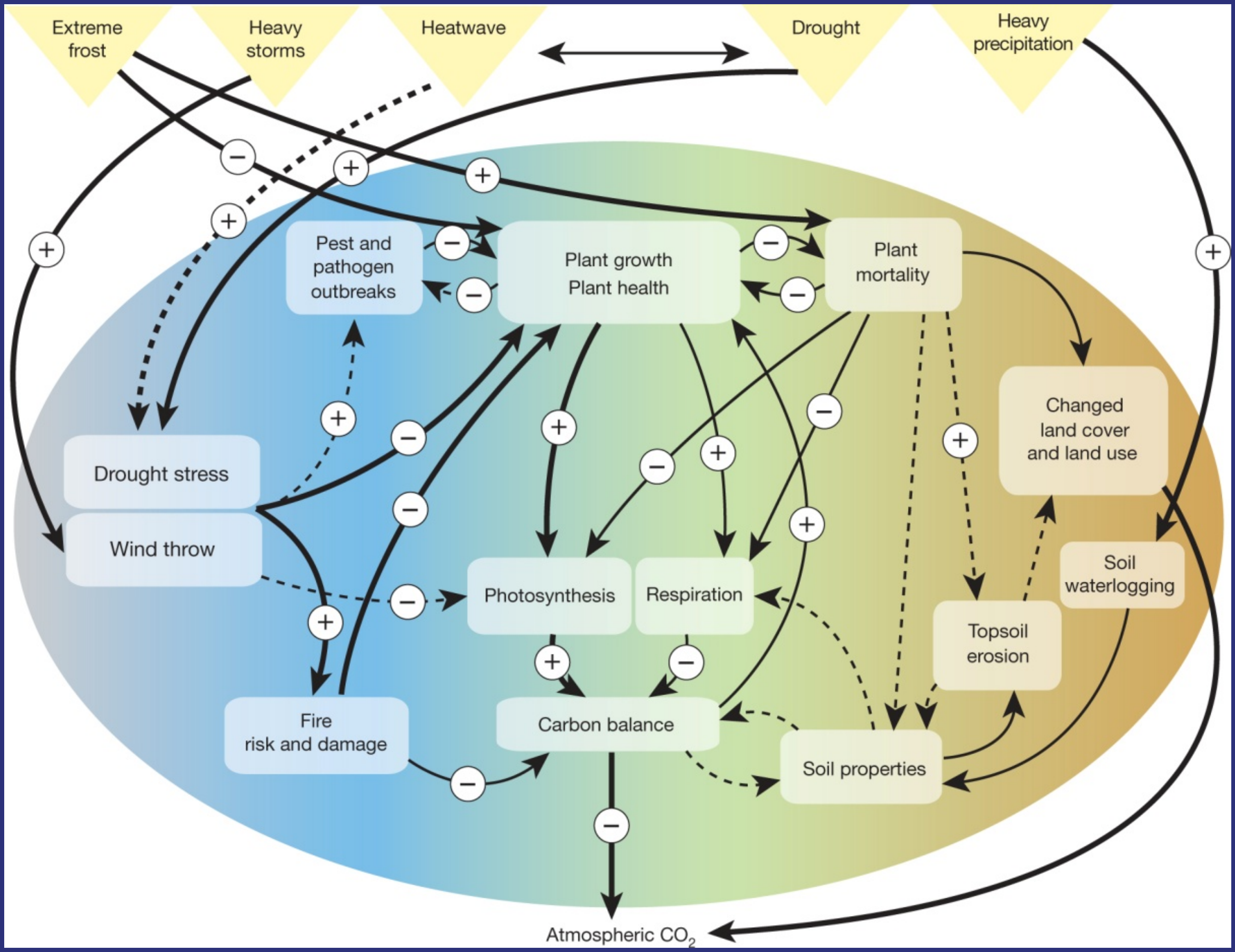
Peter M. Cox*, Richard A. Betts*, Chris D. Jones*, Steven A. Spall*
& Ian J. Totterdell†



Negative Feedbacks



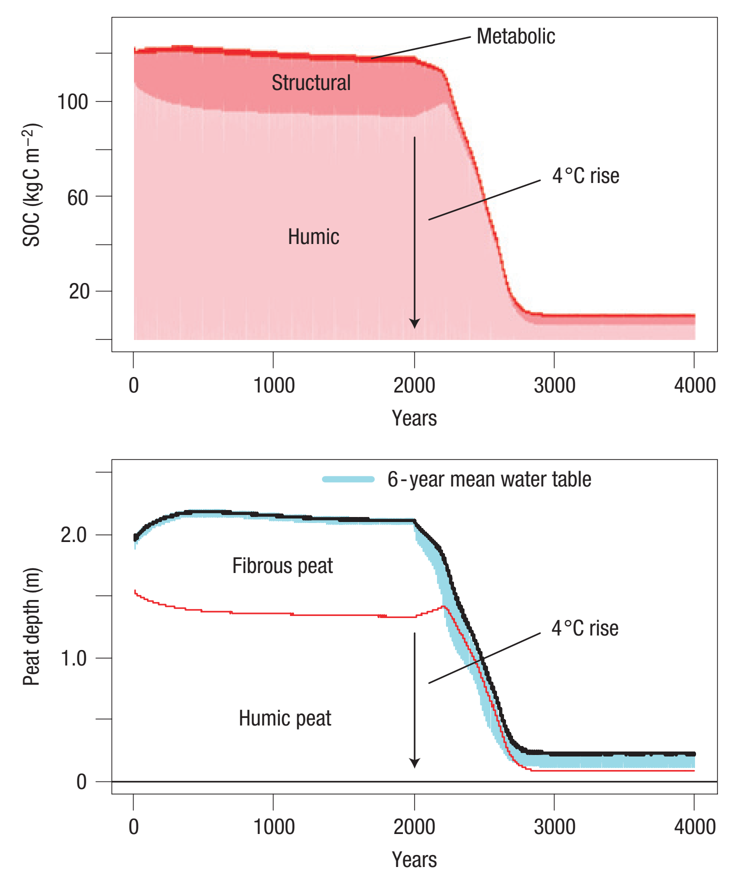
Processes and feedbacks triggered by extreme climate events?



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

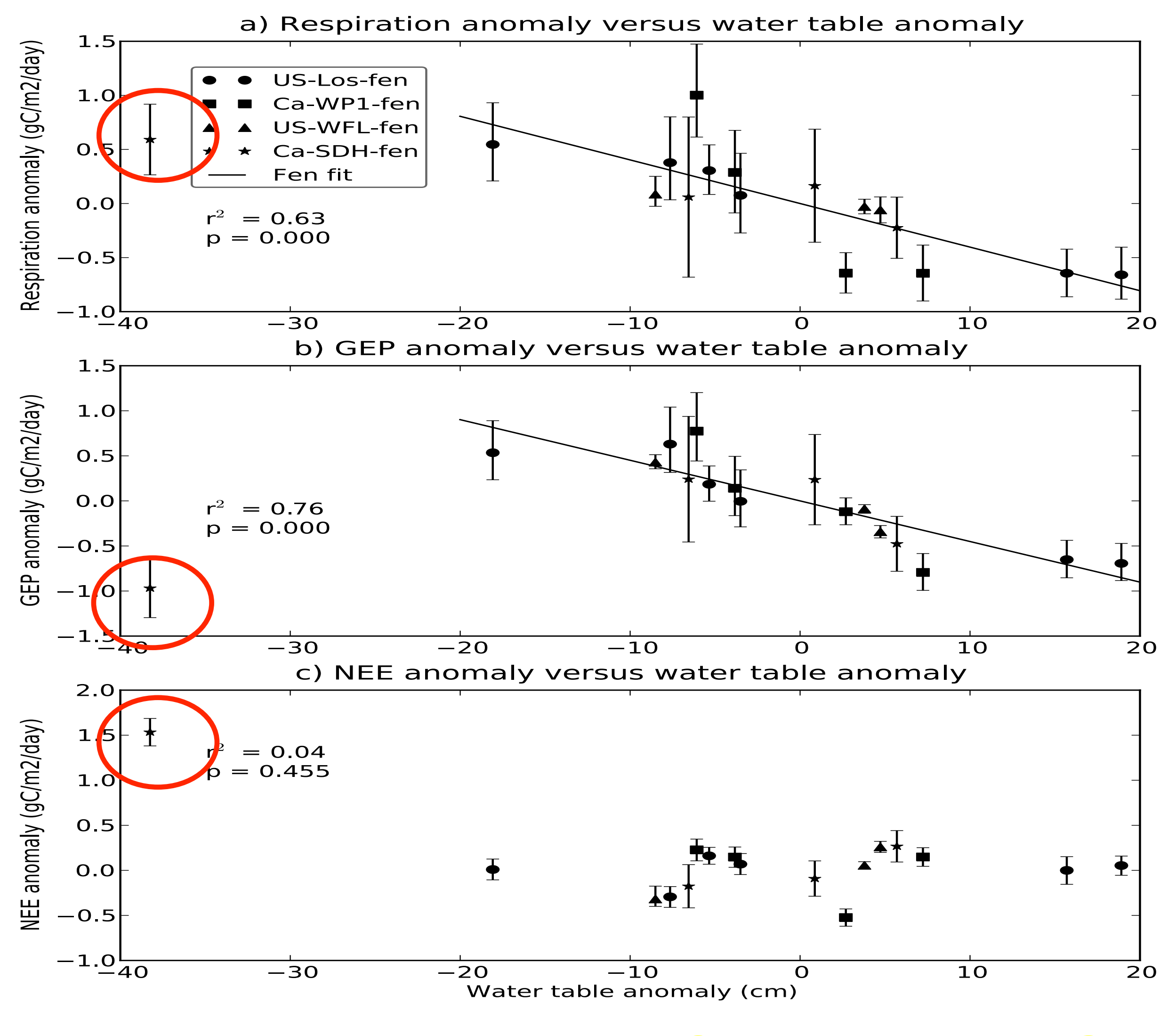
Peatland carbon is vulnerable to climate and hydrological change

- Peat carbon is preserved by cool temperatures and flooded conditions
- Warming and drying can disrupt the process and lead to carbon loss



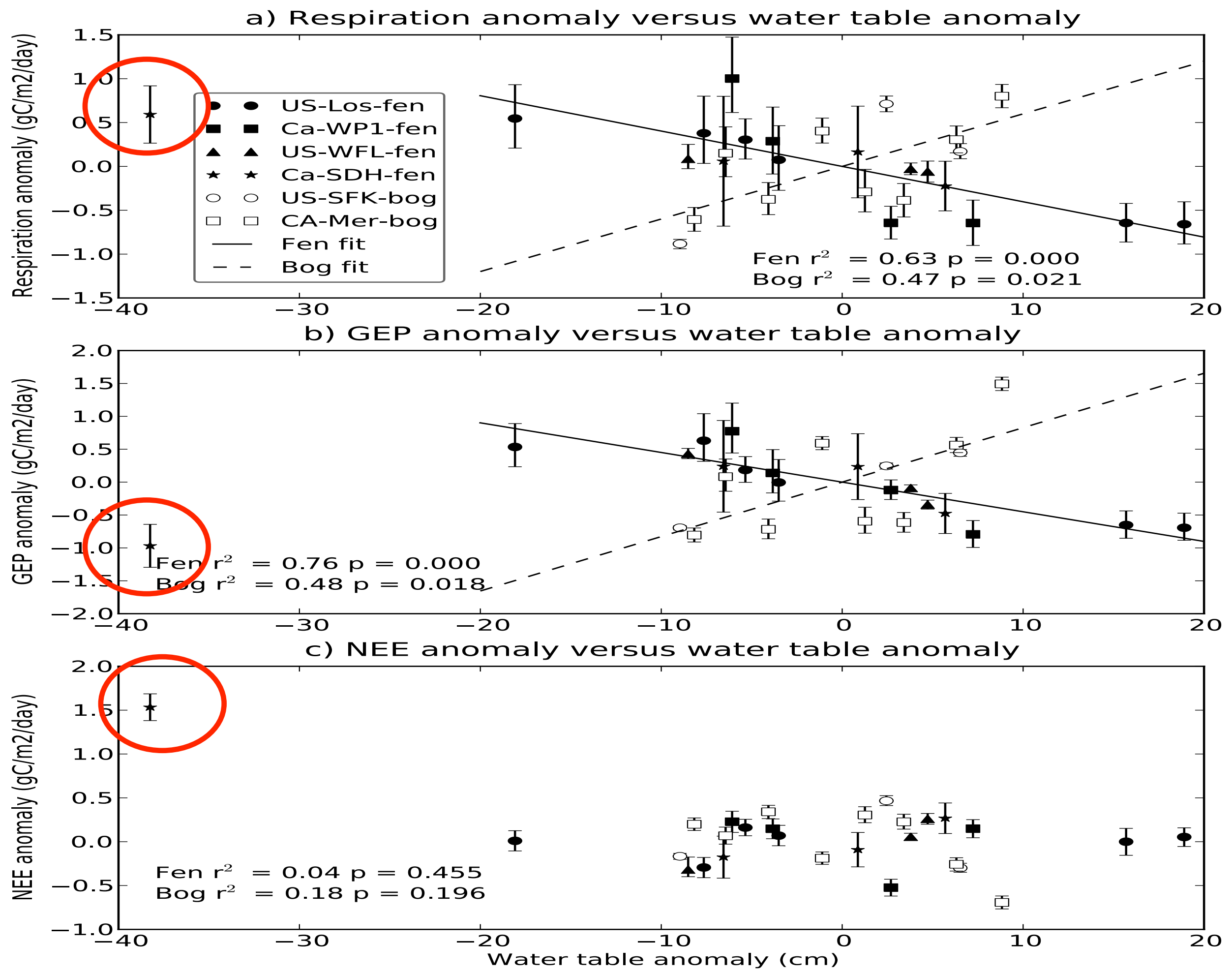
Ise et al 2008

Hydrology does not drive NEE in four fens



Sulman et al., GRL, 2010

Same for bogs, but in a different way



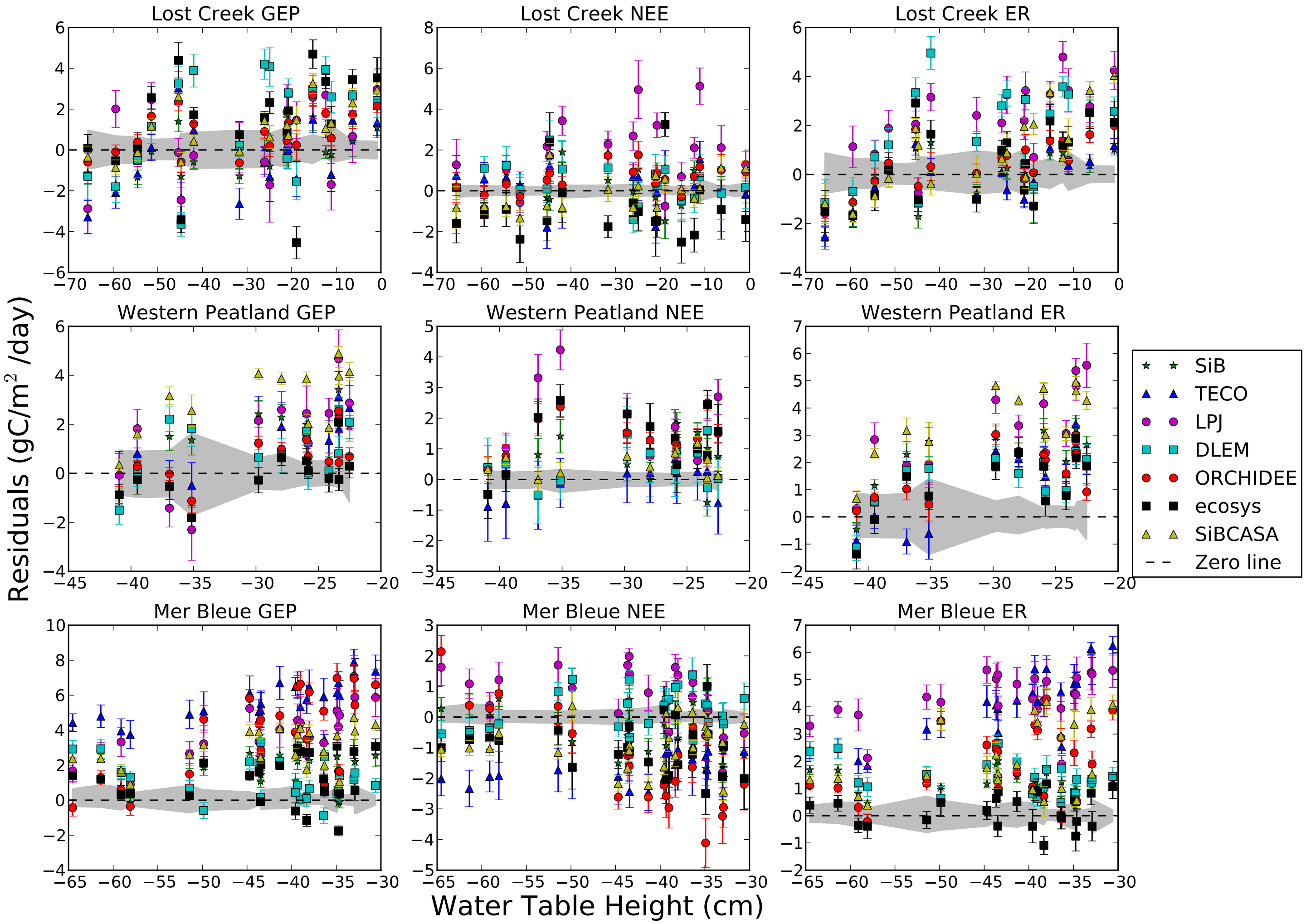
Sulman et al., GRL, 2010

How well did models simulate peatland processes?

Model name	Temporal resolution	Soil layers	Soil C pools	N cycle	Max soil moisture
DLEM	Daily	**2**	3	Yes	Saturation
Ecosys	Hourly	8	9	Yes	Saturation (with water table)
LPJ	Daily	**2**	2	No	**Field capacity**
ORCHIDEE	30-min	**2**	8	No	**Field capacity**
SiB	30-min	10	None	No	Saturation
SiBCASA	30-min	25	9	No	Saturation
TECO	30-min	10	5	No	Saturation

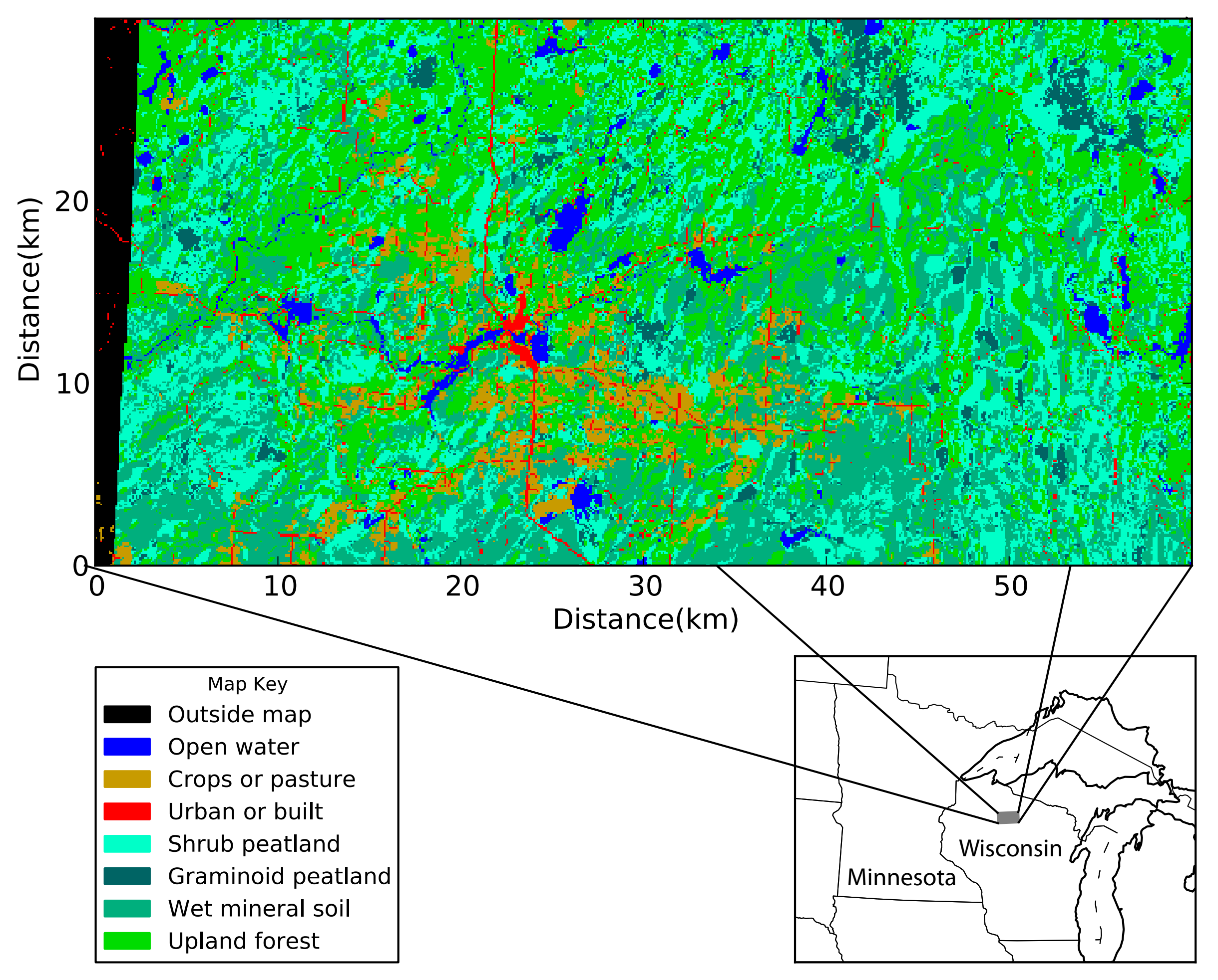
Sulman et al., JGR-G, 2011

Monthly residuals were correlated with observed water table



Maybe longer term?

Ecoregion	Active area fraction
Upland	38%
Mineral wetland	27%
Shrub peat	29%
Graminoid peat	5%



LANDIS-II model

Sulman et al., Ecosystems, 2013

Water table effects on carbon balance

Peatlands:

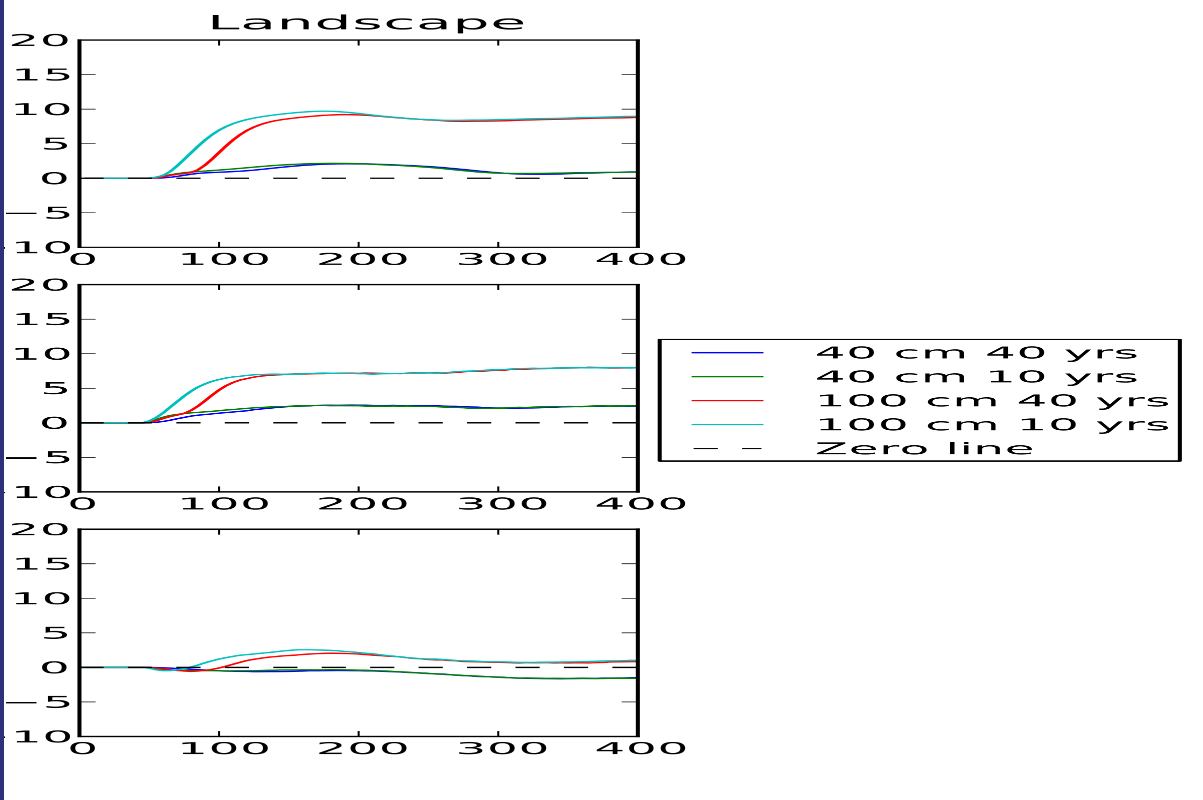
- 100 cm declines:
  - Short term: C gain
  - Long term: C loss
- 40 cm declines
  - Short term: C neutral
  - Long term: C loss

Mineral wetlands:

- C gain for both

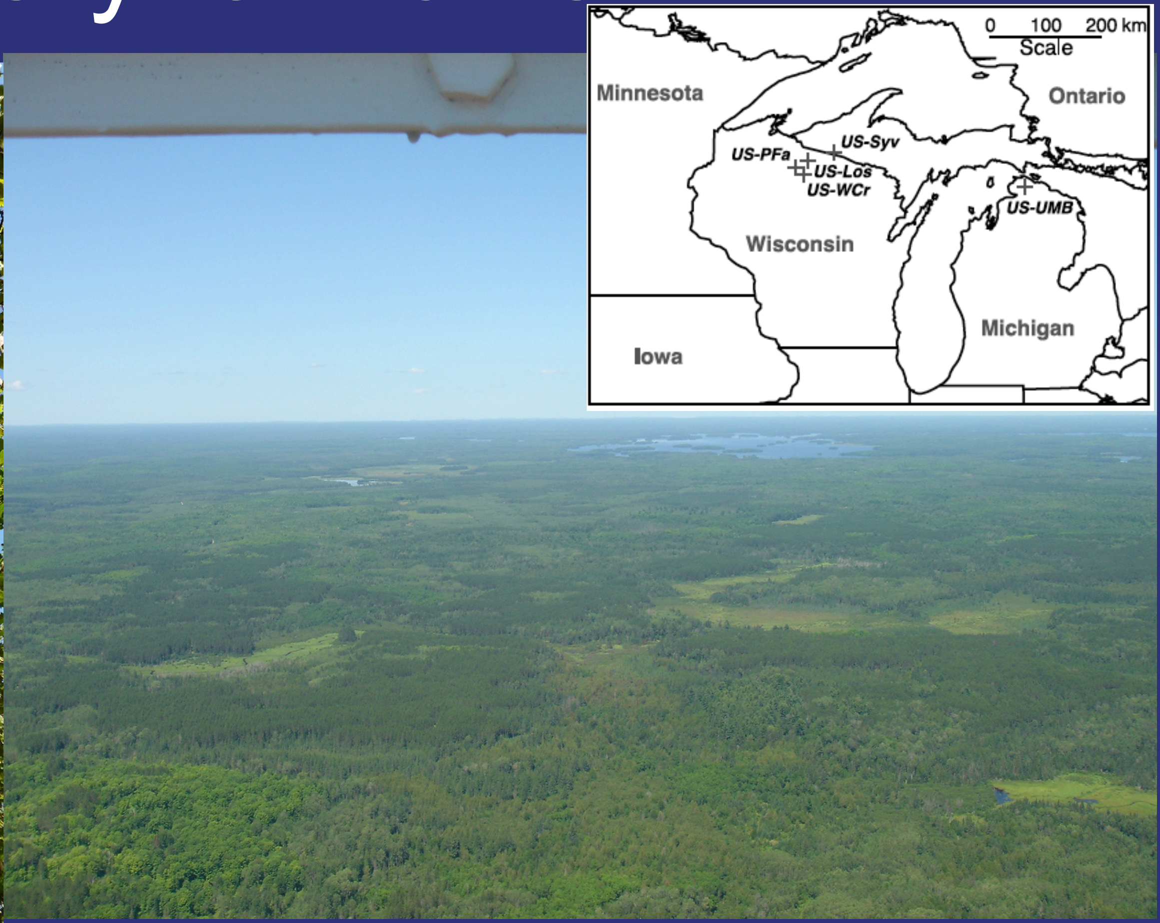
Whole landscape

- Short-term: C increase
- Long-term: C steady
- Time scale of decline made little difference

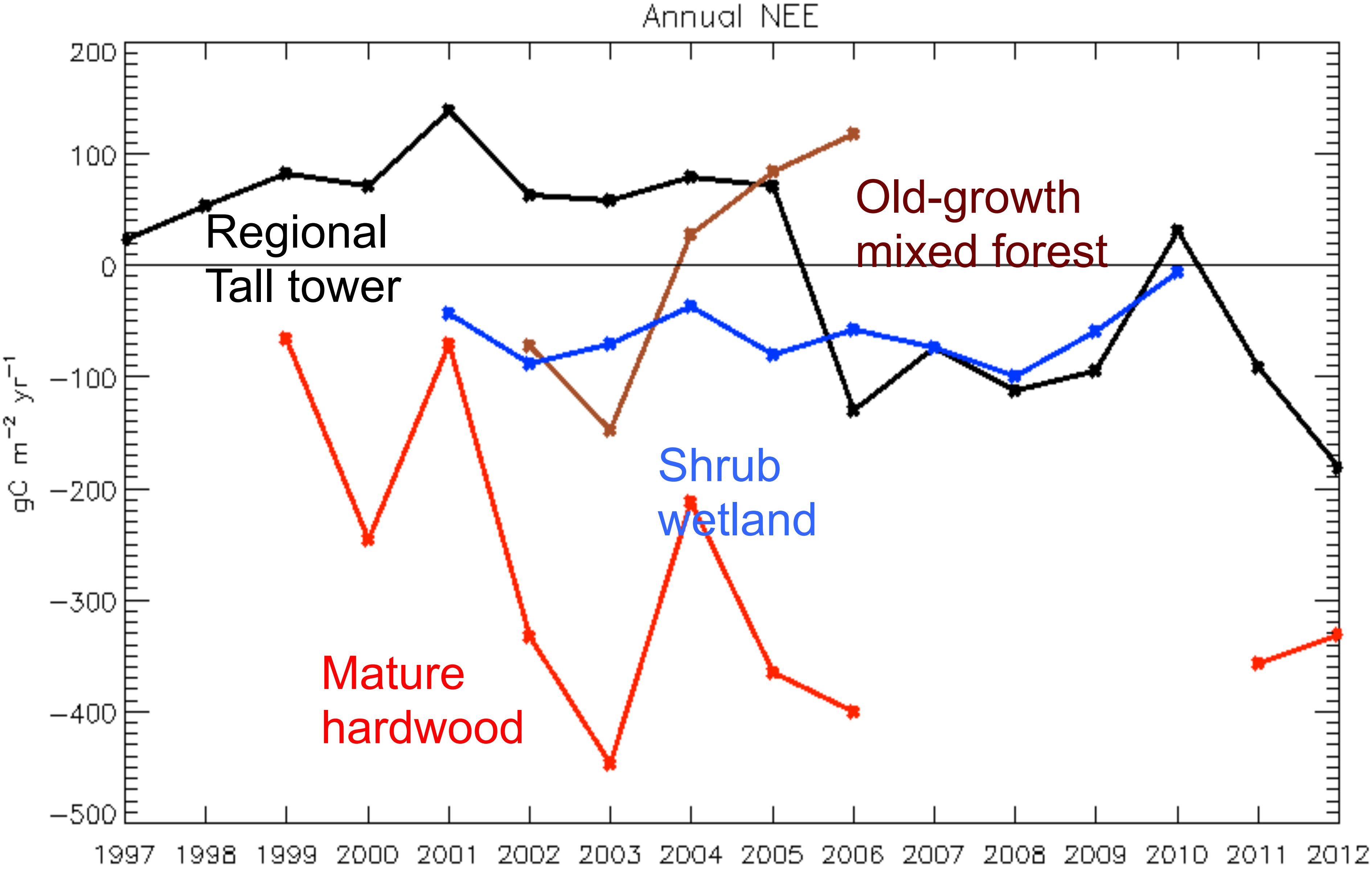


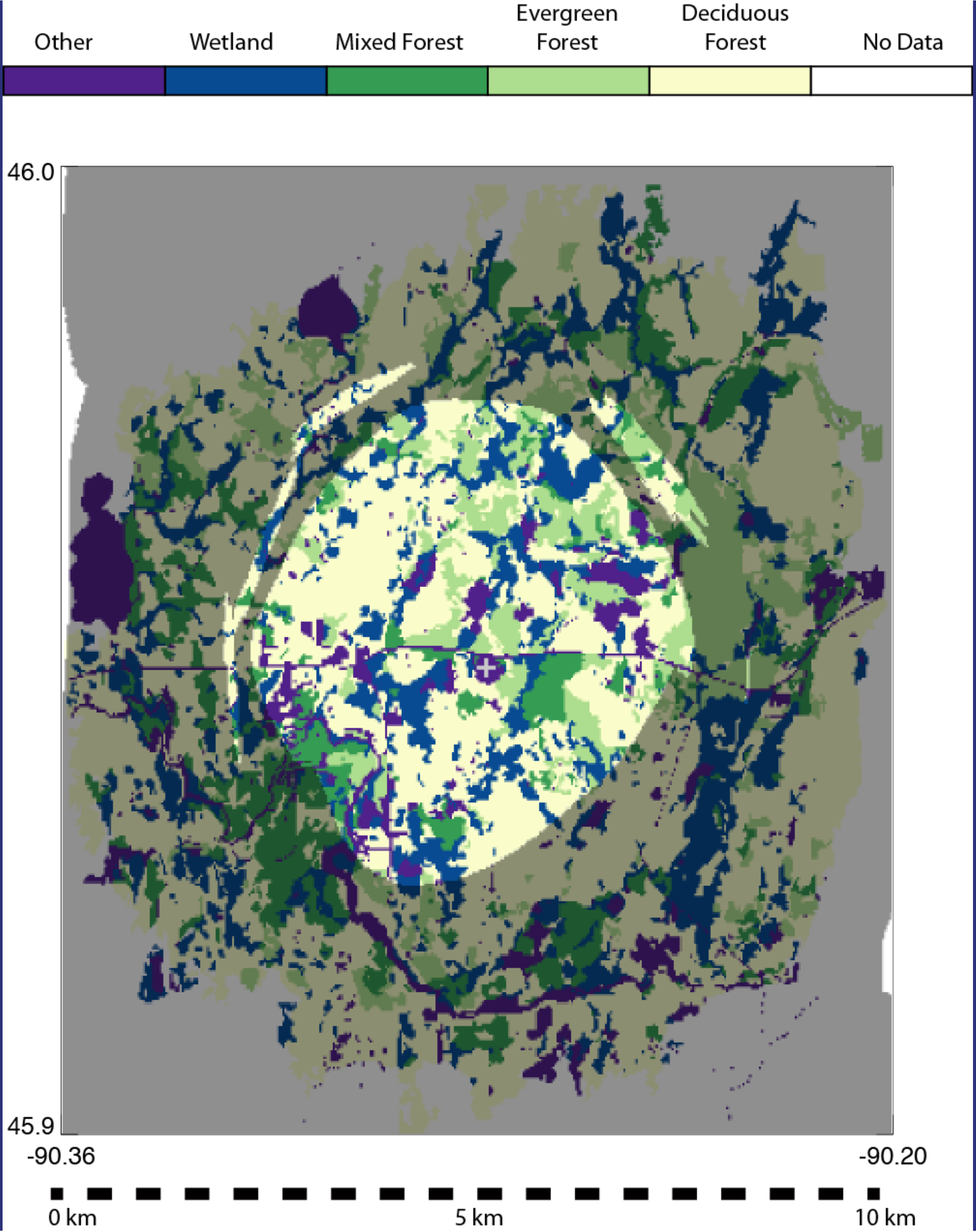
Net change from control run for shallow peat simulations: Different water table scenarios

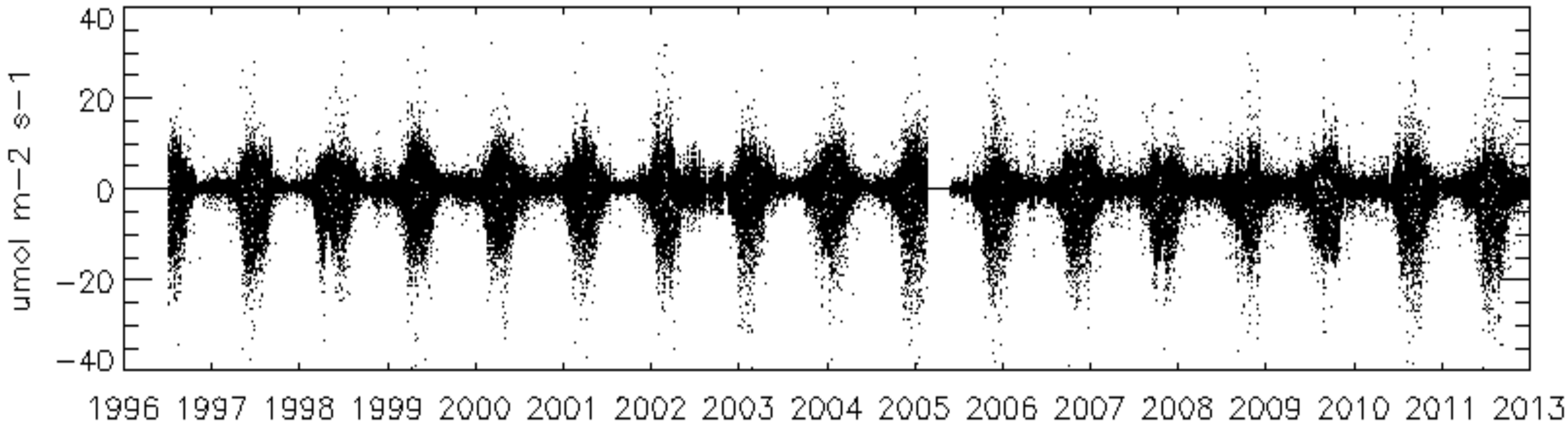
A very tall tower!



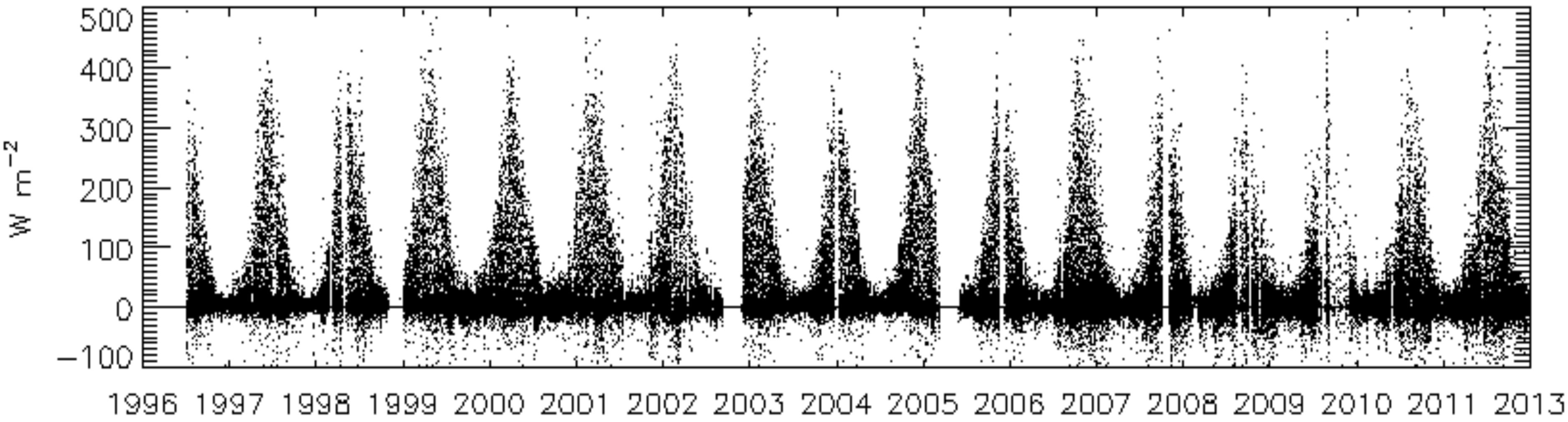
Desai, A.R., 2014. Influence and predictive capacity of climate anomalies on daily to decadal extremes in canopy photosynthesis. Photosynthesis Research, 119, 31-47, doi:10.1007/s11120-013-9925-z.


Annual NEE
gC m^{-2} yr^{-1}
200
100
0
−100
−200
−300
−400
−500
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Regional Tall tower
Old-growth mixed forest
Shrub wetland
Mature hardwood


Other
Wetland
Mixed Forest
Evergreen Forest
Deciduous Forest
No Data
46.0
45.9
-90.36
-90.20
0 km
5 km
10 km



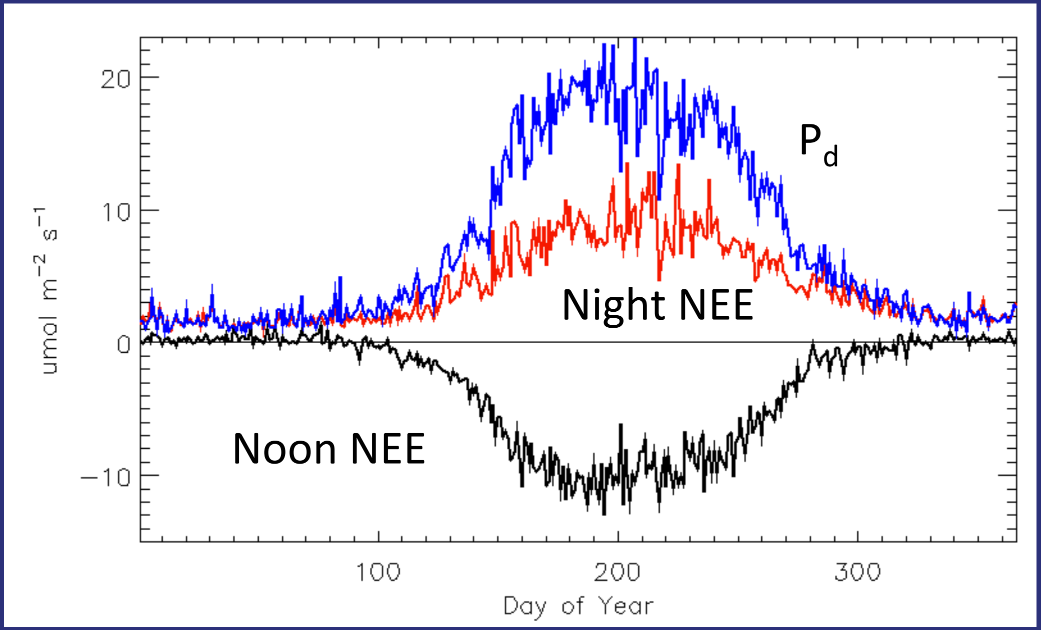
NEE of CO2



Latent Heat Flux

From NEE to Productivity

- Flux tower derived "GPP" is sensitive to model selection and gaps (Desai *et al.*, 2008)
- INSTEAD: Use a data-based approach
  - P_d = Max nighttime observed NEE – Mean noon (10-14) NEE
    - Reject noon NEE is > 50% gap-filled

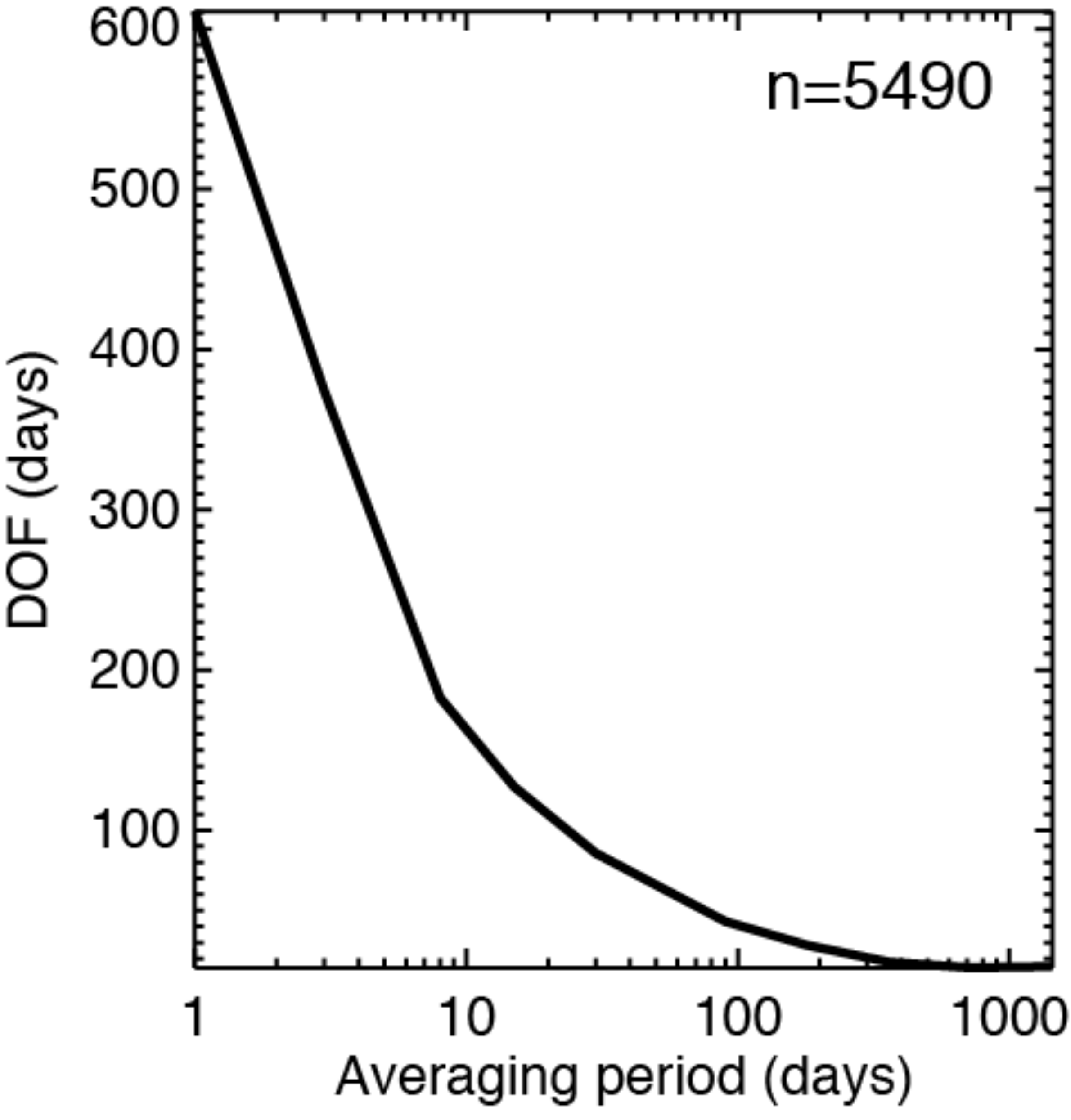


Problem

- Every flux tower based correlation is significant when you have thousands to tens of thousands of datapoints
  - Effect sizes may be small, though
- Account for autocorrelation using “reduced degrees of freedom” metric!

$$N_* = \frac{N}{\sum_{t=N/2}^{N}\left[\left(1-\frac{t}{N}\right)\rho_t^X \rho_t^Y\right]}$$

Bretherton et al., 1999, J Clim

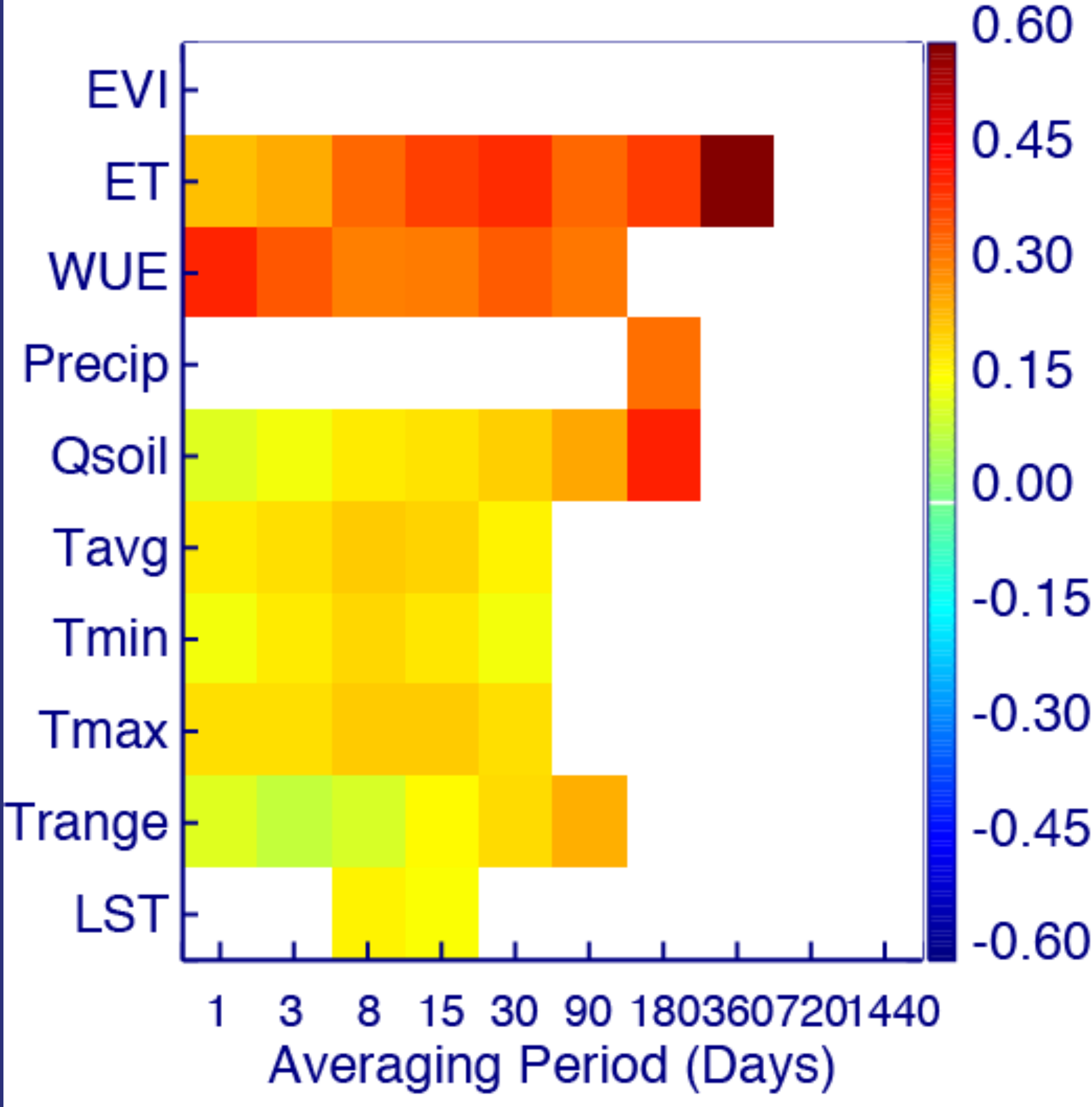

n=5490
DOF (days)
600
500
400
300
200
100
1
10
100
1000
Averaging period (days)

What to test?

Abbreviation	Description	Source
P_d	Photosynthetic drawdown	Flux tower
EVI	Enhanced Vegetation Index, 8-day average	MODIS TERRA/AQUA
ET	Evapotranspiration	Flux tower
WUE	Water Use Efficiency (P_d/ET)	Flux tower
P_{recip}	Daily precpitation	NCDC + NARR Reanalysis
Q_{soil}	10 cm soil moisture	NARR Reanalysis
T_{mean}	Daily temperature	Flux tower + NCDC
T_{min}	Minimum daily temperature	Flux tower + NCDC
T_{max}	Maximum daily temperature	Flux tower + NCDC
T_{range}	Daily temperature range (max - min)	Flux tower + NCDC
LST	Land Surface Temperature, 8-day day/night average	MODIS TERRA/AQUA

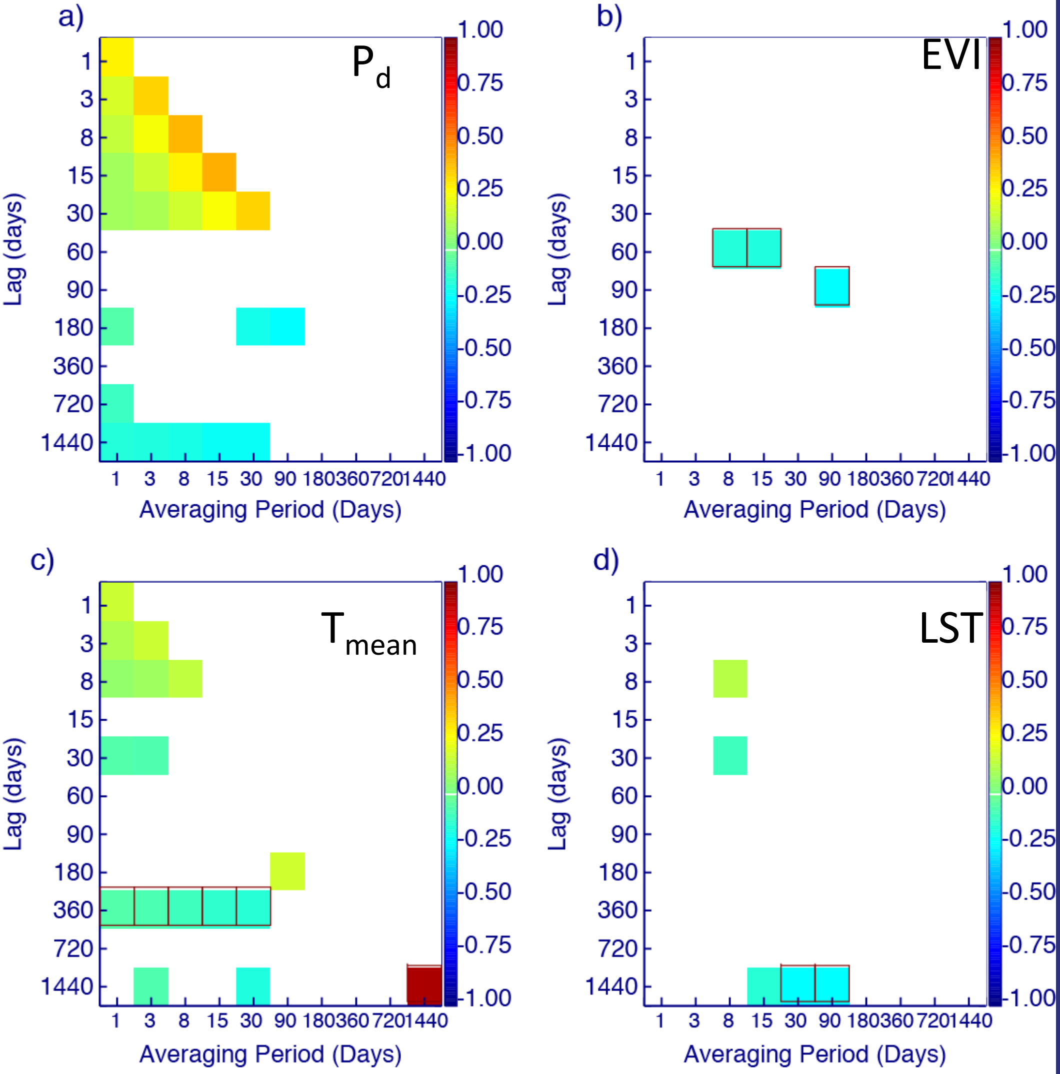
What do you get?

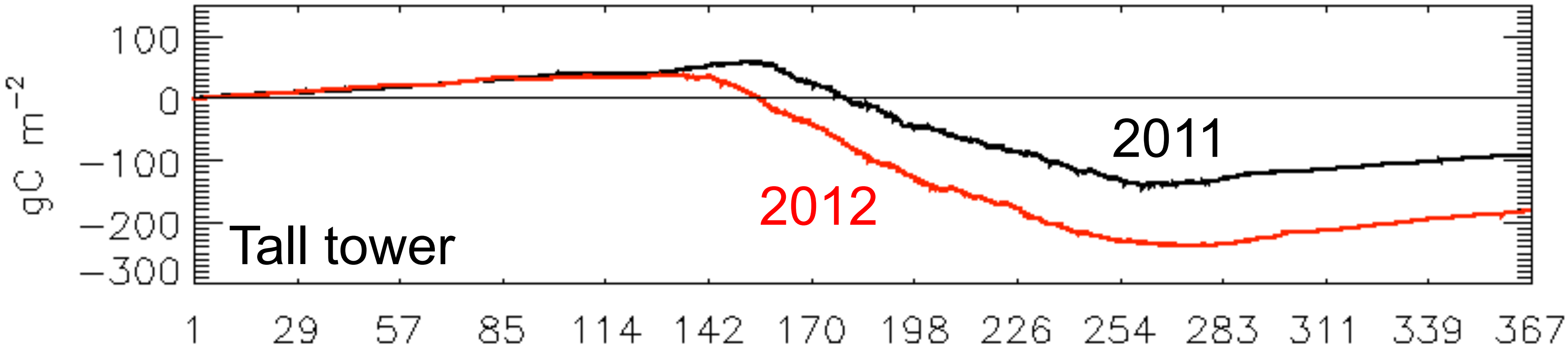
- Only significant correlations shown
- Moisture and temperature anomalies positively correlate with P_d at sub-annual scales

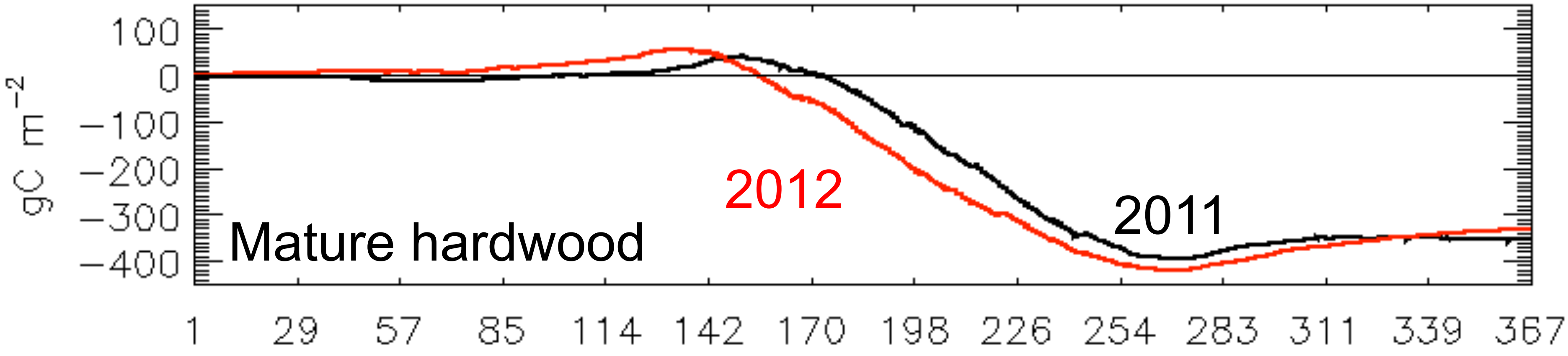


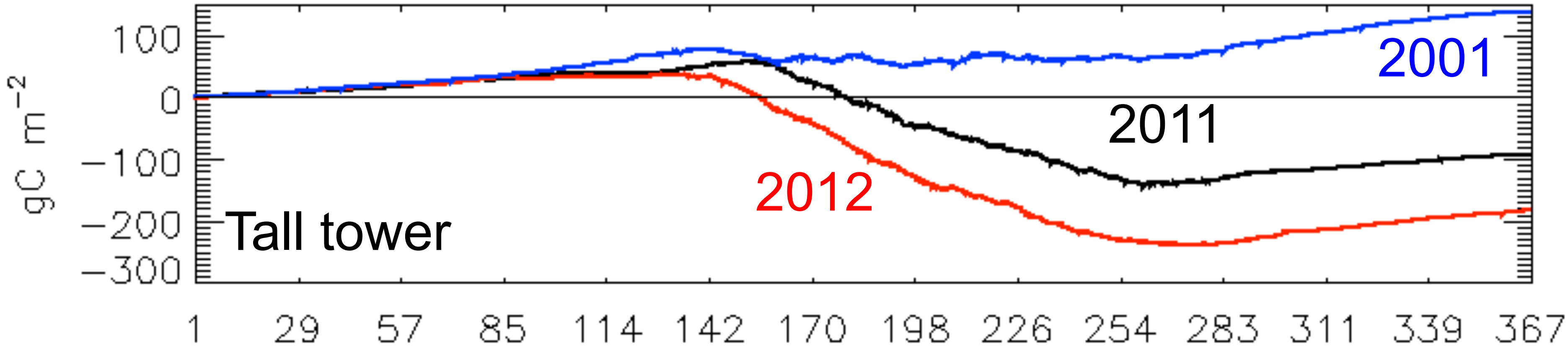
Lags are interesting

- Red squares = correlations > autocorrelation
- Remotely sensed variables (EVI,LST) have limited ability to predict P_d
- Previous year weekly-monthly temperature has a weak negative relationship to P_d




100
0
−100
−200
−300
gC m^{-2}
Tall tower
2012
2011
1
29
57
85
114
142
170
198
226
254
283
311
339
367


100
0
−100
−200
−300
−400
gC m^{-2}
Mature hardwood
2012
2011
1
29
57
85
114
142
170
198
226
254
283
311
339
367


gC m^{-2}
100
0
−100
−200
−300
1
29
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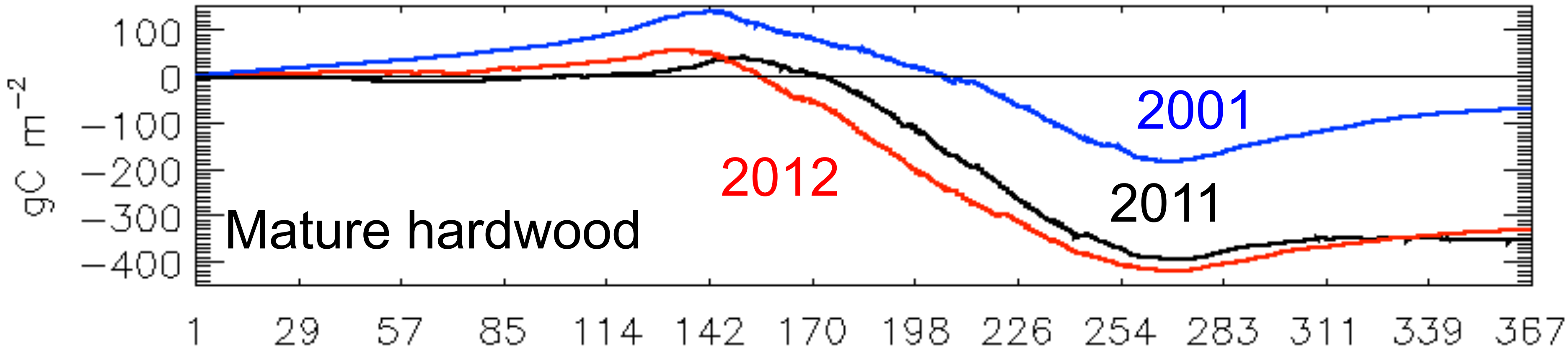
85
114
142
170
198
226
254
283
311
339
367
Tall tower
2001
2011
2012


gC m^{-2}
100
0
−100
−200
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−400
1
29
57
85
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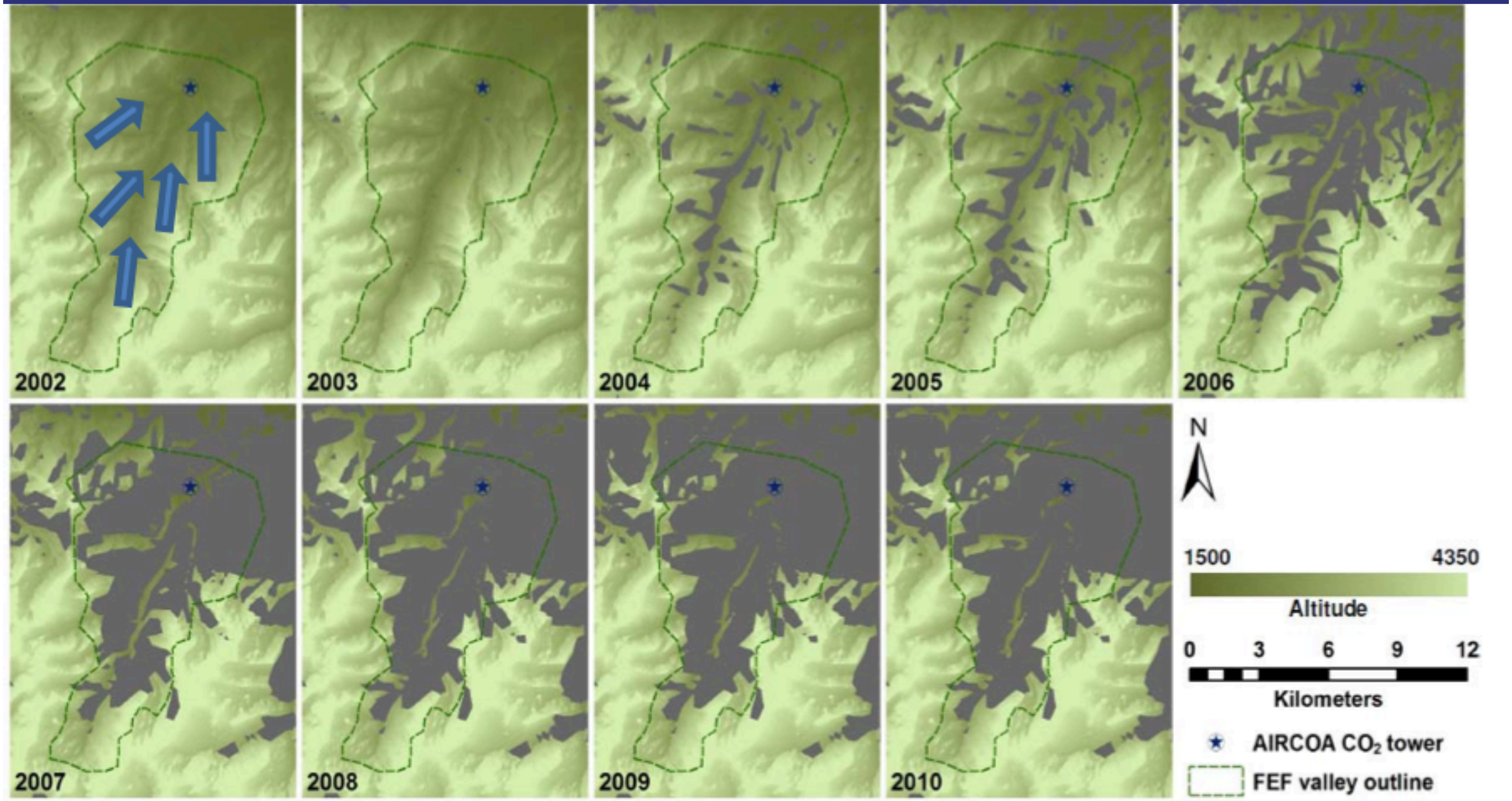
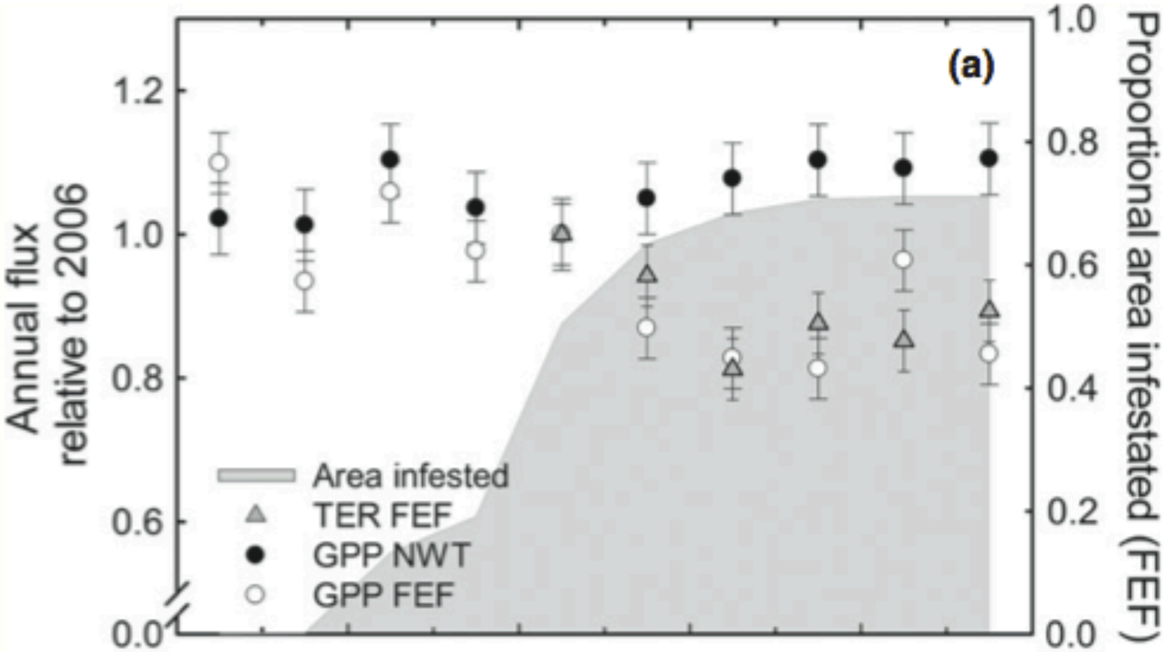
142
170
198
226
254
283
311
339
367
Mature hardwood
2001
2012
2011

Attack of the beetles





ECOLOGY LETTERS

Ecology Letters, (2013) doi: 10.1111/ele.12097

LETTER

Persistent reduced ecosystem respiration after insect disturbance in high elevation forests

David J. P. Moore,[1,†]* Nicole A. Trahan,[2,†] Phil Wilkes,[3] Tristan Quaife,[4] Britton B. Stephens,[5] Kelly Elder,[6] Ankur R. Desai,[7] Jose Negron[6] and Russell K. Monson[1,8]

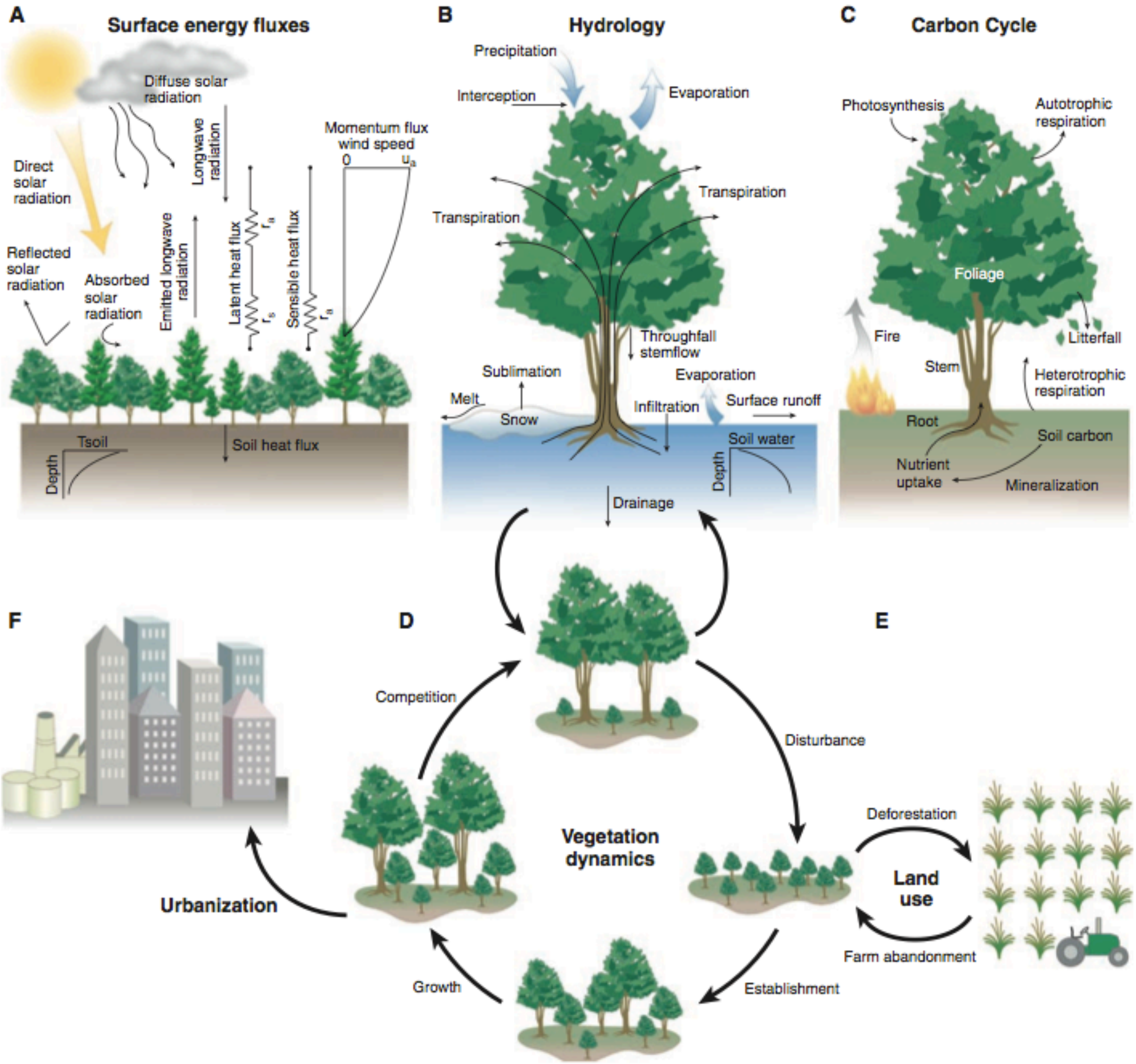
Abstract

Amid a worldwide increase in tree mortality, mountain pine beetles (*Dendroctonus ponderosae* Hopkins) have led to the death of billions of trees from Mexico to Alaska since 2000. This is predicted to have important carbon, water and energy balance feedbacks on the Earth system. Counter to current projections, we show that on a decadal scale, tree mortality causes no increase in ecosystem respiration from scales of several square metres up to an 84 km^2 valley. Rather, we found comparable declines in both gross primary productivity and respiration suggesting little change in net flux, with a transitory recovery of respiration 6–7 years after mortality associated with increased incorporation of leaf litter C into soil organic matter, followed by further decline in years 8–10. The mechanism of the impact of tree mortality caused by these biotic disturbances is consistent with reduced input rather than increased output of carbon.

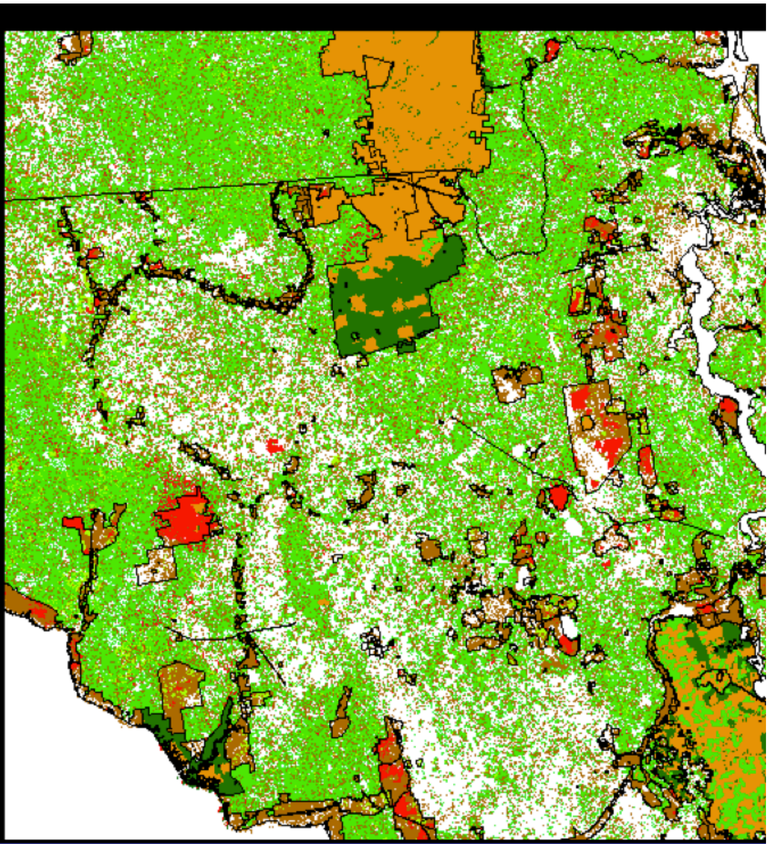
IV. YOU

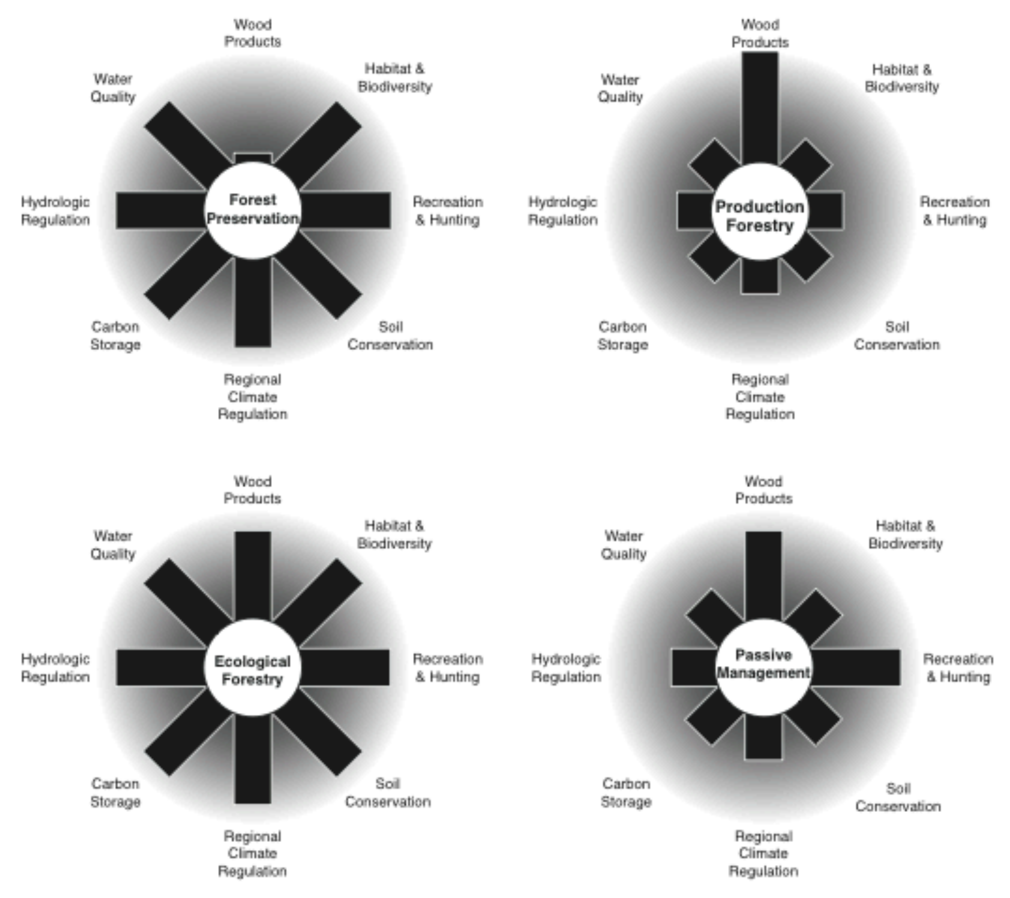
No one trusts a model except the one who wrote it; everyone trusts an observation except the one who made it – Harlow Shapley (by way of Matt Disney)

Forests in Flux

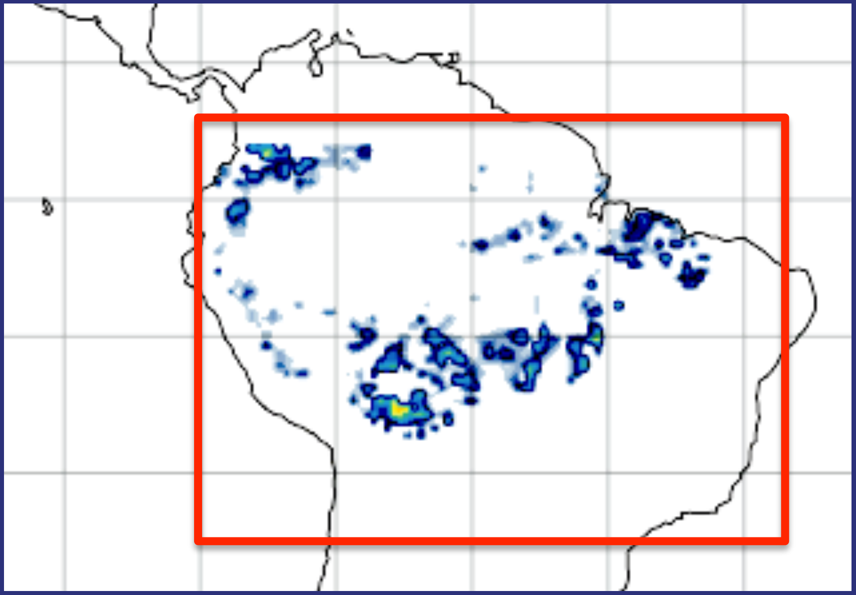


- 🟧 Passive
- 🟩 Preservation
- 🟥 Preservation/Change
- 🟩 Production
- 🟫 Change Unknown





WRF-Noah Setup



Bagley, J.E., Desai, A.R., Harding, K.J., Snyder, P.K., and Foley, J.A., 2014. Drought and deforestation: Has land cover change influenced recent precipitation extremes in the Amazon? *J. Climate*, 27, 345-361, doi:10.1175/JCLI-D-12-00369.1.

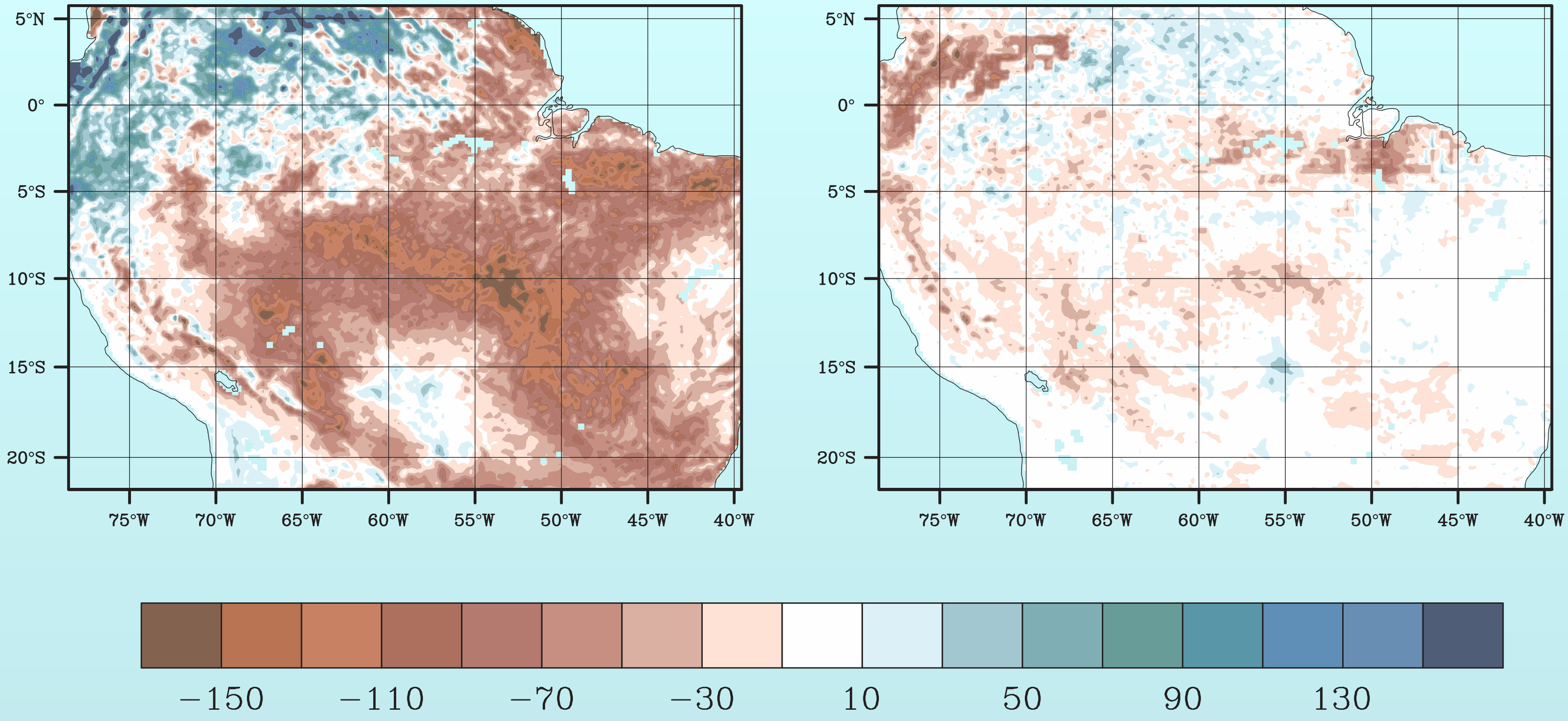
- Spatial Resolution: 20km x 20km

- 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

Precipitation Rate (mm/month)

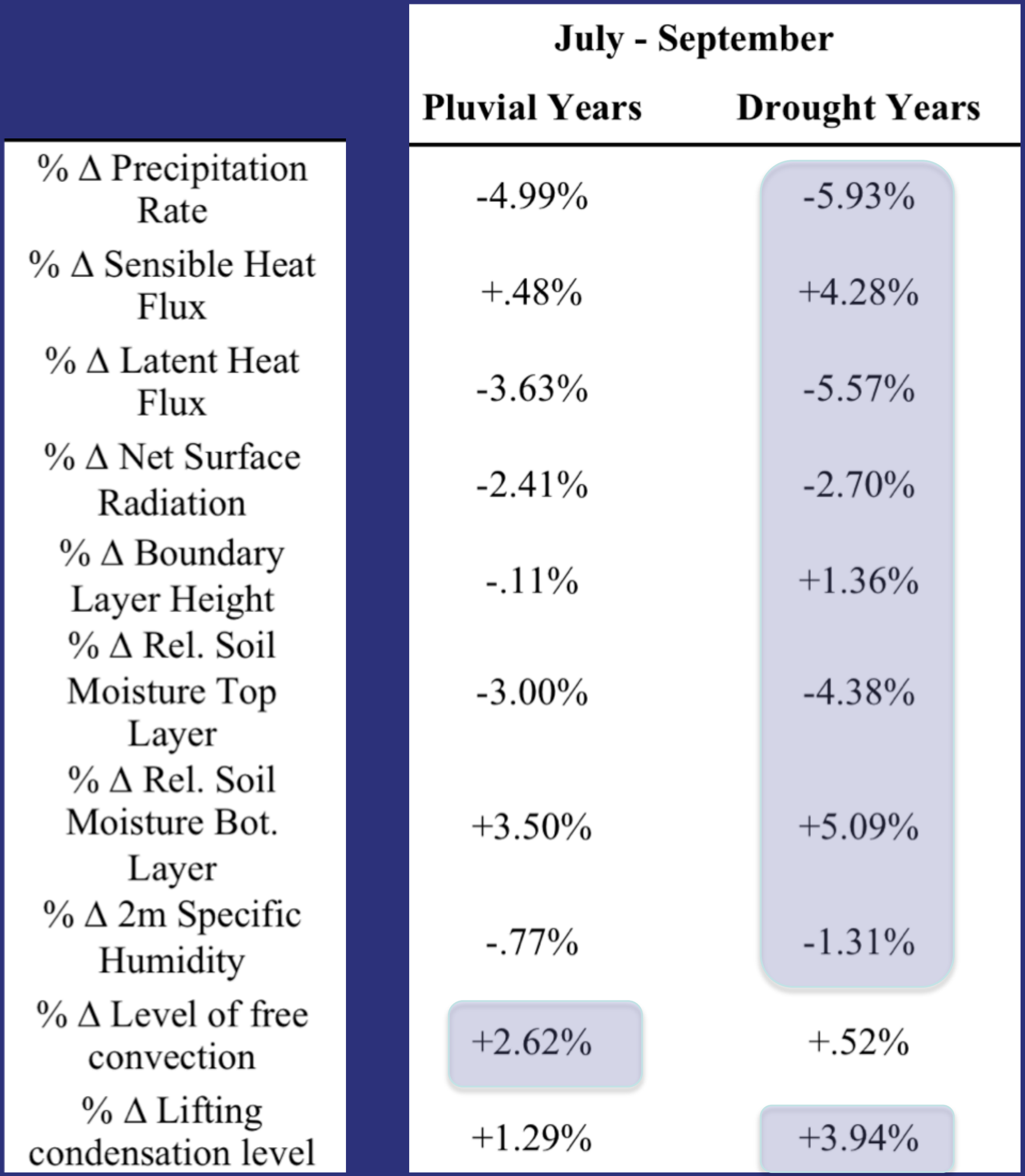


Dry Season
Anomaly

Deforestation
perturbation

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%

Final Thoughts

- Terrestrial ecosystem carbon cycle responds to a number of climatic, disturbance, and management forces, but feedbacks can go both ways
- Ecosystem management needs to consider these and Earth system models need to consider management
- All processes are time and space dependent
- Meteorologists need your help!

Thanks!

- Contributors:
  - Jonathan Thom, Ke Xu, Arlyn Andrews, Dan Baumann, Bruce Cook, Dave Moore, Britt Stephens, Justin Bagley, Ben Sulman, Mike Dietze, Sebastien Wolf, many others…
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