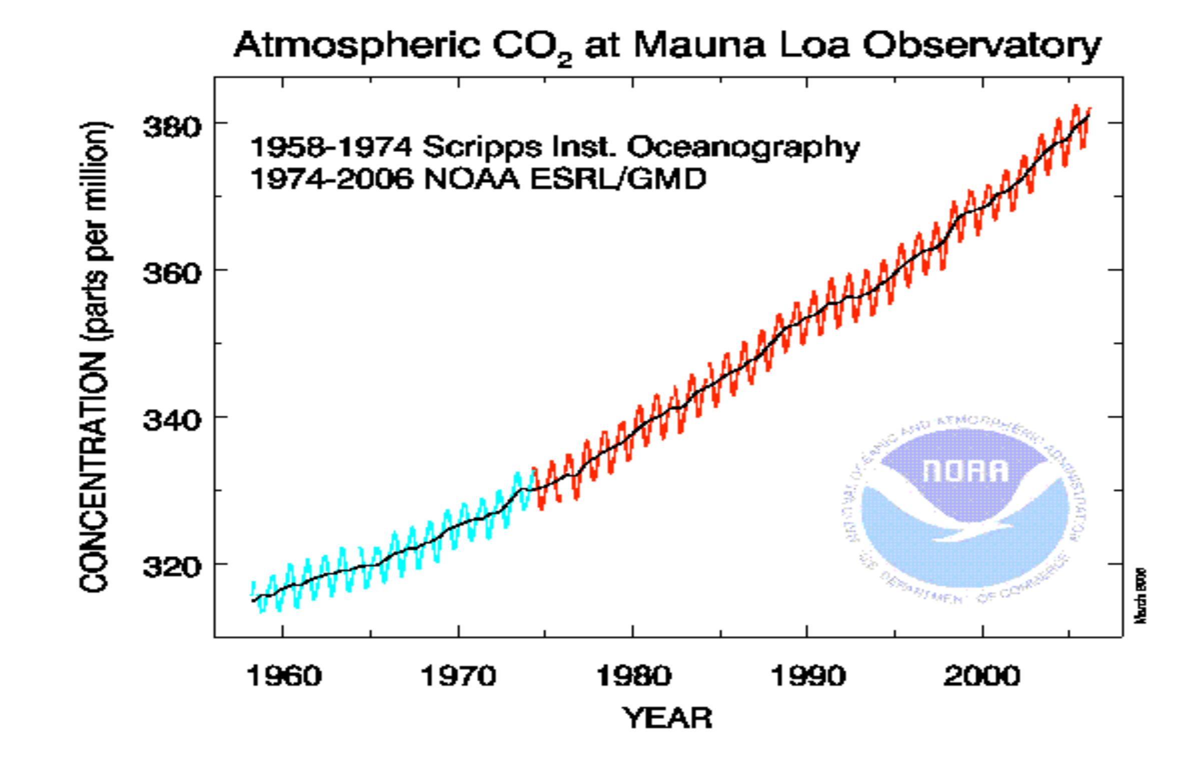
From eddies to the breath of the planet

Flux towers, data assimilation, and the global carbon cycle



Ankur Desai
AOS, UW-Madison

907 Seminar

20 Feb 2008

PROLOGUE

What's a meteorologist doing playing in the woods?

There's gold in dem hills…

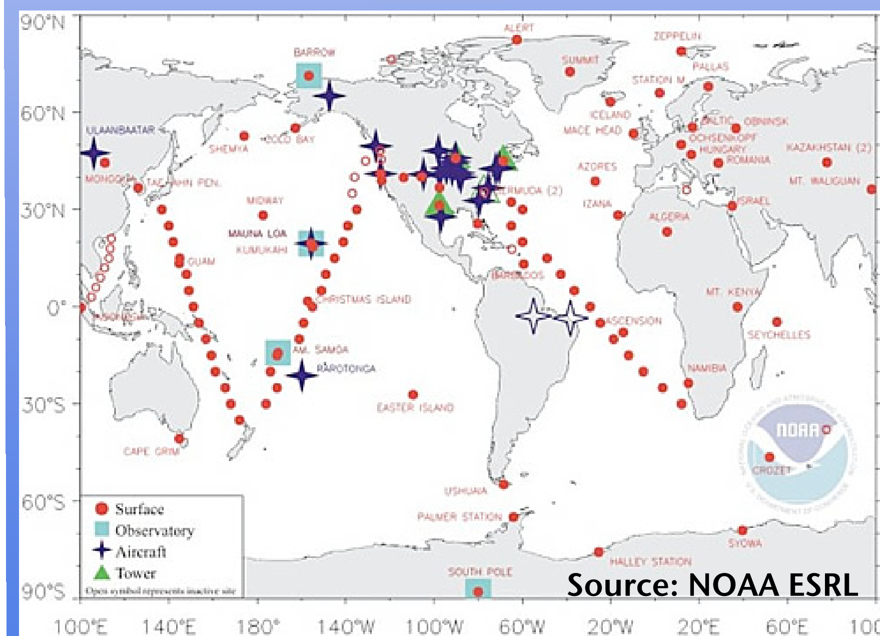
- It's alive…
  - Living organisms are strongly influenced by the atmosphere
  - And vice versa: living organisms play a large role in regulation of atmospheric composition, surface boundary conditions, air mass modification, and climate.
- You can play too!
  - Land surface processes (AOS 532, Environmental Biophysics)
  - Boundary layers (AOS 773, Boundary layers, turbulence and micrometeorology)
  - Biogeochemistry (AOS 520, Bioclimatology)
  - Land-ocean-atmosphere interaction (AOS 425, Global Climate Processes; AOS 773, AOS 532)

Ask not what Earth system science can do for meteorologists…

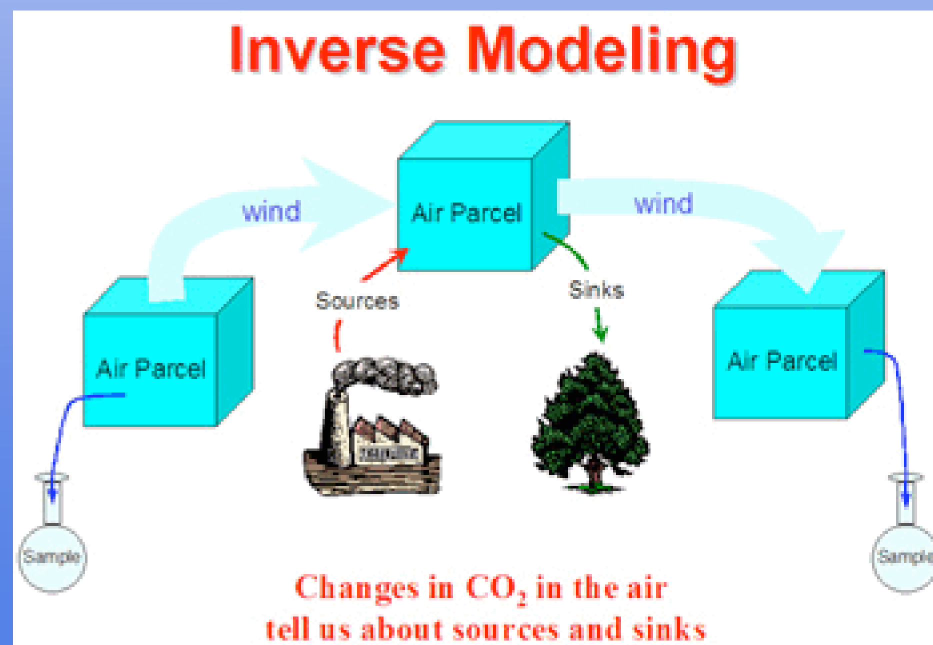
- Ask: What can meteorologists do for Earth system sciences?
  - Apply/develop novel tools for observing and modeling Earth systems
    - Atmosphere as the great mixer
    - We have the best toys
  - Physics based view of ecology
    - Ecology has traditionally been about local effects
    - Universal equations, parameters, paradigms are few
  - Rigorous mathematical analysis
    - Long history of working with large datasets and model output
    - Success with data assimilation

We really do have the best toys

- Example: Atmospheric inversion
  - d **C**oncentration / dt = **F**lux *X* **T**ransport
  - If you know d**C**/dt and **T**, solve for **F**
  - A giant matrix inversion



Source: NOAA ESRL



Courtesy of A.S. Denning

Outline

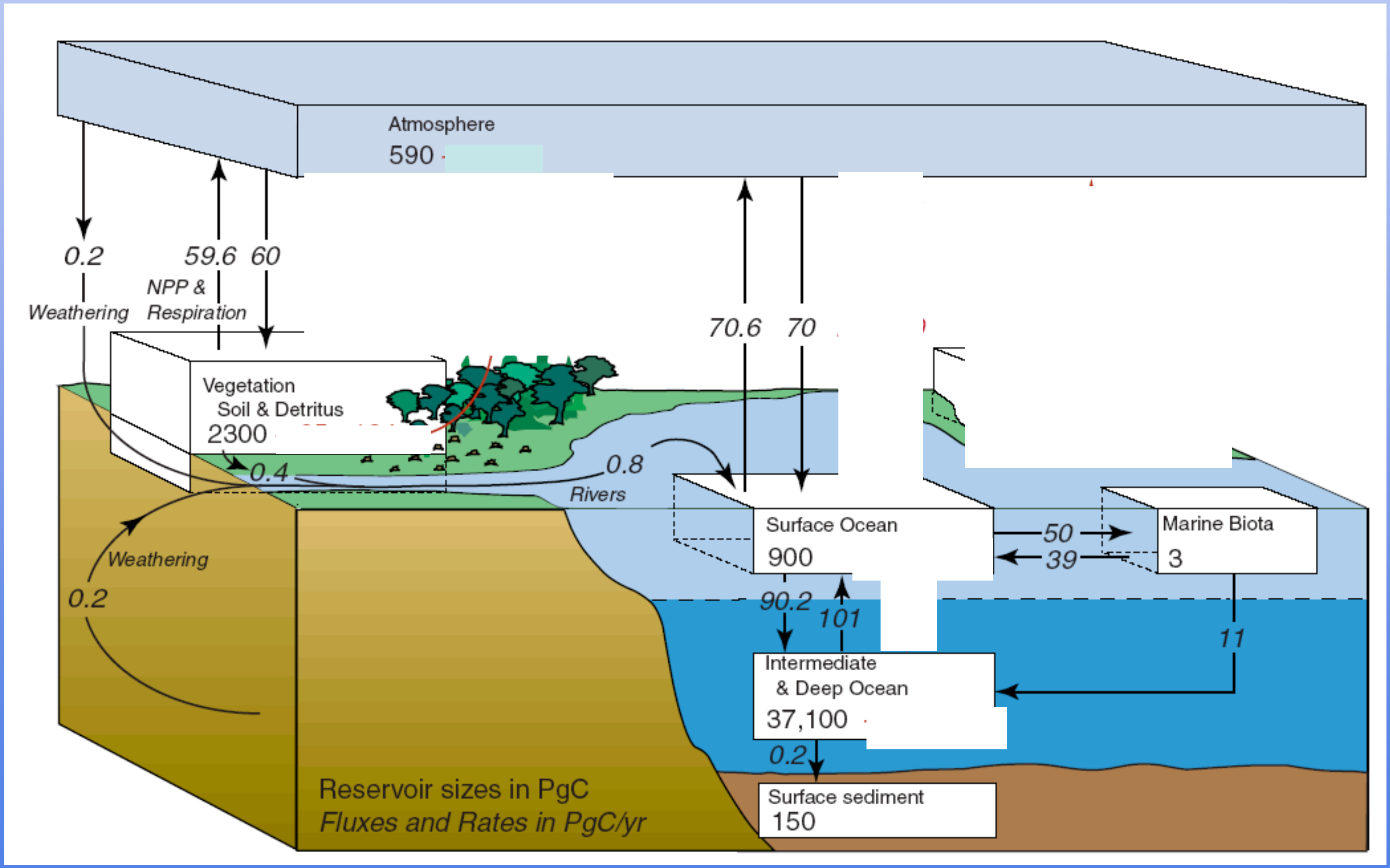
- What is the carbon cycle?
- How do we observe it?
- How can we use these observations to make better models?
- What’s next?

ACT I

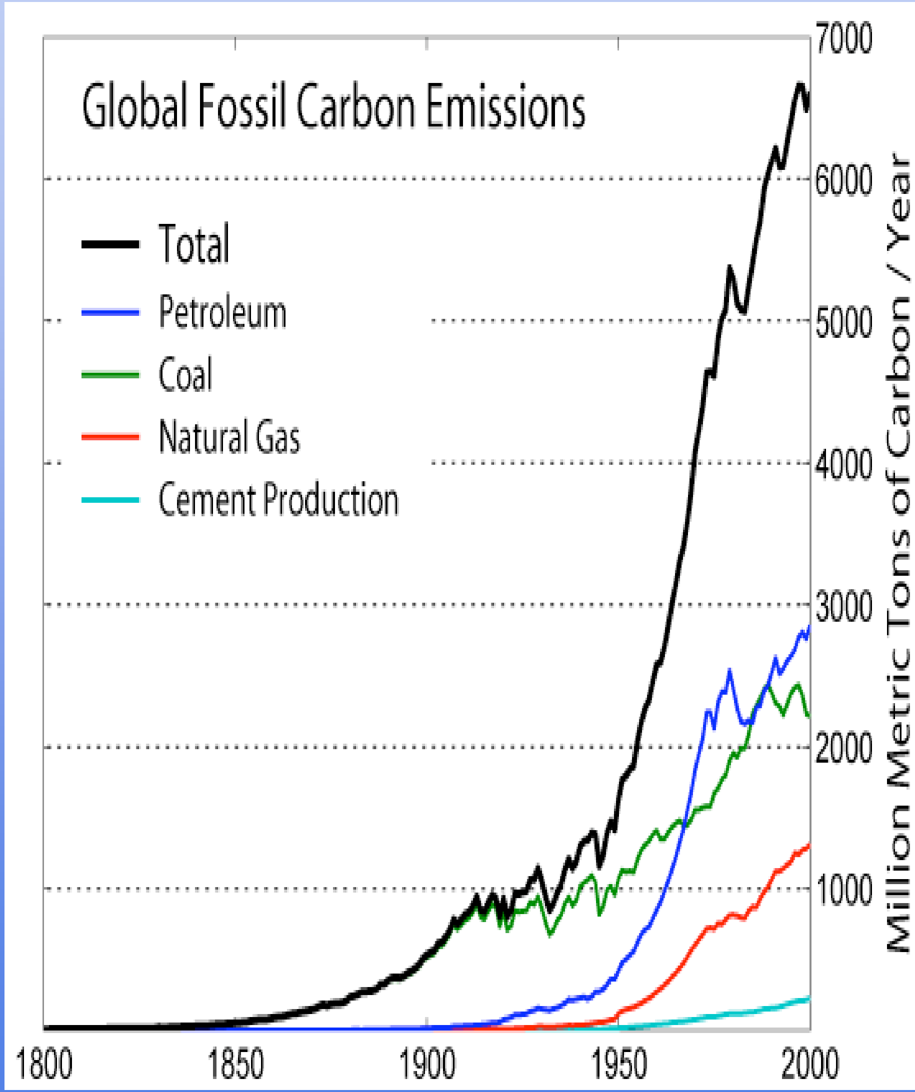
Where we meet the carbon cycle and discover a breathing planet

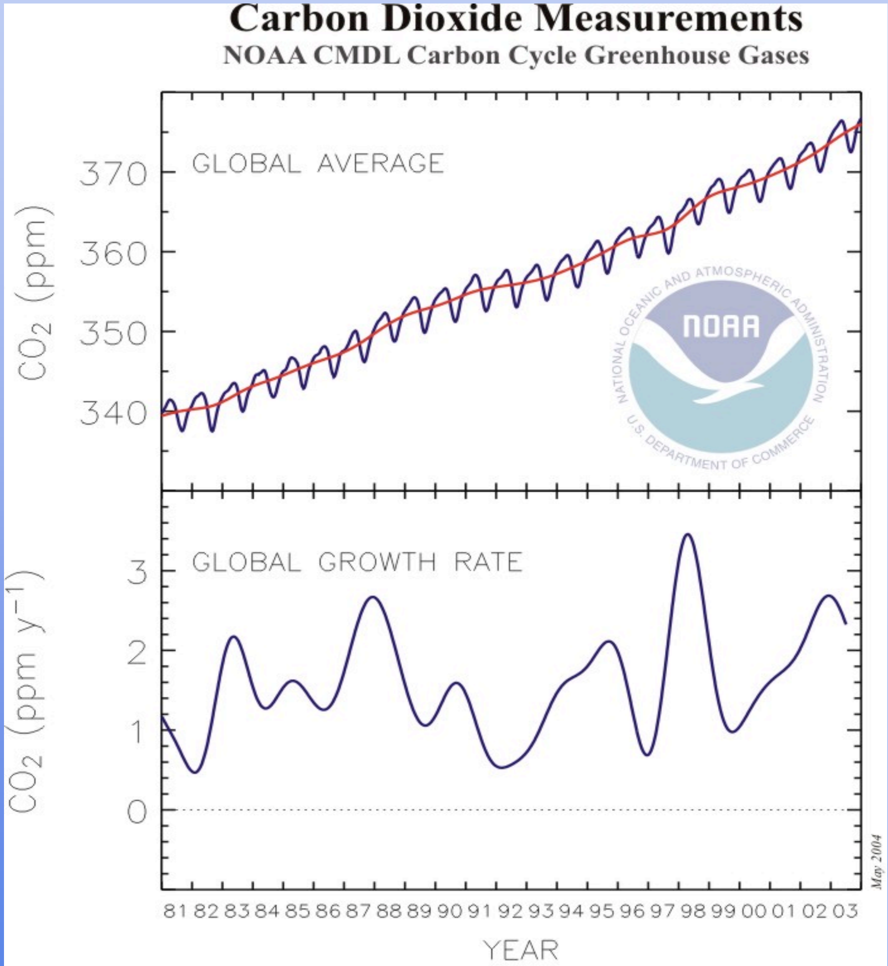
Living planet, pt 1

- Sarmiento and Gruber, 2002, *Physics Today*



A global experiment

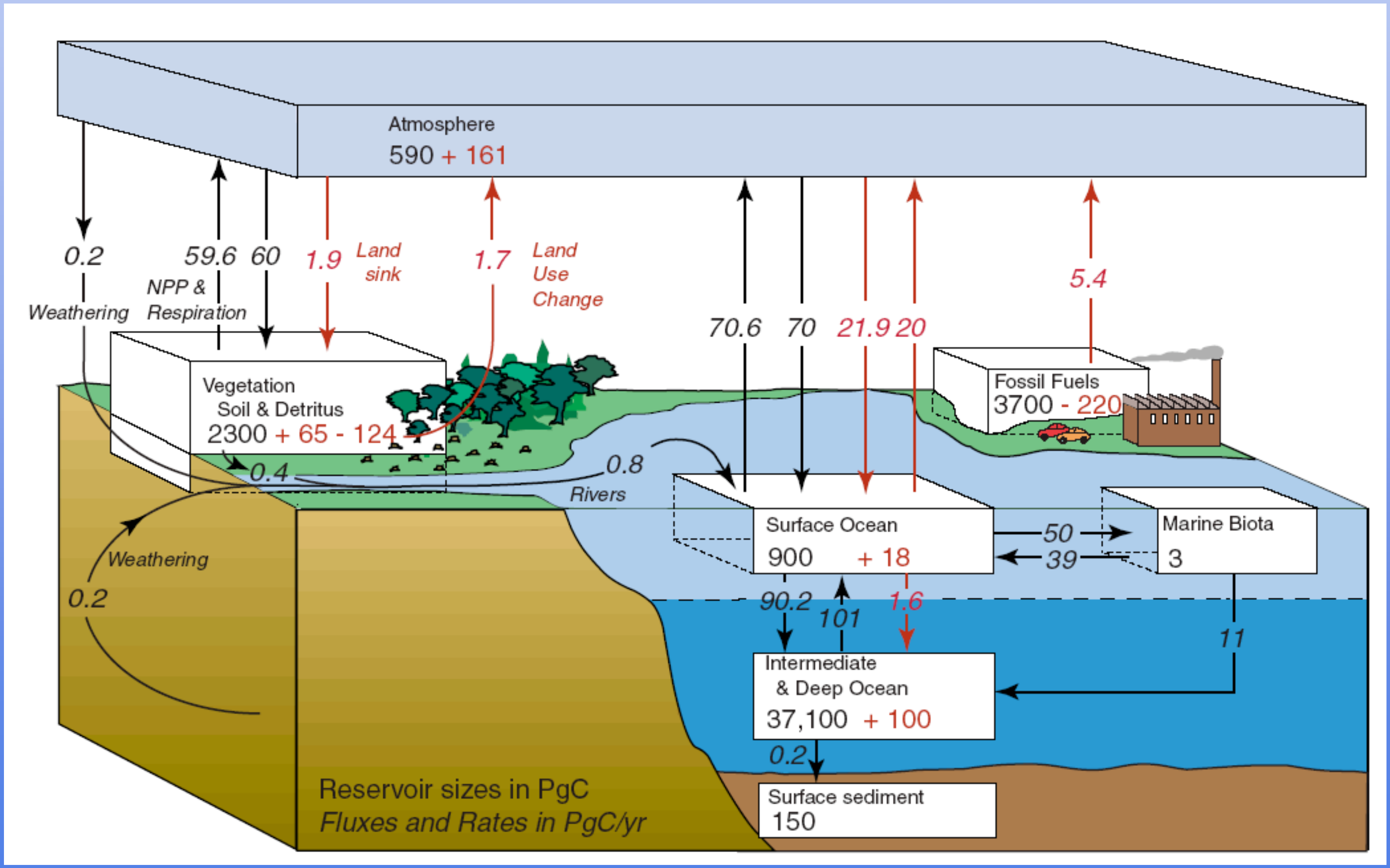




Top: Global average atmospheric carbon dioxide mixing ratios (blue line) determined using measurements from the NOAA CMDL cooperative air sampling network. The red line represents the long-term trend. Bottom: Global average growth rate for carbon dioxide. Principal investigator: Dr. Pieter Tans, NOAA CMDL Carbon Cycle Greenhouse Gases, Boulder, Colorado, (303) 497-6278 (pieter.tans@noaa.gov, http://www.cmdl.noaa.gov/ccgg).

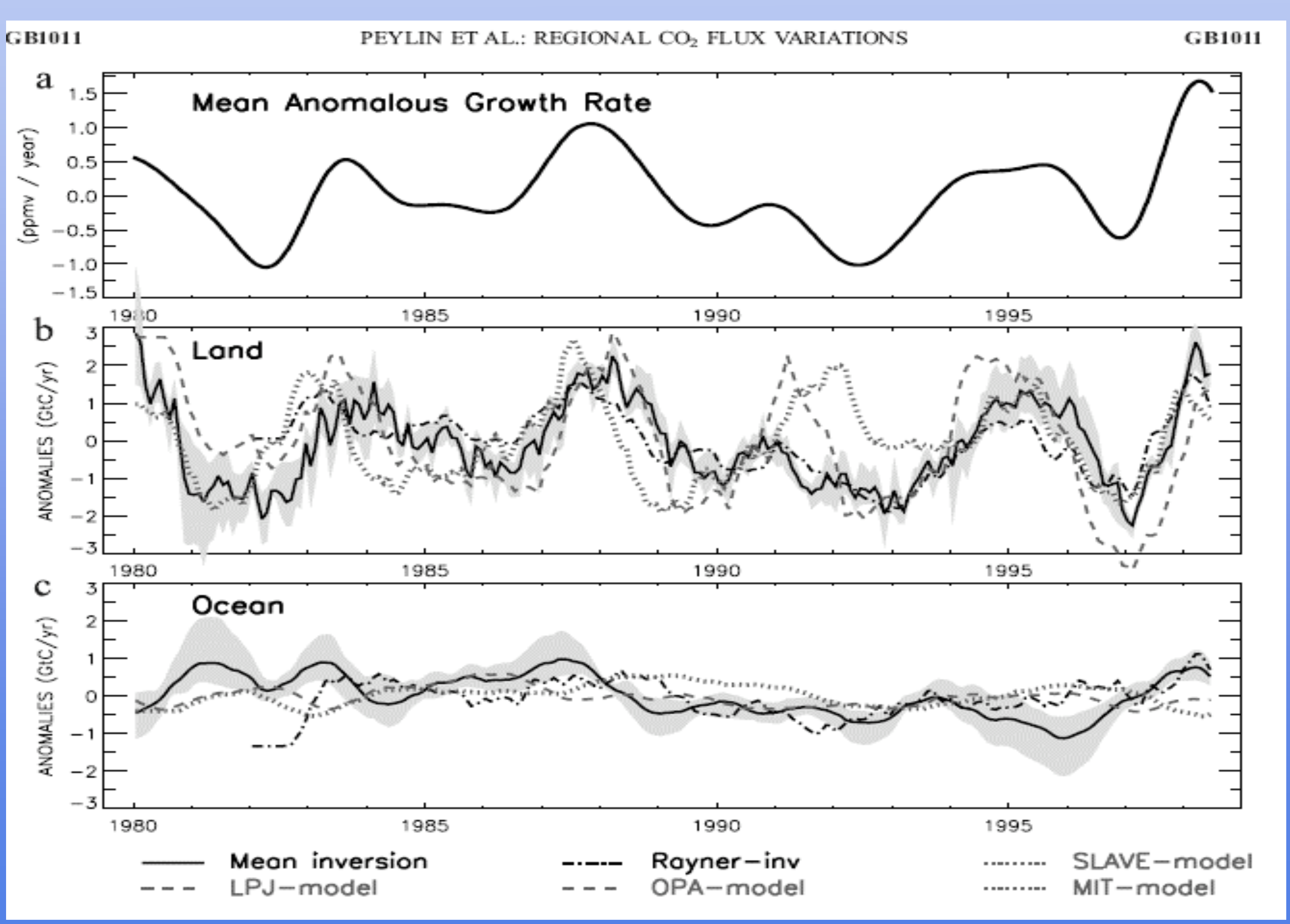
Living planet, pt 2

- Sarmiento and Gruber, 2002, *Physics Today*



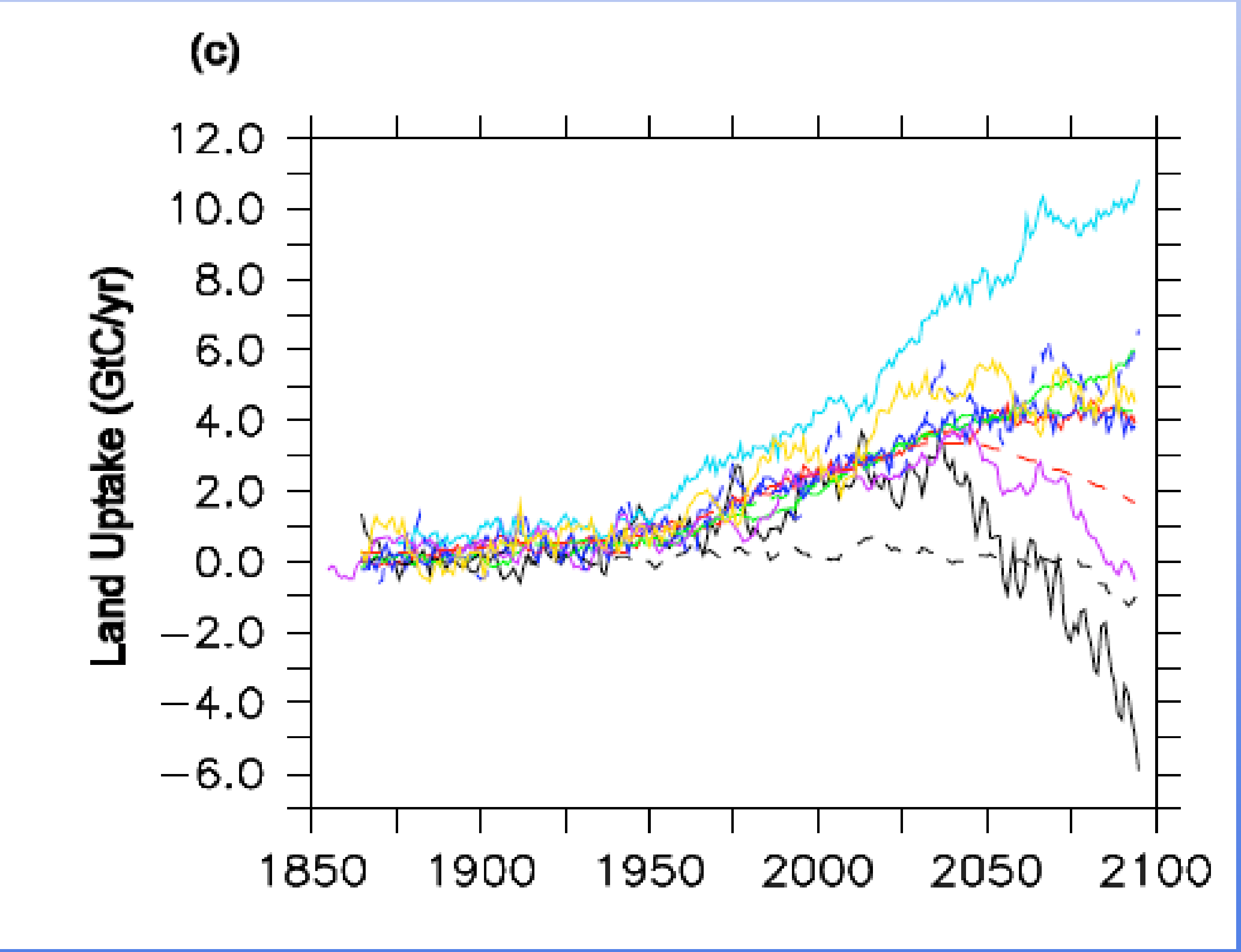
Interannual variability

- Peylin et al., 2005, *GBC*



An uncertain future

- Friedlingstein et al., 2005, *J. Clim*



Moral

- We need a way forward…
- Can meteorology help ecology?
  - Can we go beyond local to global and universal?
- Observations and models need a unifying framework
  - Use data assimilation, parameter estimation
    - Meteorologists know how to do this
  - Try to uncover controls, feedbacks, future sources, sinks and interactions
- Counterintuitive results are likely

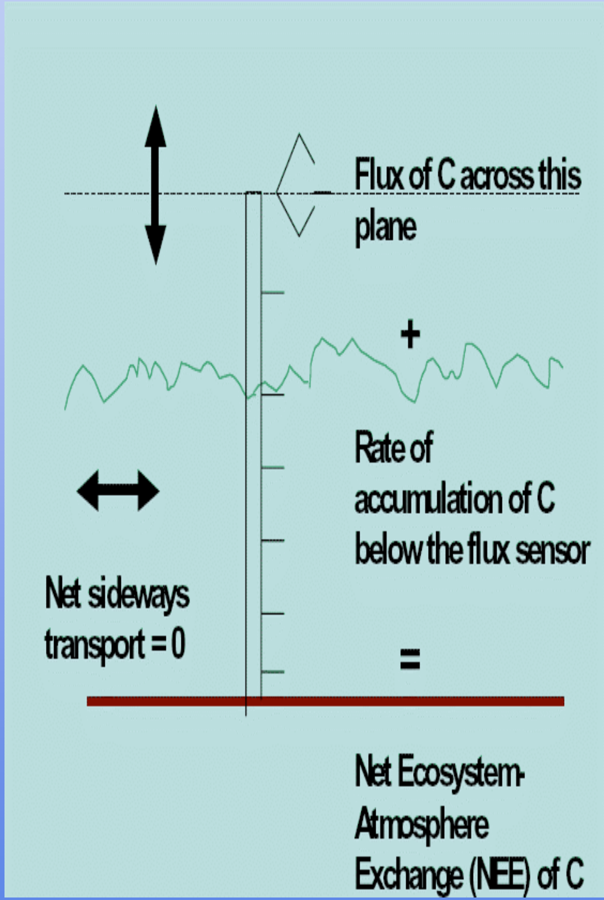
ACT II

Much ado about eddies:
Observing the exchange
of a colorless, odorless gas

My friend eddy…

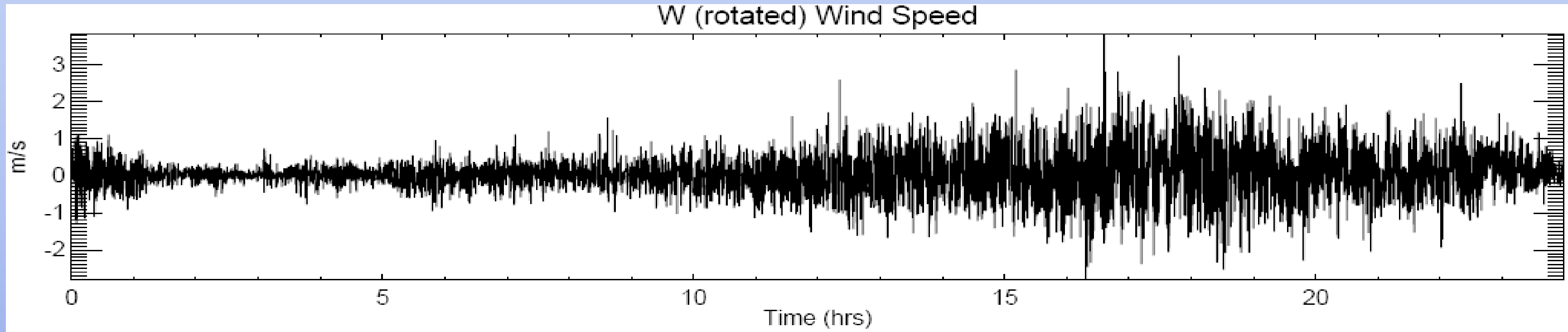
- Tracers in boundary layer primarily transported by turbulence
- Ensemble average turbulent equations of motion and tracer concentration provide information about the effect of random, chaotic turbulence on the evolution of mean tracer profiles with time
- In a quasi-steady, homogenous surface layer, we can simplify this equation to infer the surface flux of a tracer

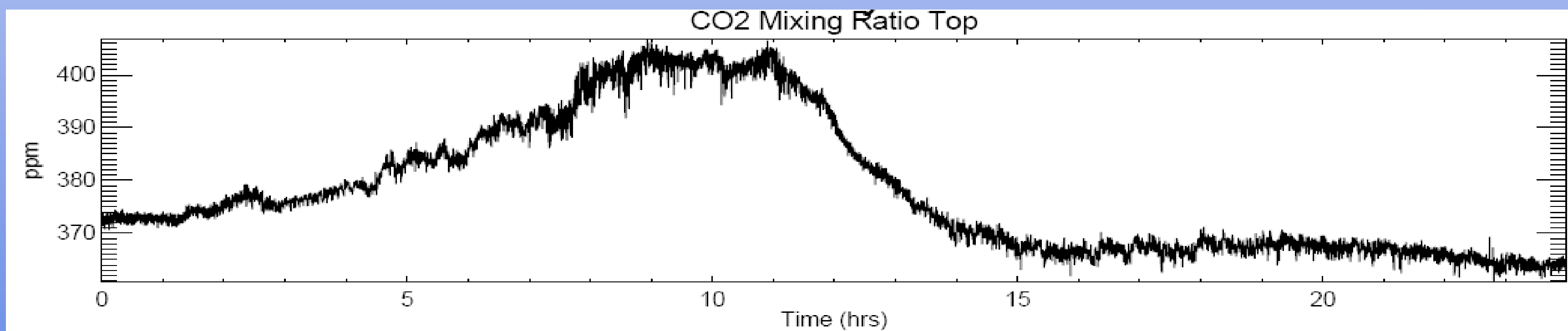
Eddy flux

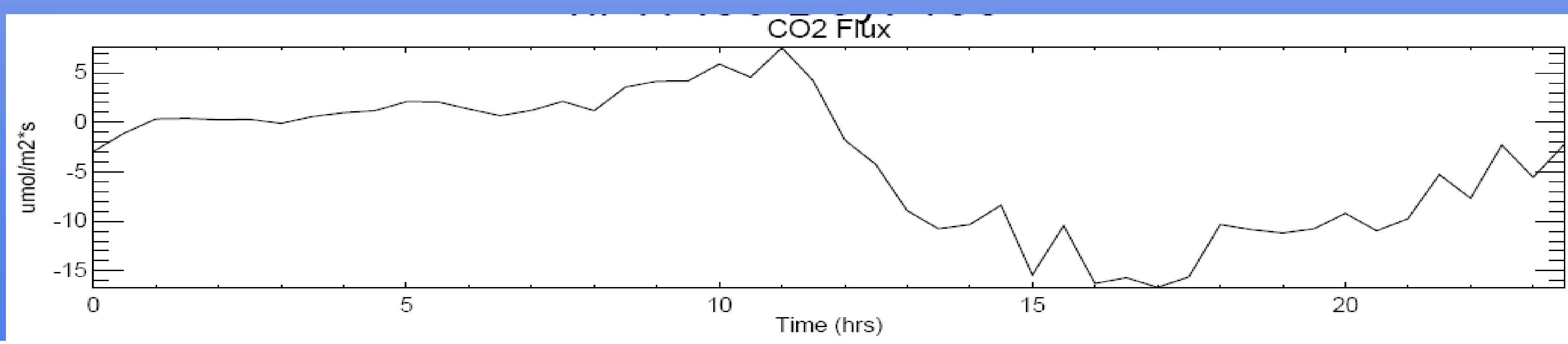


Flux of C across this plane
+
Rate of accumulation of C below the flux sensor
Net sideways transport = 0
=
Net Ecosystem-Atmosphere Exchange (NEE) of C

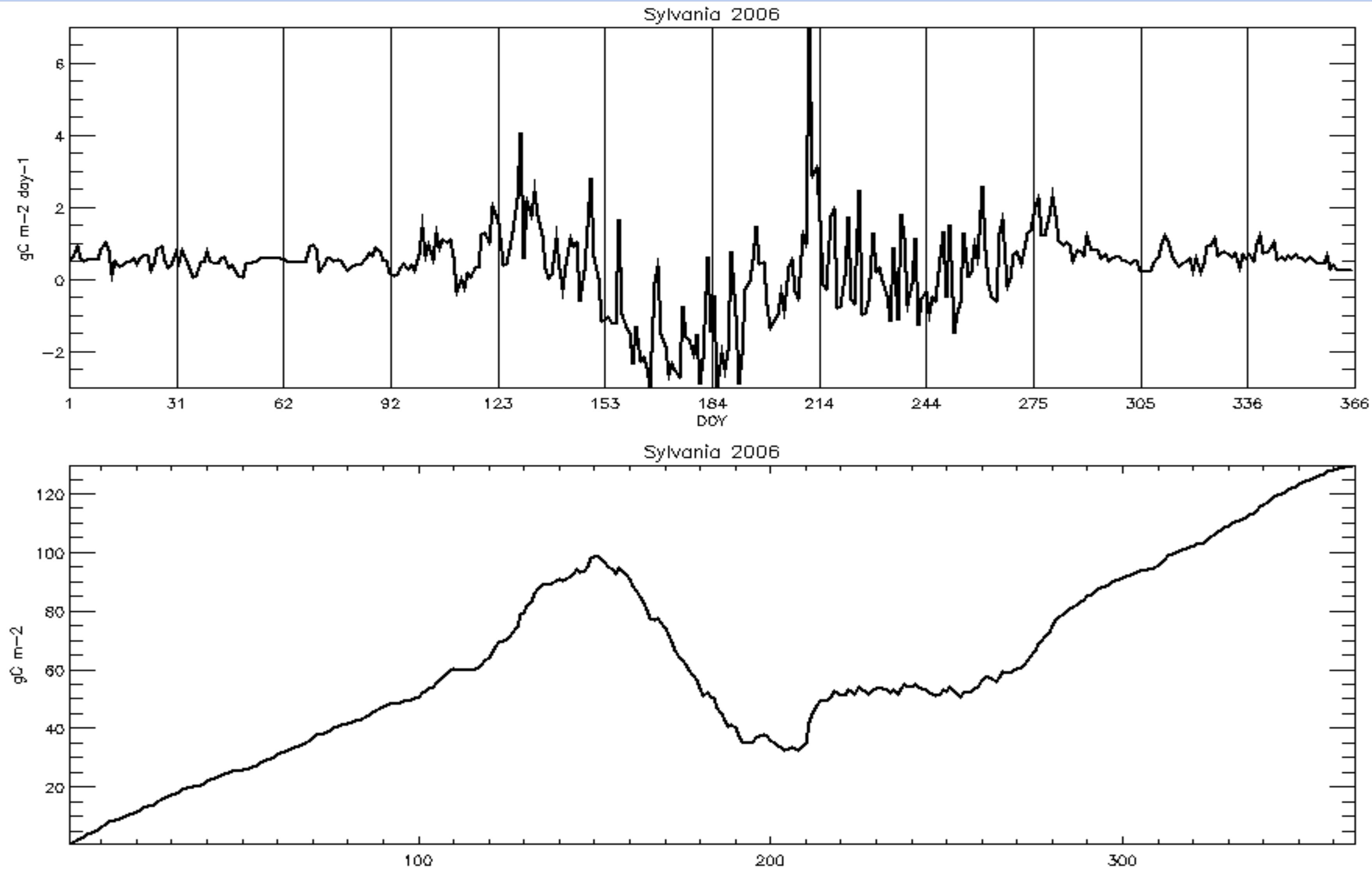
What we see


W (rotated) Wind Speed
m/s
3
2
1
0
-1
-2
0
5
10
15
20
Time (hrs)

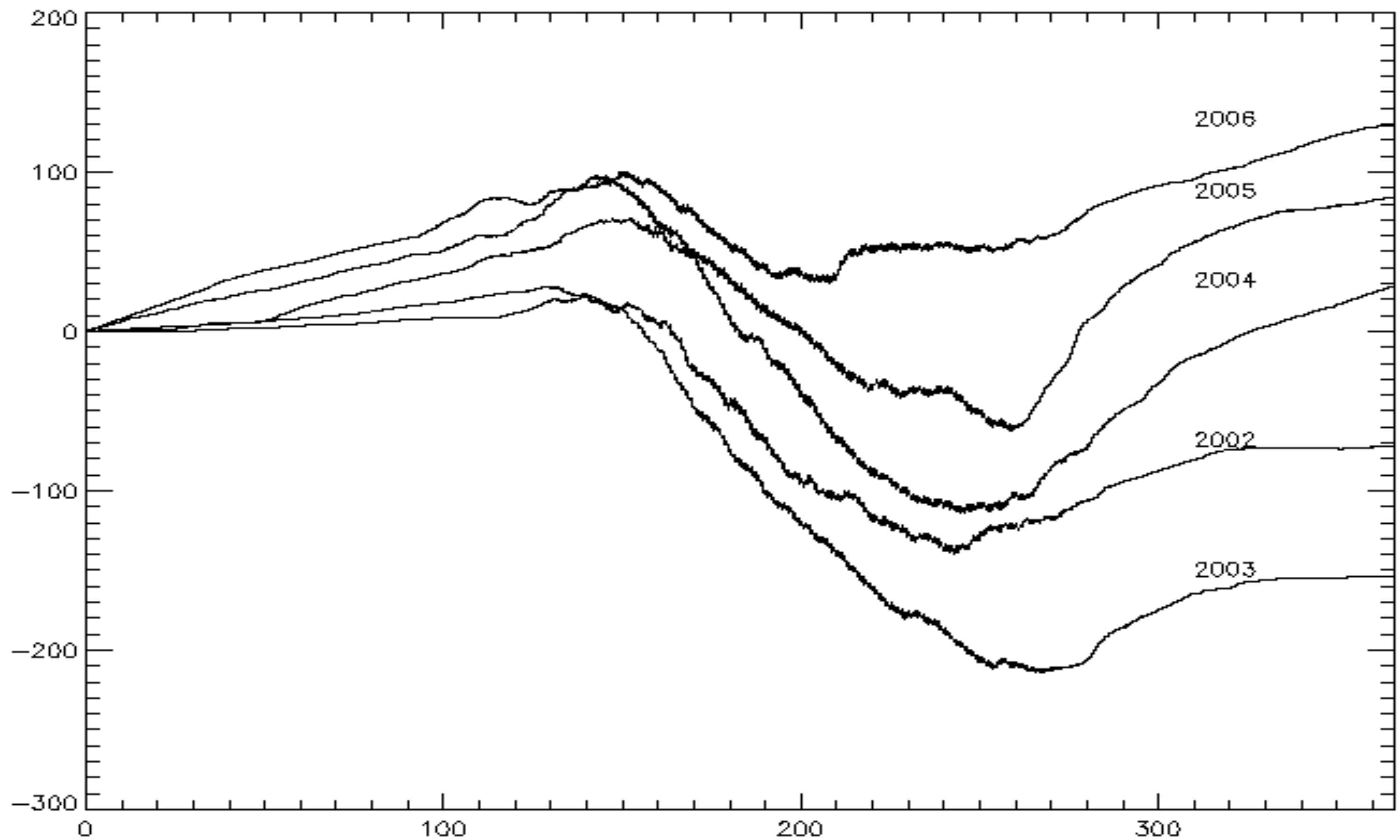

CO2 Mixing Ratio Top
ppm
400
390
380
370
0
5
10
15
20
Time (hrs)


CO2 Flux
umol/m2*s
5
0
-5
-10
-15
0
5
10
15
20
Time (hrs)

What we see

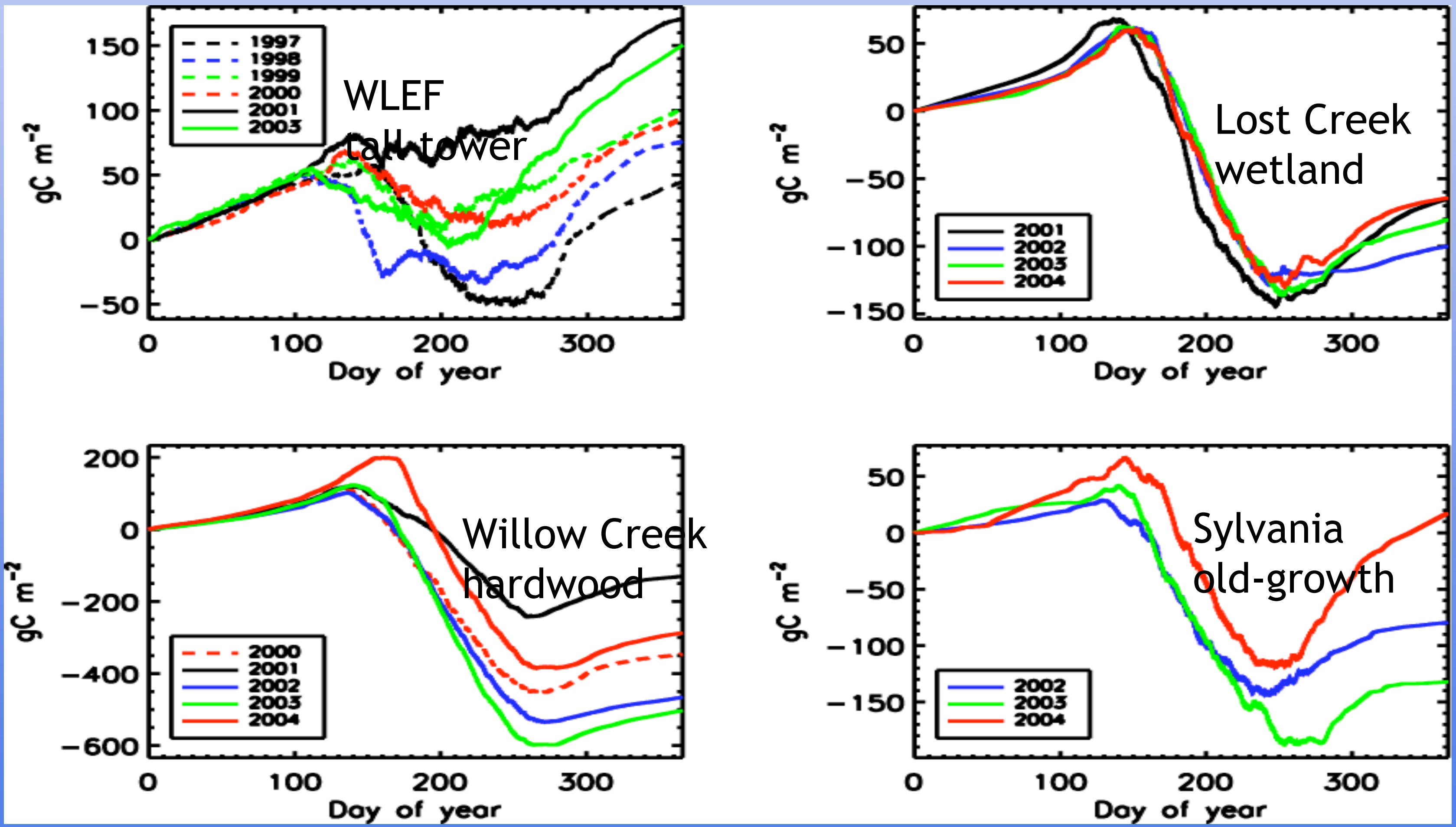

Sylvania 2006
gC m−2 day−1
6
4
2
0
−2
1
31
62
92
123
153
184
214
244
275
305
336
366
DOY
Sylvania 2006
gC m−2
120
100
80
60
40
20
100
200
300

What we see



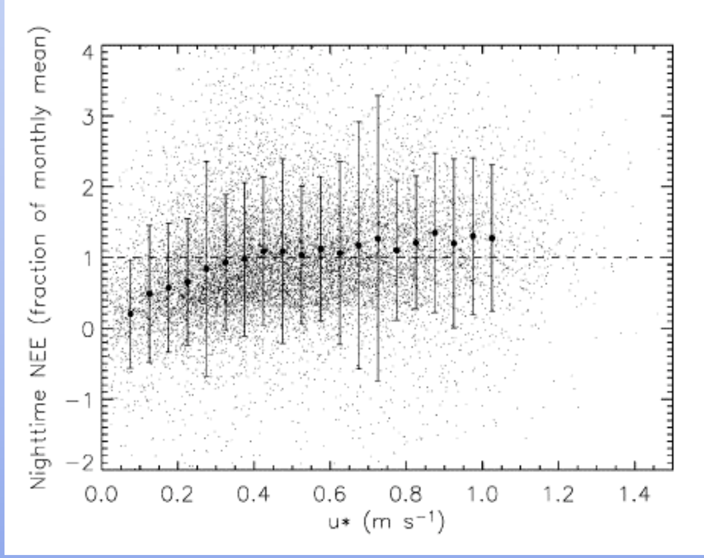
What we see

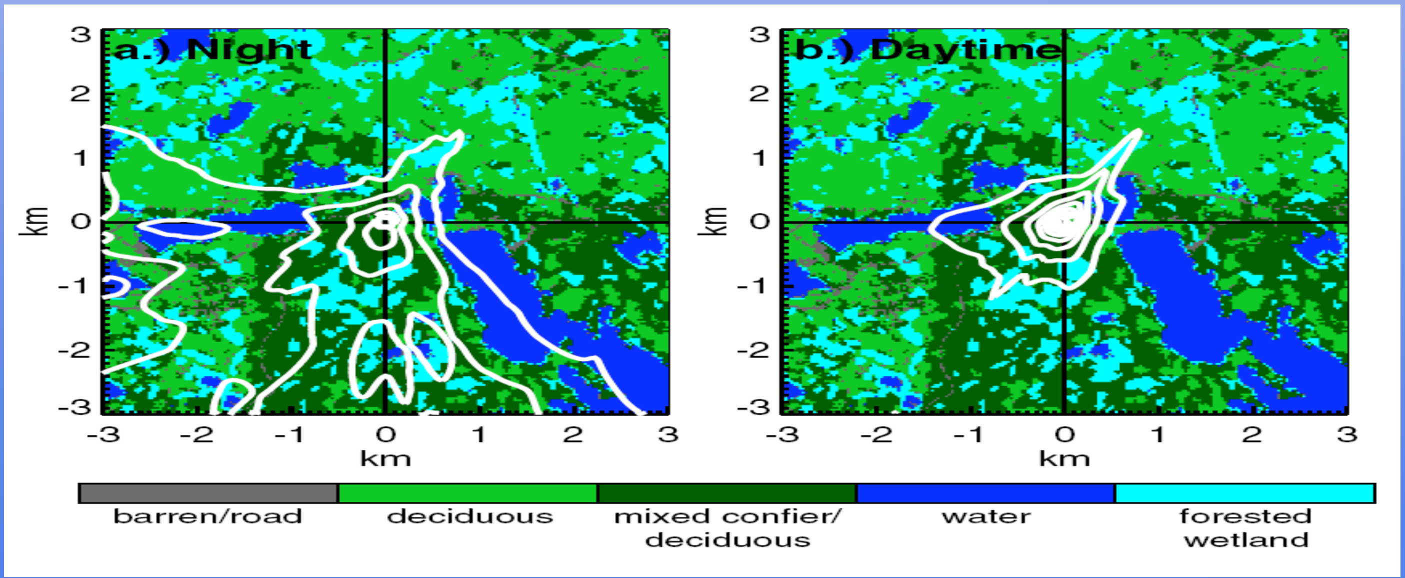
- Lots of variation, some coherence



What we don't see

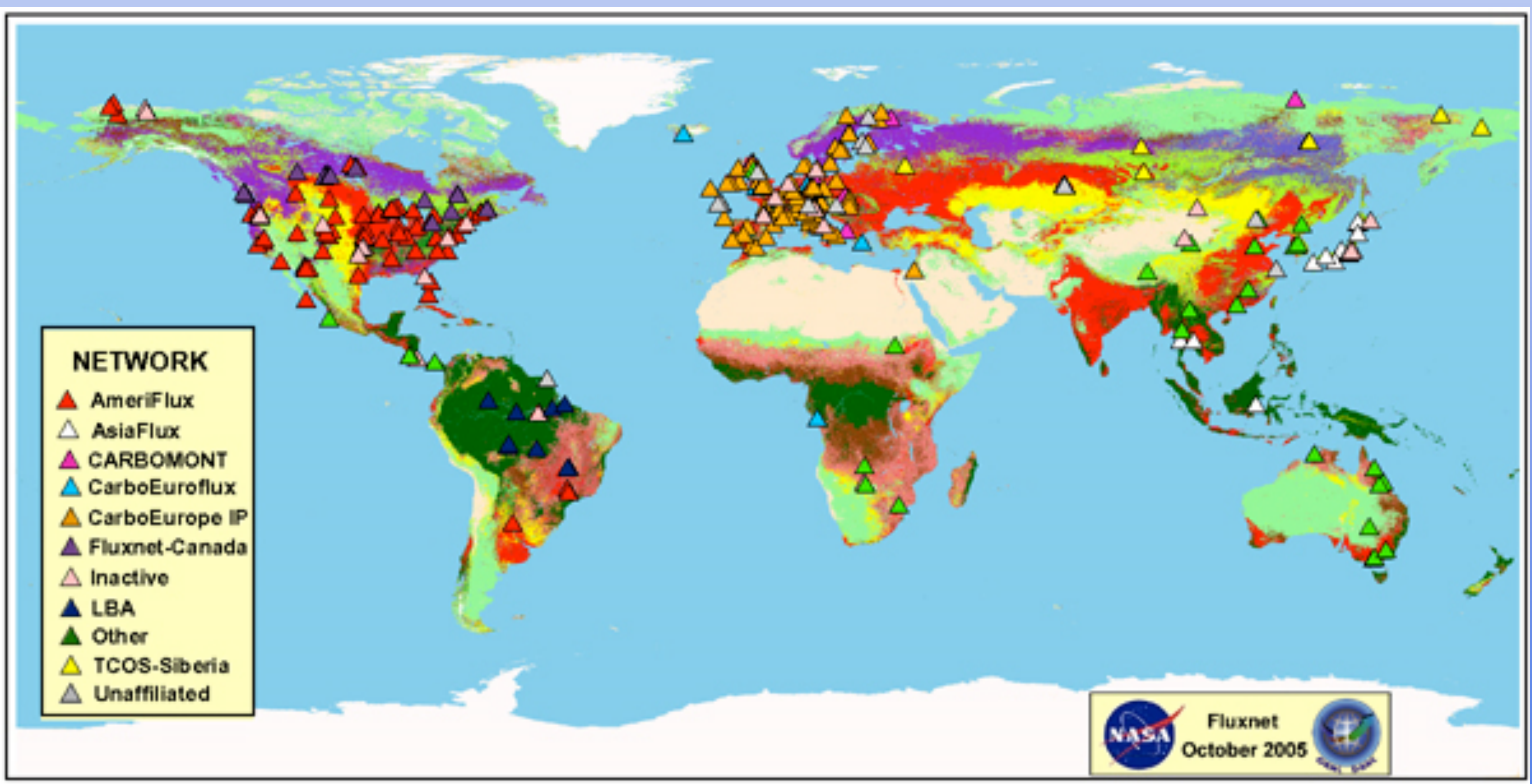
- Fluxes in low turbulence
- Constant "footprint"
- Components of flux
- Energy balance





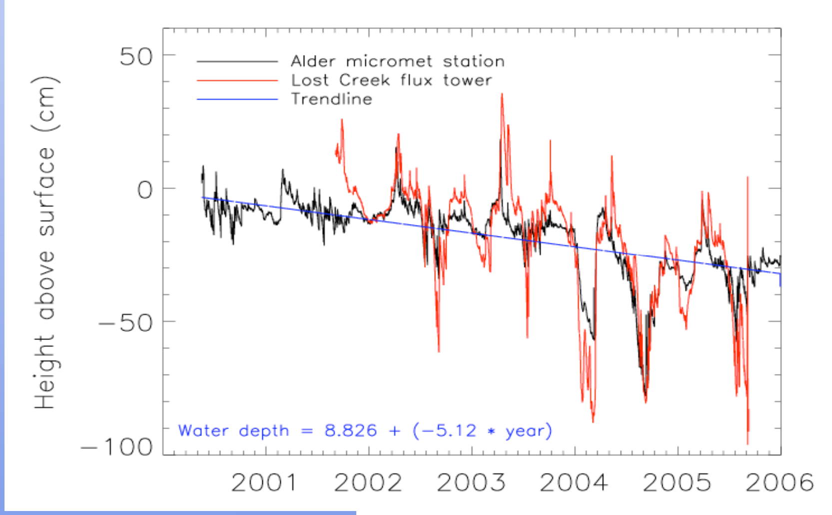
What we all see

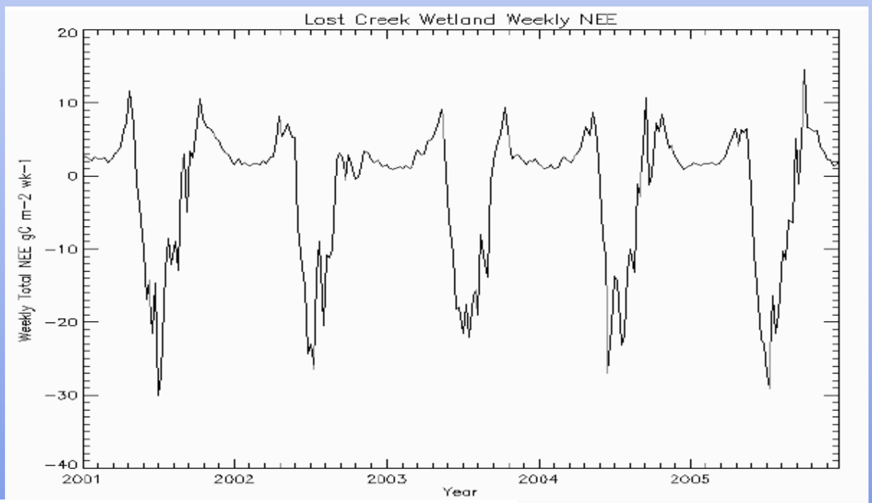
- Fluxnet database is growing!

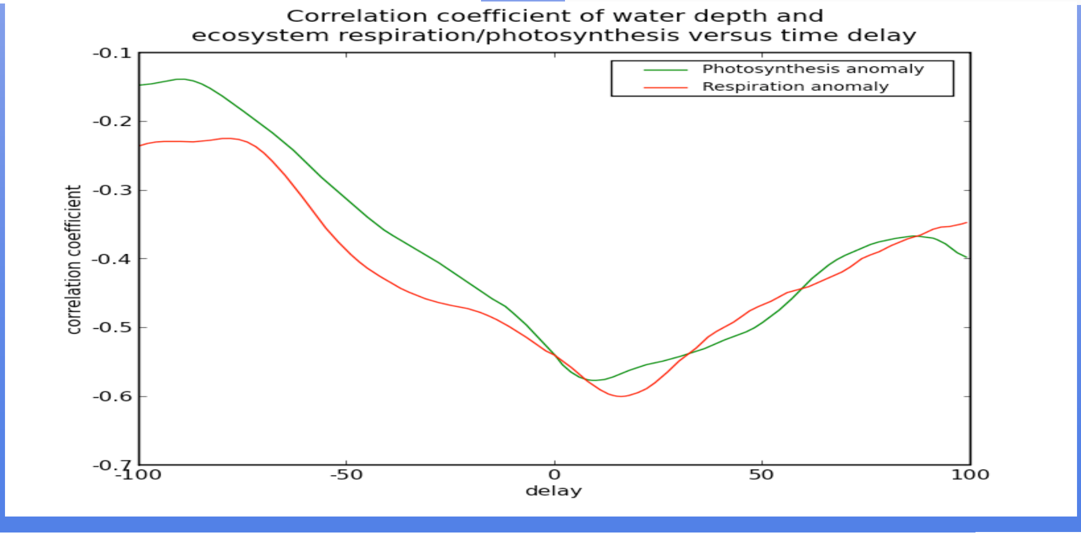


What it means

- Example: Carbon-water interactions in wetlands







Source:
B. Sulman

What it means

- Micrometeorological forcing (air/soil temperature, light, water) explains much of hourly and daily fluxes
- Synoptic forcing is important for understanding subweekly variability
- Larger time lags exist in seasonal forcing (snow melt, growing degree days, canopy / micromet interaction…)
- Fundamental rate reaction equations for photosynthesis, respiration, decomposition generally pan out
- Long term variation is driven by vegetation type and age since disturbance - not easily observed by EC

What it doesn't mean

- Cannot directly observe / constrain flux components (e.g., GPP)
- Parameters for many equations are not directly found from EC observations
- Large heteroscedastic noise in EC observations and high frequency of low turbulence events makes long term continuous time series from EC hard to develop
- Short term equations are non-linear, do not scale across averaging time
- Long term ecosystem evolution equations are not well understood or known
- Cannot simply scale or interpolate many flux measurements to get large region or global averages

Moral

- Observations are a good thing
- But they have no meaning without quality control
- Moreover, they have no meaning without good interpretation
- Can a model of land-atmosphere interaction help us out?

ACT III

In which we decide how to build a better model*

***Especially one that avoids Rube Goldberg syndrome**

Why a model?

- Complex, non-linear interactions are not easily understood with linear theory and empirical regression
- Meteorological models are sensitive to initial conditions
  - Initial observation characterization/ensembles is key
- But ecosystem models, like climate models, are more sensitive to boundary conditions (forcing)
  - Therefore, parameter estimation and trends in forcing become more important

Why data assimilation?

- Old way:
  - Make a model
  - Guess some parameters
  - Compare to data
  - Publish the best comparisons
  - Attribute discrepancies to error
  - Be happy

Why data assimilation?

- New way:
  - Constrain model(s) with observations
  - Find where model or parameters cannot explain observations
  - Learn something about fundamental interactions
  - Publish the discrepancies and knowledge gained
  - Work harder, be slightly less happy, but generate more knowledge

The basic idea of assimilation

[A|B] = [AB] / [B]

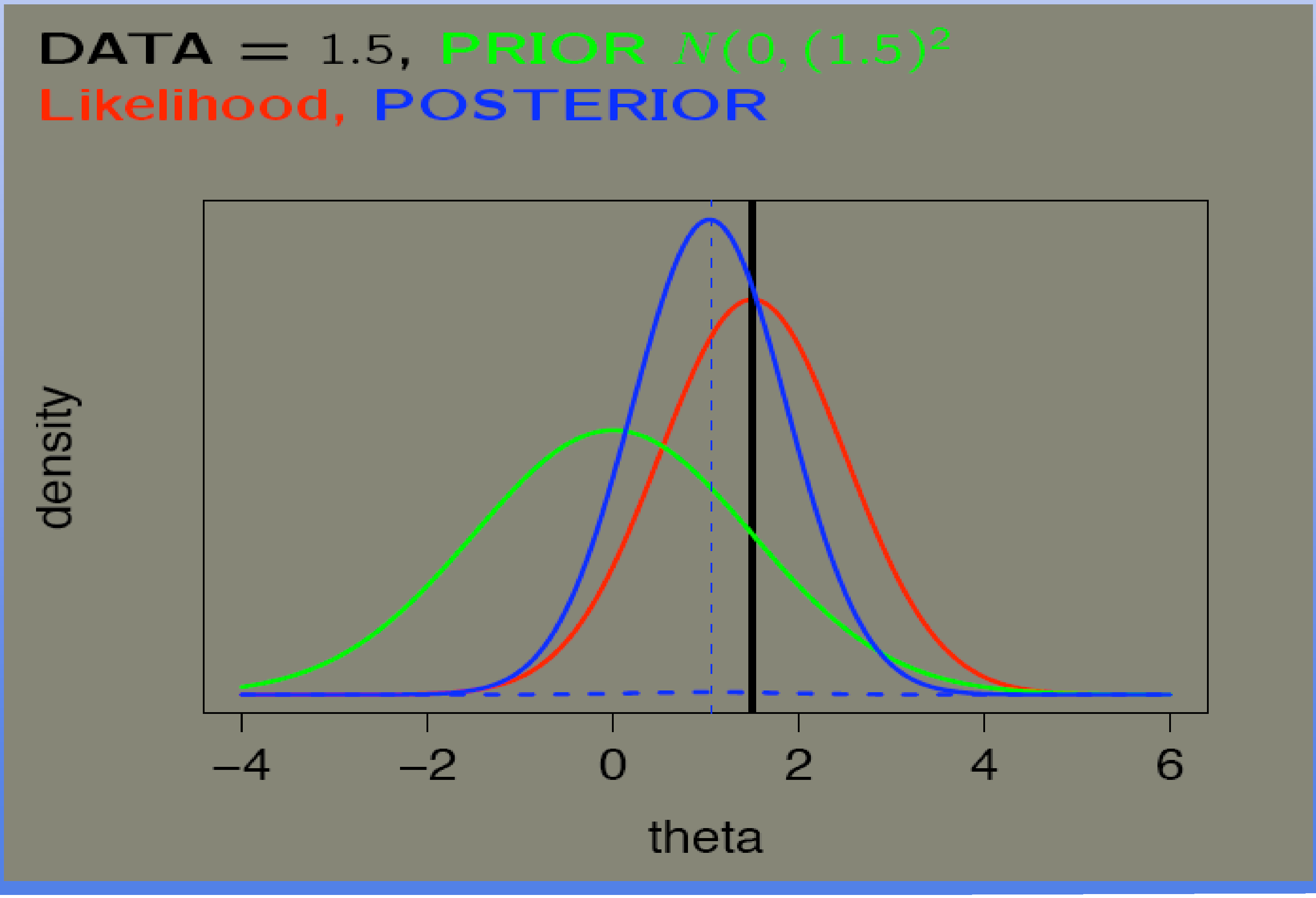
[P|D] = ([D|P] [P]) / [D]

(parameters given data) = [(data given parameters)×
(parameters)] / (data)

Posterior = (Likelihood x Prior) / Normalizing Constraint

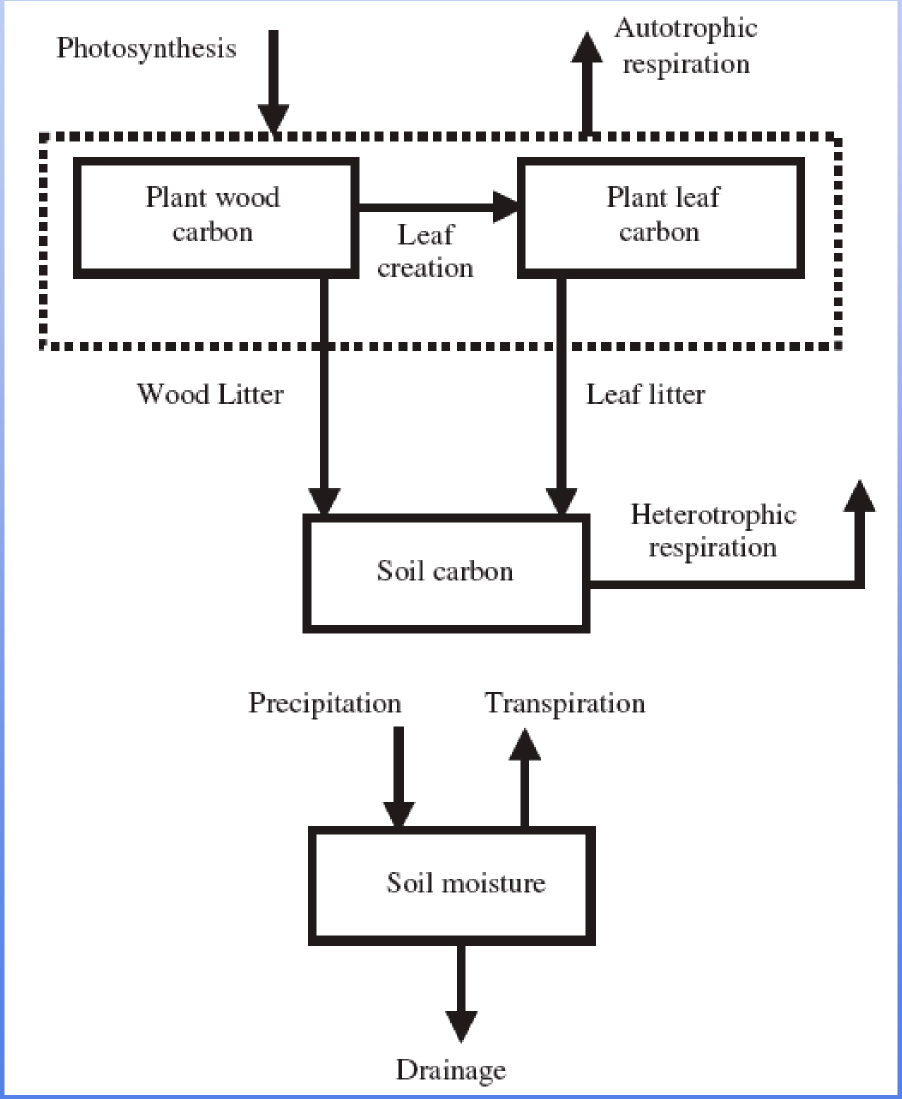
The basic idea of assimilation

- Courtesy of D. Nychka, NCAR



Model of the day: Sipnet

- A simplified model of ecosystem carbon / water and land-atmosphere interaction
  - Minimal number of parameters
  - Driven by meteorological forcing
- Braswell et al., 2005, *GCB*
- Sacks et al., 2006, *GCB* added snow

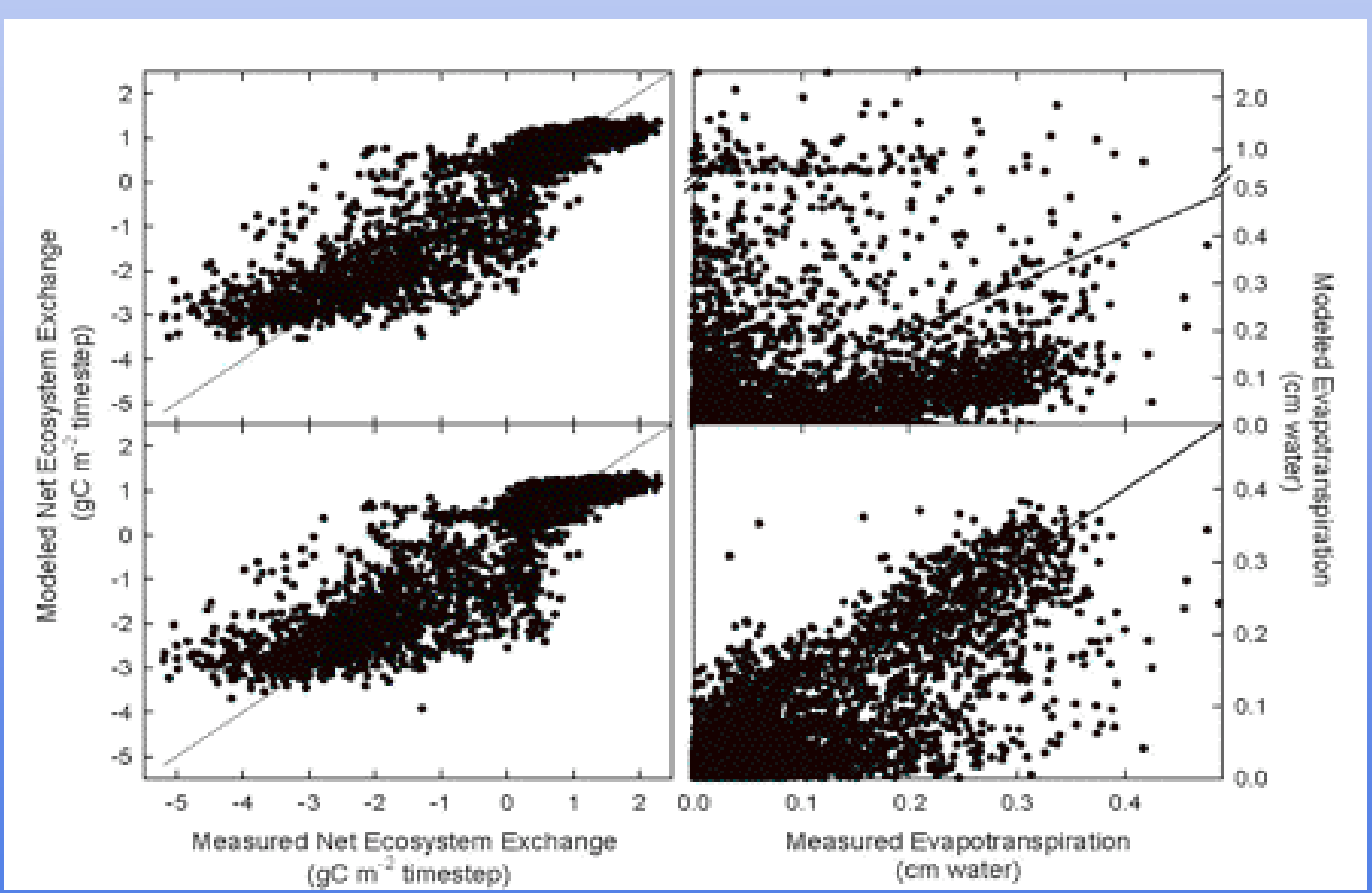


Hip-hop sensation: MC MC

- Markov Chain Monte Carlo (MCMC)
  - A quasi-random walk in parameter space (Metropolis-Hastings algorithm)
  - From a prior parameter distribution, move in parameter space to minimize model-data RMS
    - ~100,000 iterations
    - Apply posterior parameters to get posterior "best" fit dataset and confidence
  - In Sipnet, NEE and LE fluxes from eddy covariance can be used to constrain the model using MCMC
    - Sipnet runs really fast (100 ms)

Case study 1: Sipnet Niwot Ridge

- D. Moore, in review, *Ag. For. Met.*



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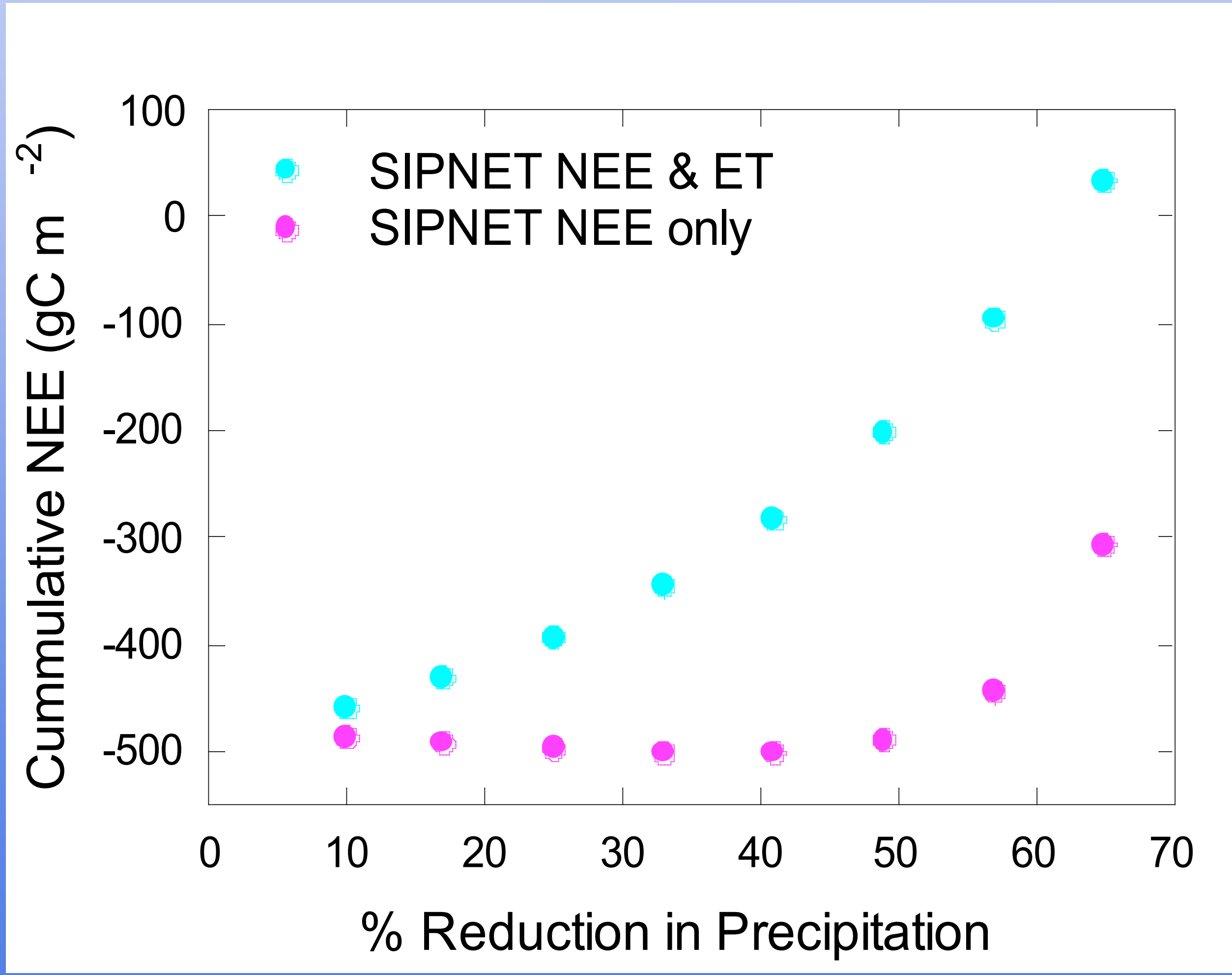
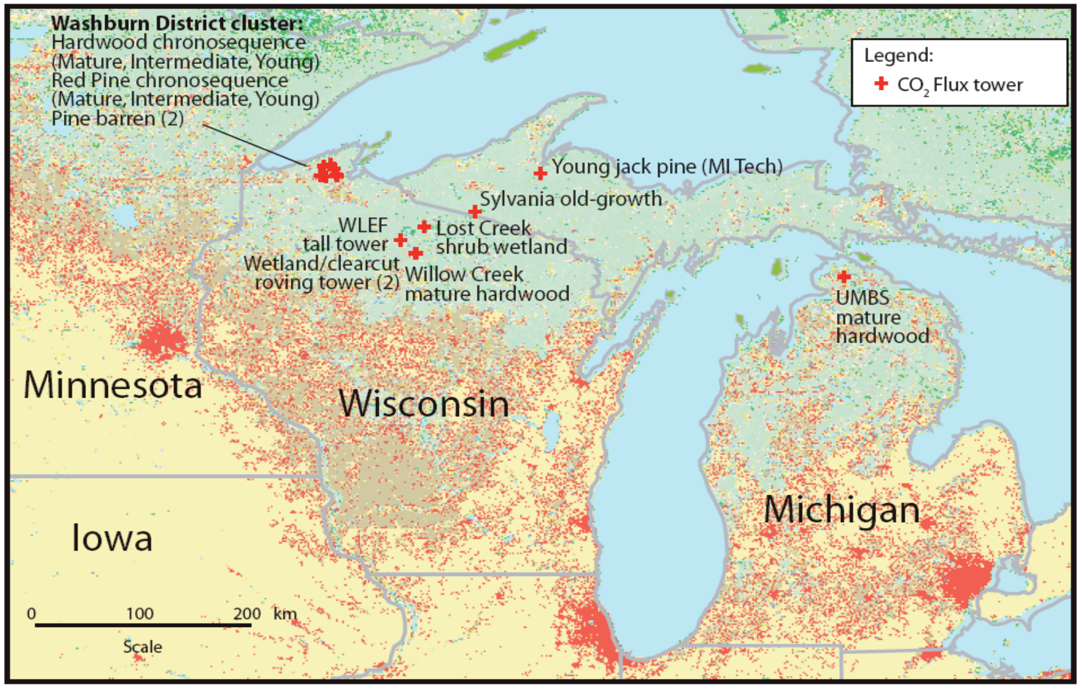


Case study 2: Sipnet WLEF

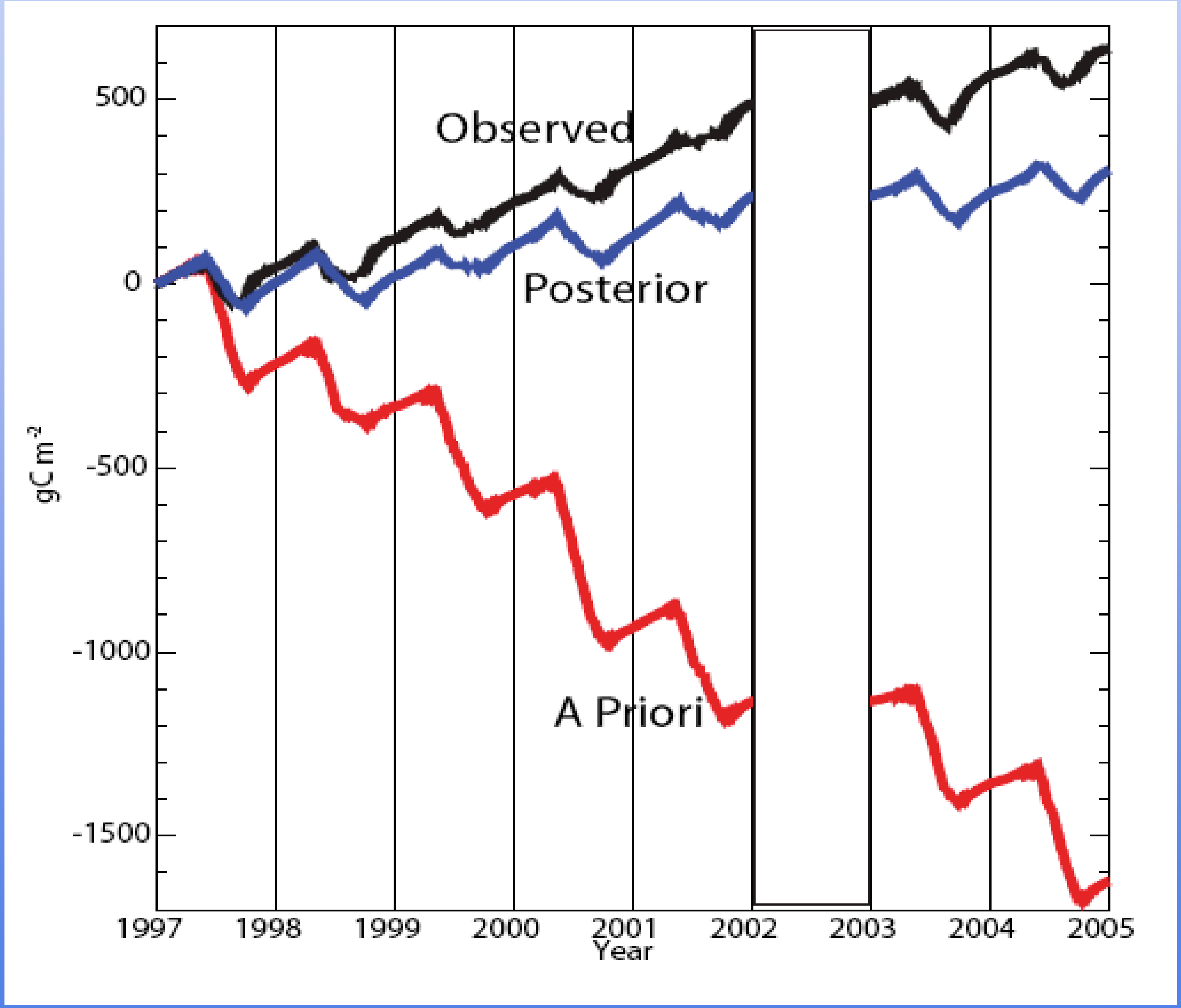
- Part of ChEAS project…
- 30m 122m 396m fluxes of CO_2, H_2O, H, u*



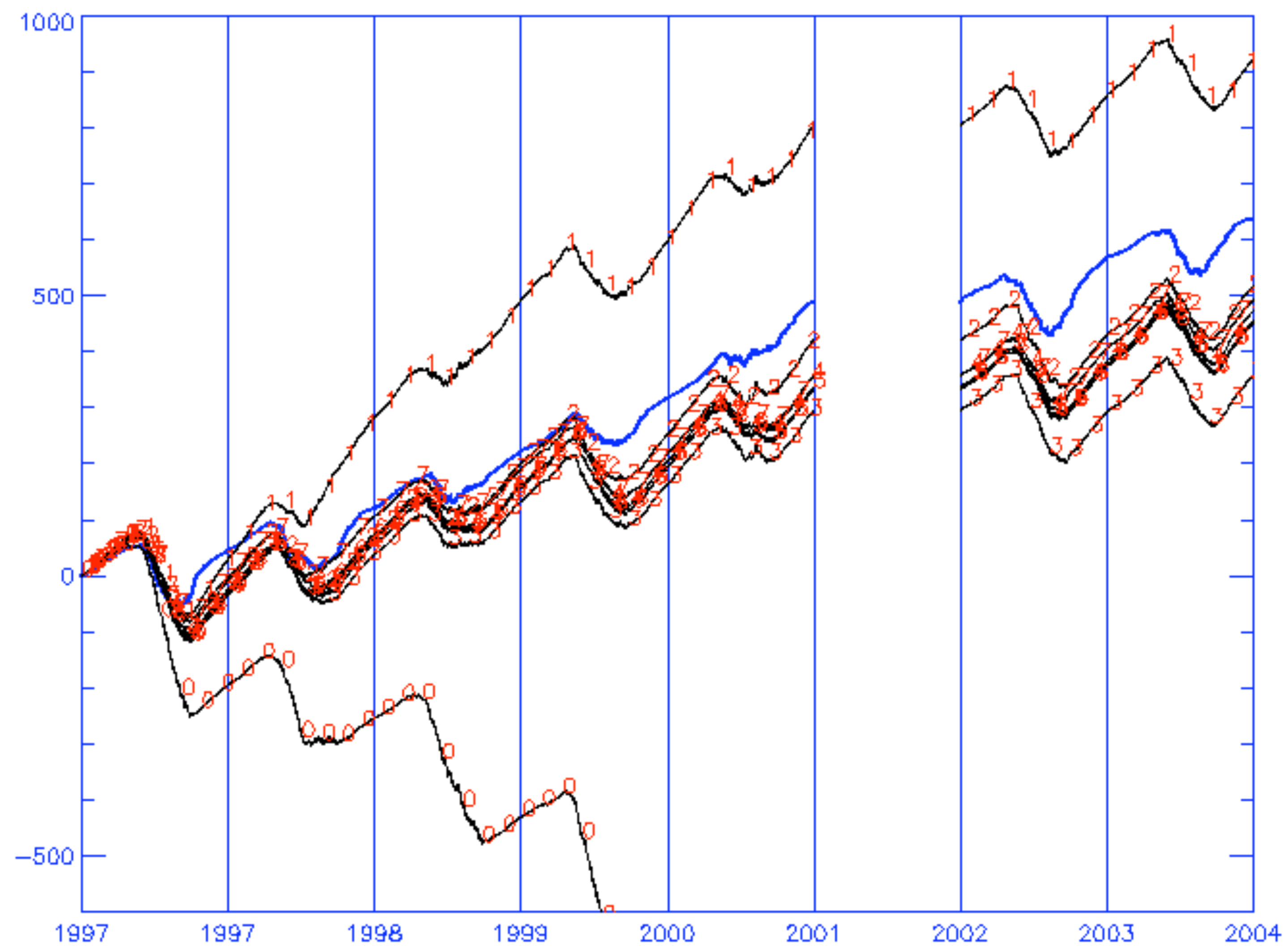
Case study 2: Sipnet WLEF

	Prior	Posterior
Growth related parameters		
photosynthetic capacity (amax)	112	58.6 +/- 2.2
growth respiration fraction	0.33	0.34 +/- 0.06
VPD modifier slope	0.05	0.066 +/- 0.009
Half saturation PAR	17	9.0 +/- 0.76
Light attenuation	0.5	0.67 +/- 0.02
WUE factor	10.9	13.4 +/- 0.46*
Decomposition parameters		
Lloyd-Taylor E0	309	448 +/- 121
Lloyd-Taylor T0	-46	-59.5 +/- 10.6
Turnover rate	0.03	0.19 +/- 0.02

Case study 2: Sipnet WLEF



Case study 2: Sipnet WLEF



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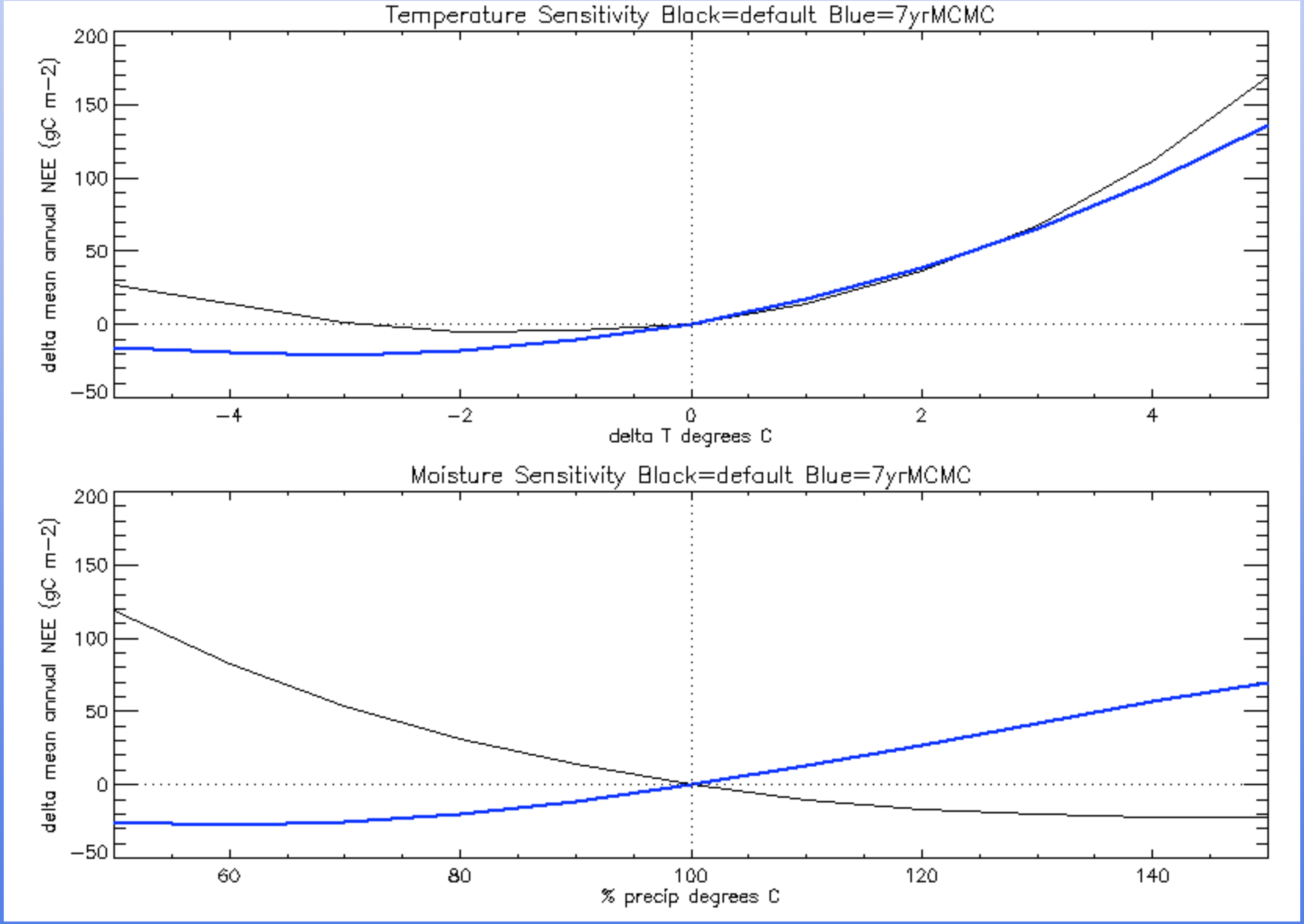
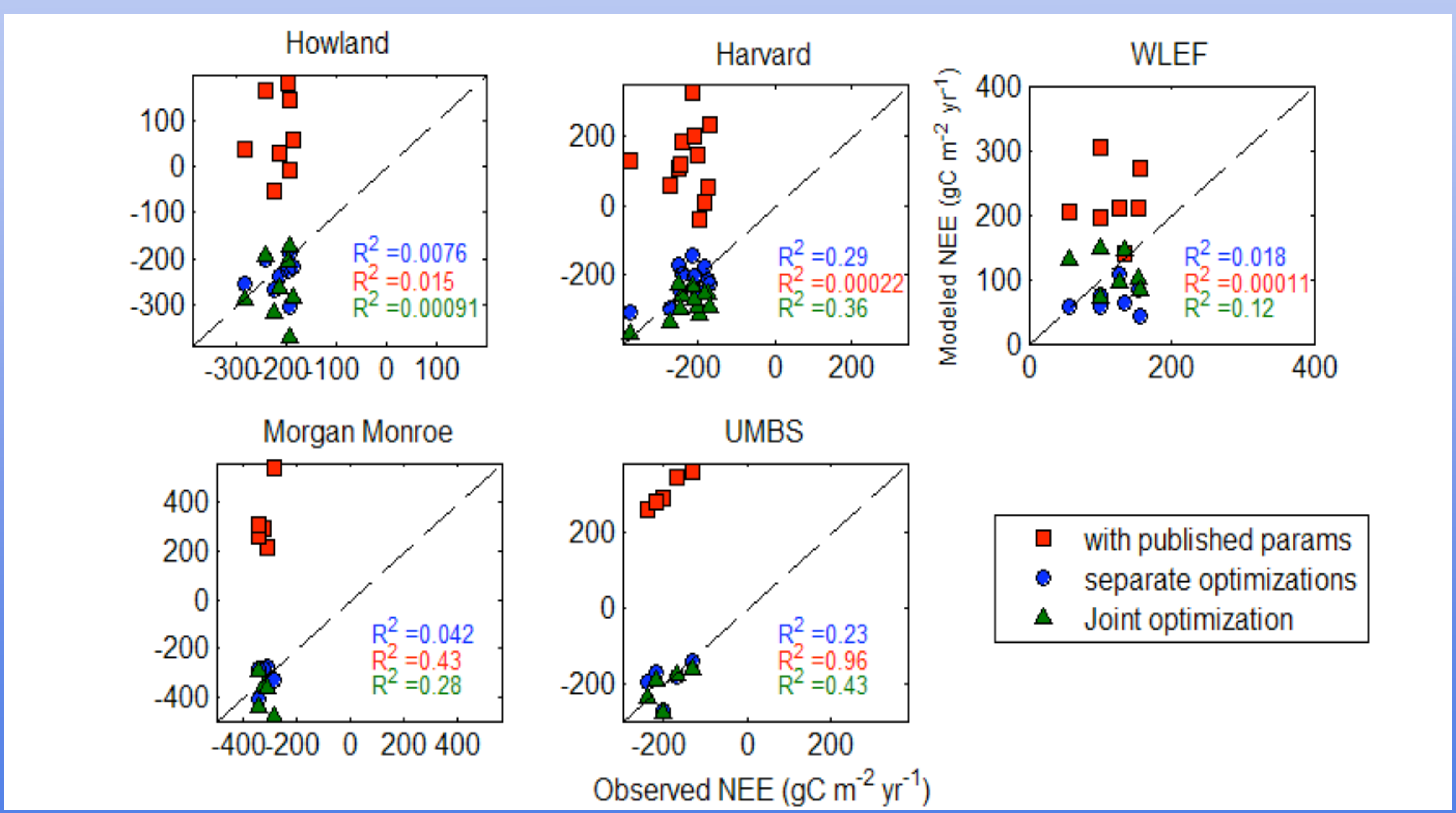


Caveat: Interannual variability

- Ricciuto et al., in prep, Ag. For Met.

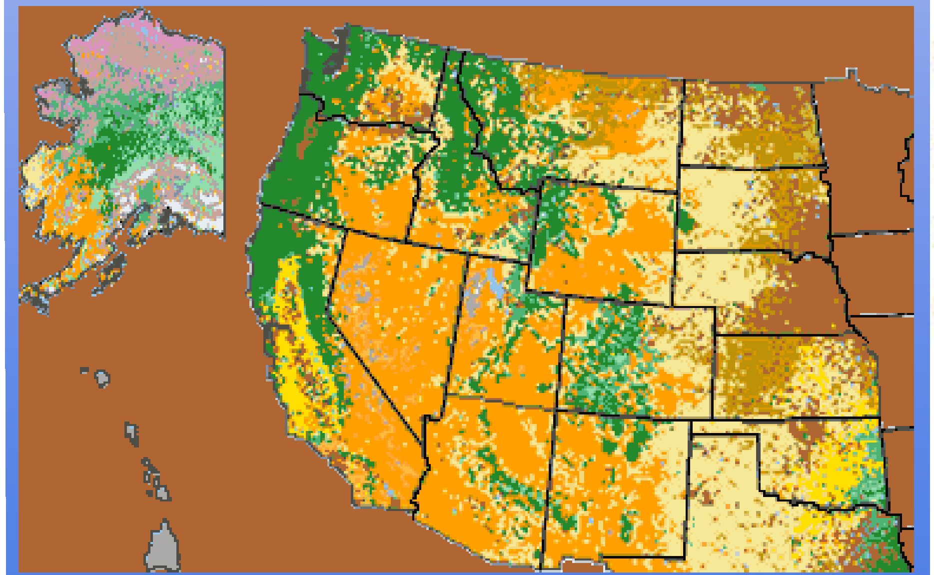


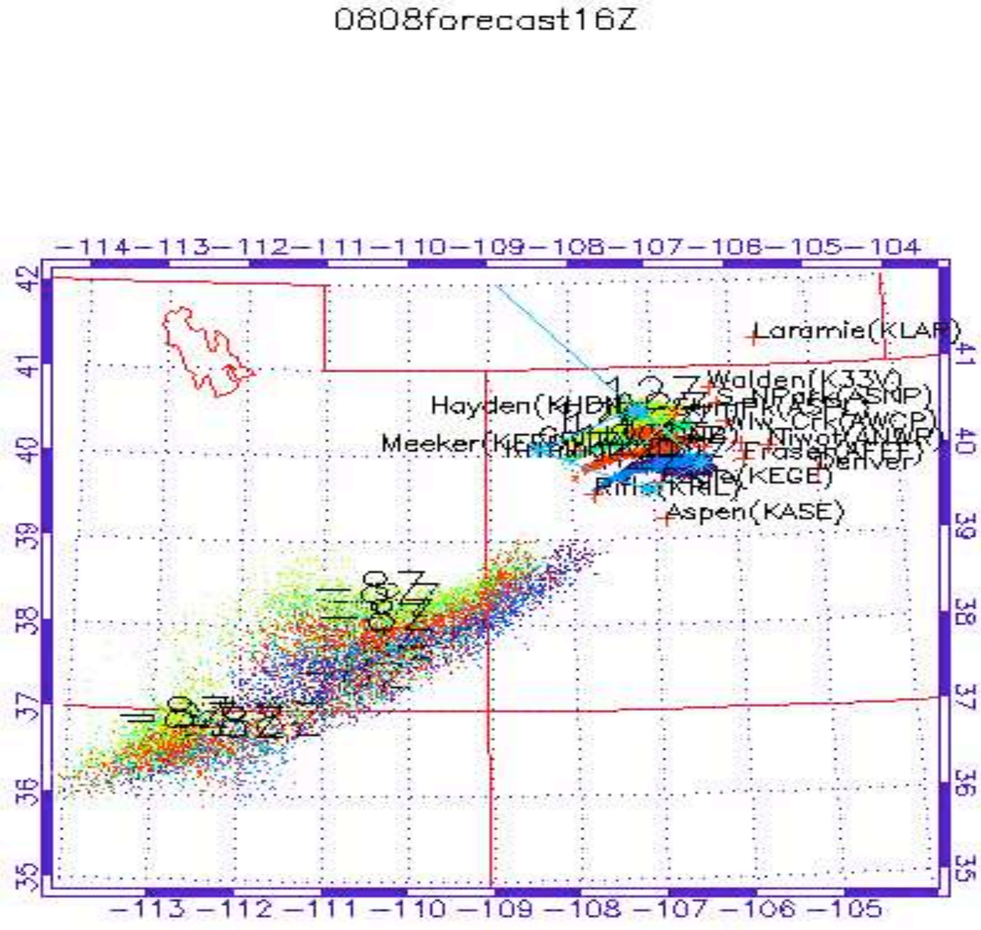
A brief word on other techniques

- MCMC isn't good for slow models and for real-time forecasting
- Variational assimilation, Kalman filters, matrix inversion, etc… all have potential (mostly underutilized)
- Ensemble Kalman Filter (EKF) is particularly appealing for constraining regional scale ecosystem models with atmospheric observations

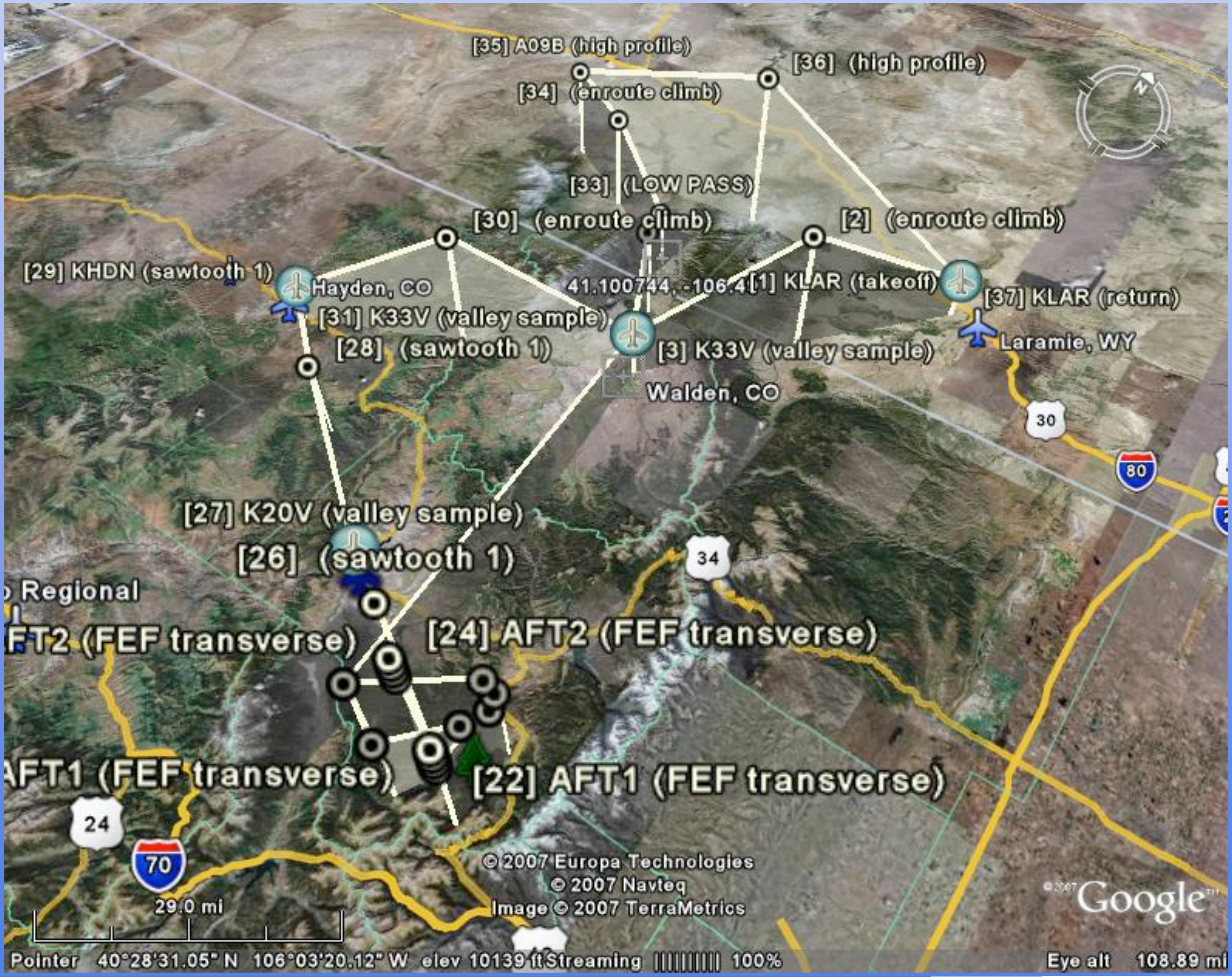
Case study 3: ACME 2007

- Airborne Carbon in the Mountains Experiment

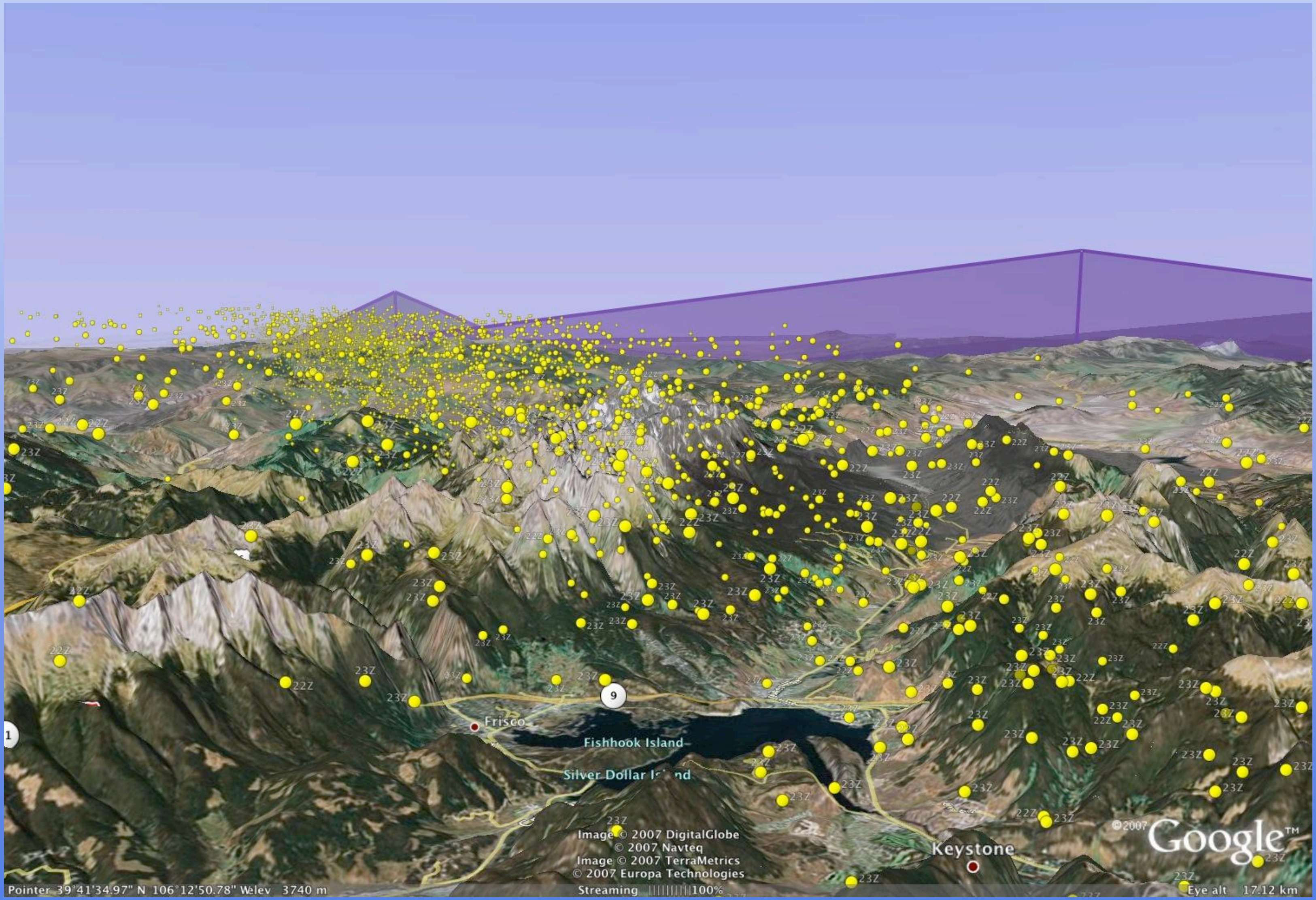




Case study 3: ACME 2007



Case study 3: ACME 2007

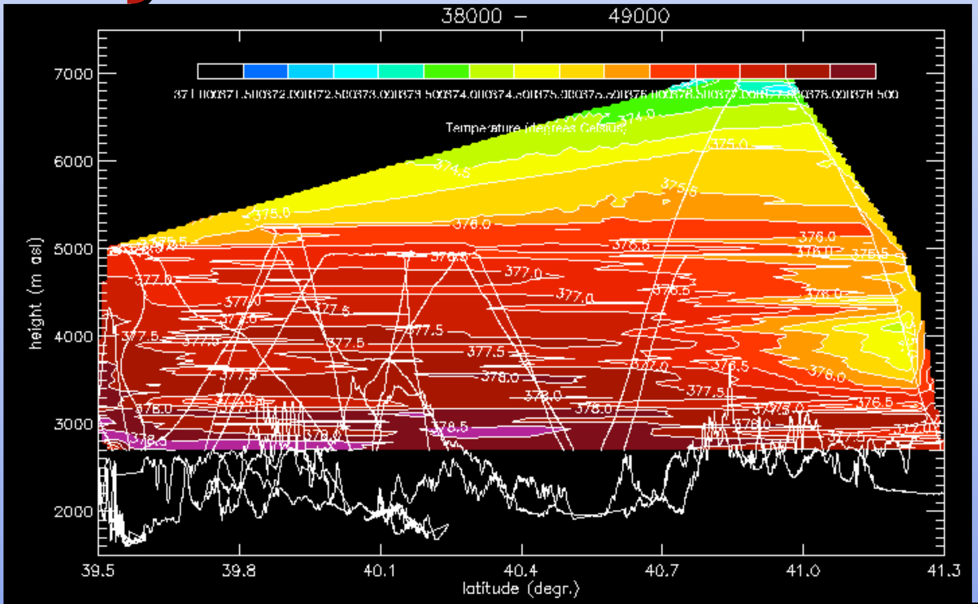


Case study 3: ACME 2007

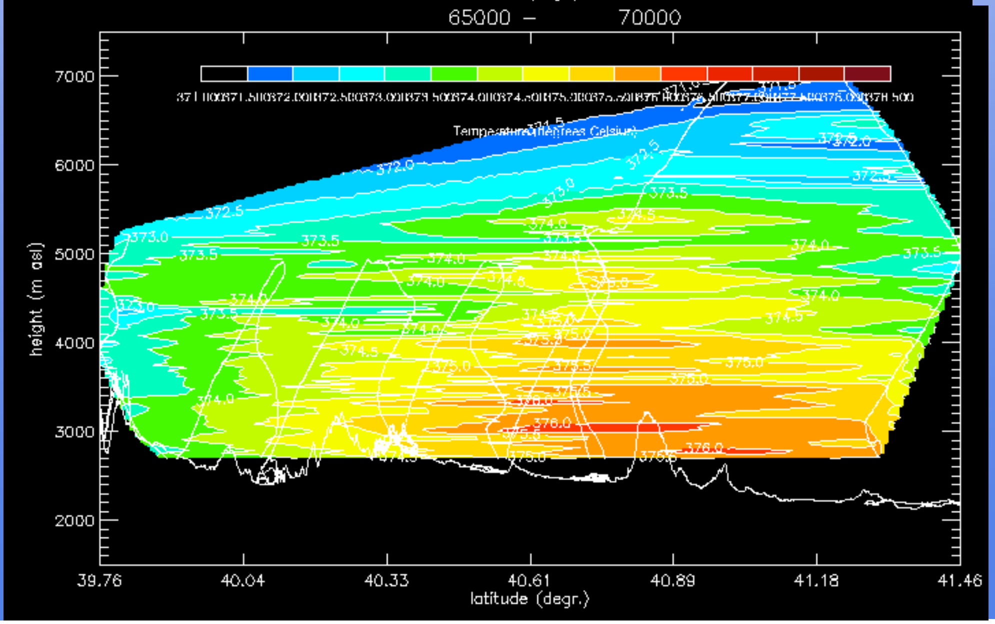
Case study 3: ACME 2007

CO_2

MORNING
UPWIND



AFTERNOON
DOWNWIND



Moral

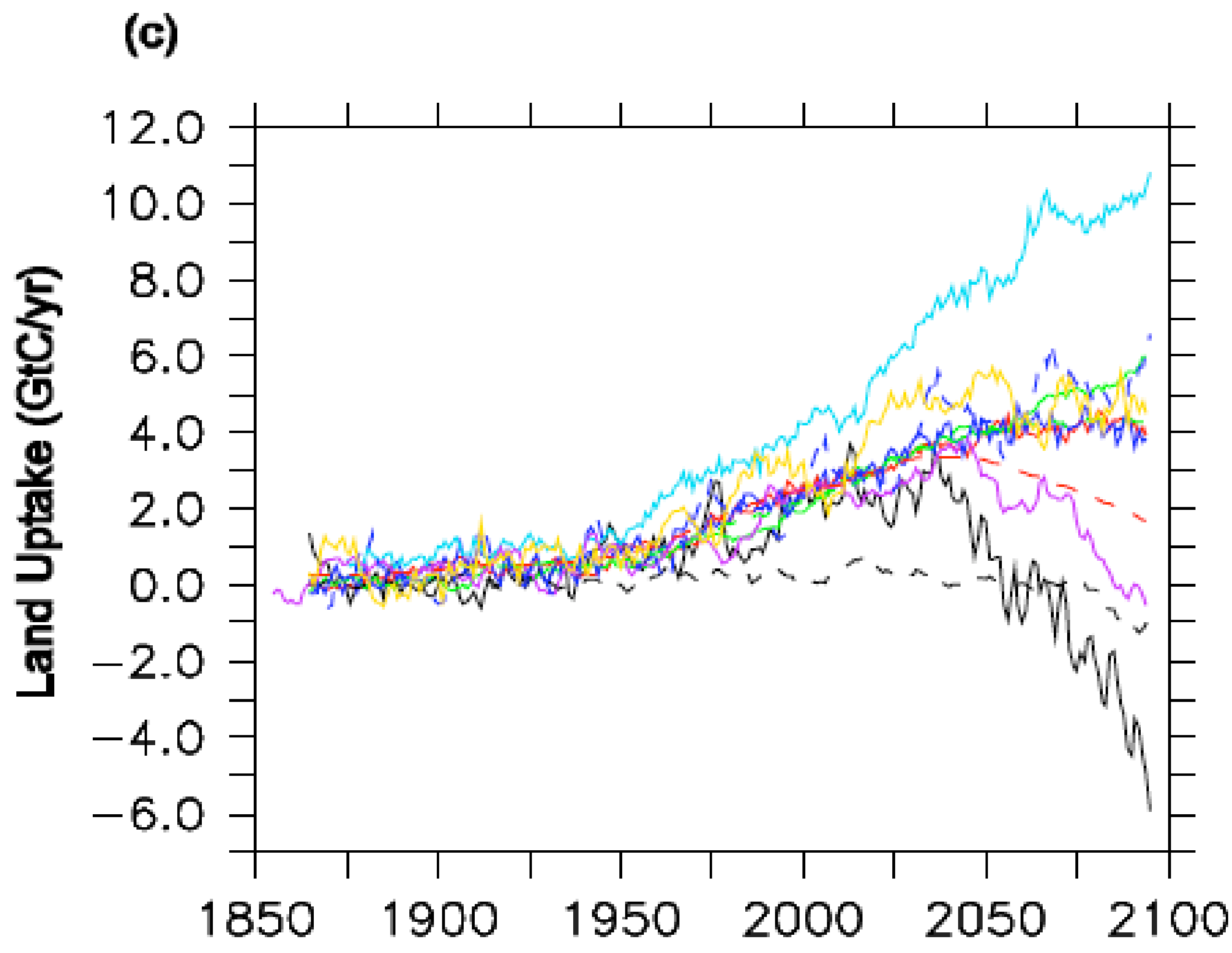
- Data assimilation and parameter estimation help us move beyond scratching heads over errors in observations and model logic
- Formal ways to estimate fluxes and parameters are not necessarily hard to understand or implement
- Assume large spread in prior parameters in land-atmosphere models
- Long-term and high density datasets can have value beyond their original purposes

ACT IV

Dénouement or Sequel:

Where do we go from here?

Remember this?



What's up?

- Eddy covariance is a mature technology, but QC and fundamental physics issues do remain
- We're just at the stage with the flux tower network to get major global results on ecosystem-atmosphere interactions
  - Potential to even impact weather forecasting
- Coupled carbon-climate modeling
  - More focus on canopy radiation profiles, turbulence, albedo, feedbacks
- Moving from carbon to biogeochemistry ($C:N:P:H_2O$)
  - From microbes to people
- Regional analyses with model-data fusion
- Working in "hard" places

What my lab does or plans to do

- ChEAS
  - Carbon-hydrology-climate interactions in small wetlands and lakes
  - Ecosystem modeling and data assimilation with flux tower mesonets and long-term datasets
  - Scaling of regional land-atmosphere fluxes from top-down and bottom-up techniques
  - *Forest management and climate change interactions*
  - *Beyond CO_2: the role of CH_4, atmospheric chemistry*
- ACME - Airborne tracers to constrain biogeochemistry in complex terrain
- Lake Superior carbon cycling
- *Fluxnet "many tower" syntheses*
- *The advection problem*
- *Fundamental boundary layer, micromet and turbulence studies*

Moral

- The grand global experiment isn't stopping anytime soon
- There's lots to do and lots of data!
- Multidisciplinary work is hard, but rewarding
- We need good students

Thanks

- Desai lab and friends: Ben Sulman, Jonathan Thom, Shelley Knuth, Bill Sacks
- Project teams: Sipnet, ChEAS, ACME07
- Funding: DOE NICCR, NSF, USDA, NSF/NCAR

- Come visit: AOSS 1549, desai@aos.wisc.edu
- More info: http://flux.aos.wisc.edu