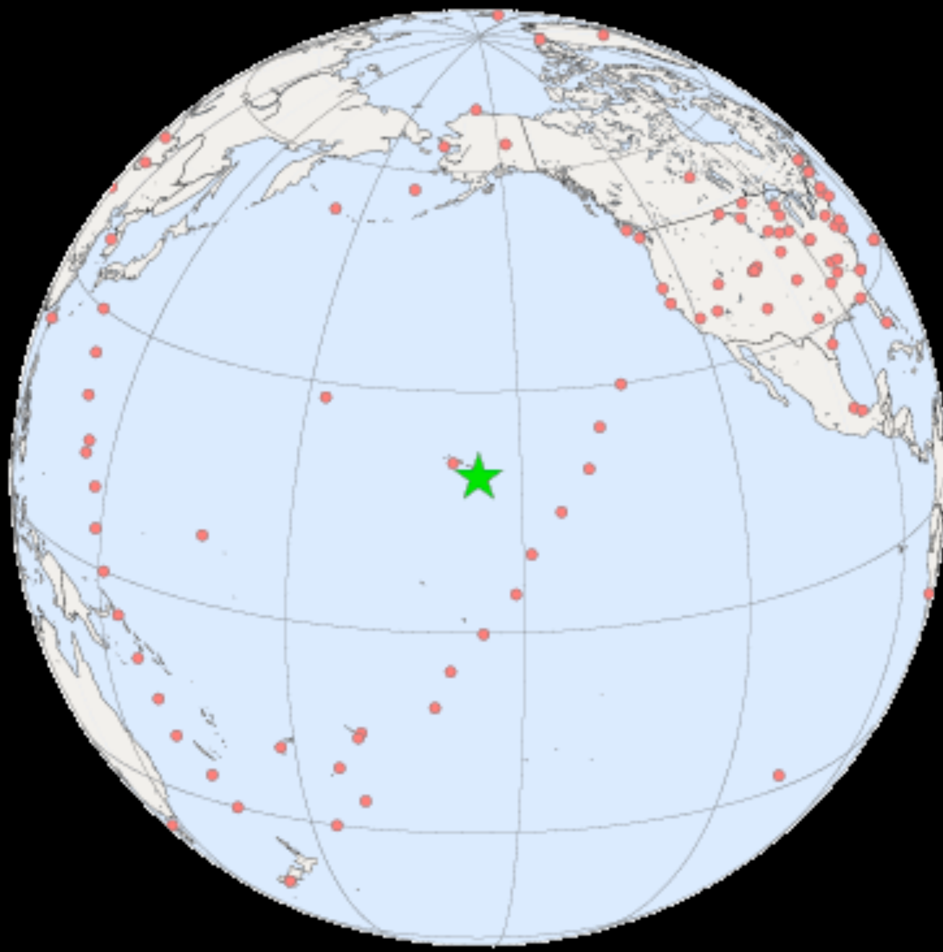
The Art of Doing the Problem Wrong:
(as opposed to doing the wrong problem)
Underdeterminacy in the Carbon Cycle

Andy Jacobson, CIRES & NOAA

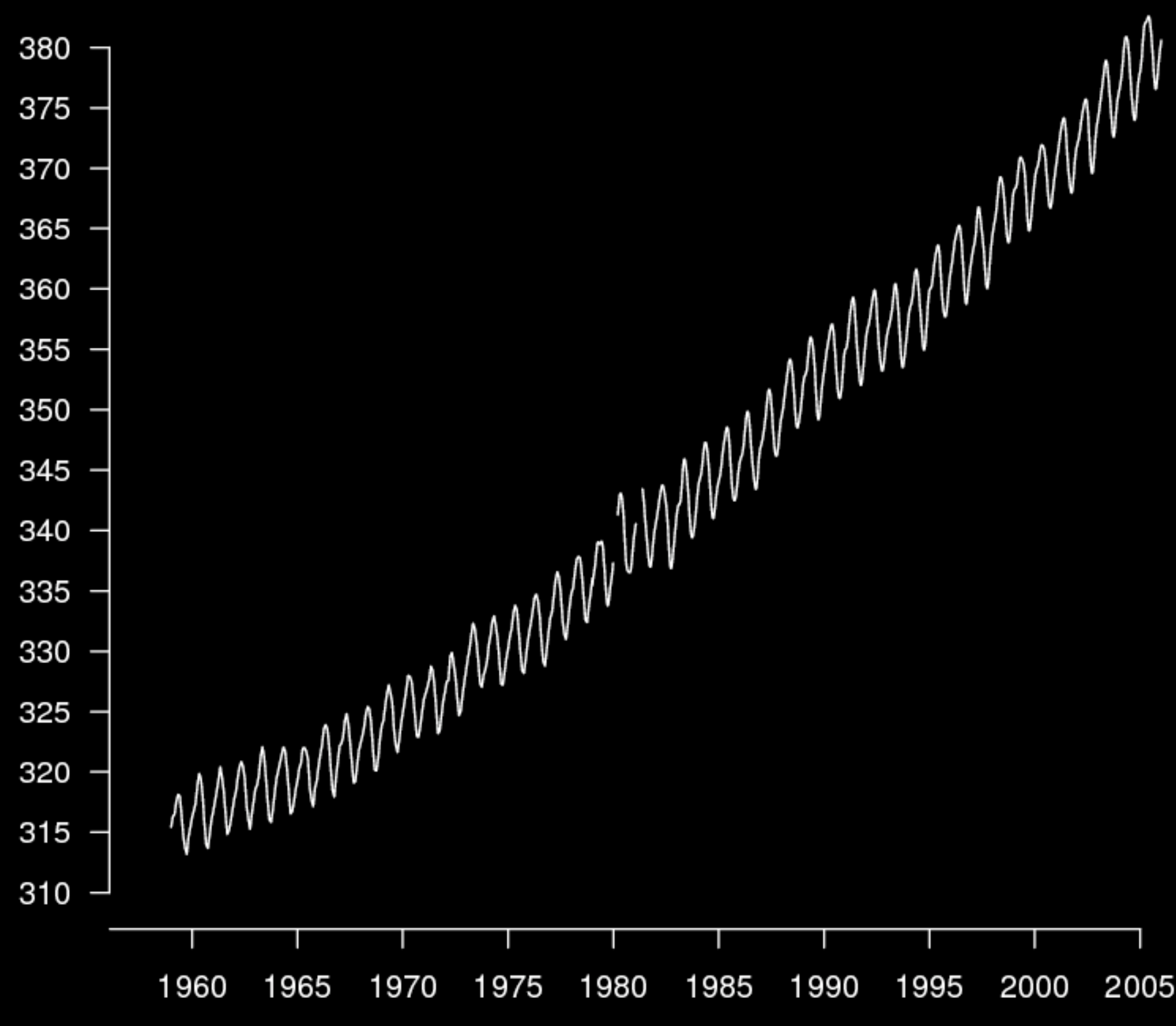
Outline
1. Atmospheric CO_2 gradients
2. Inversions find a large sink!
3. Novel measurements
4. Comparing forward & inverse models

Topics
1. What conclusions are robust?
2. Use of biased models & MIPs
3. Rich, interesting dataset!
4. Footprint of an observation – scale of analysis
5. How best to reconcile models and data

the Mauna Loa record



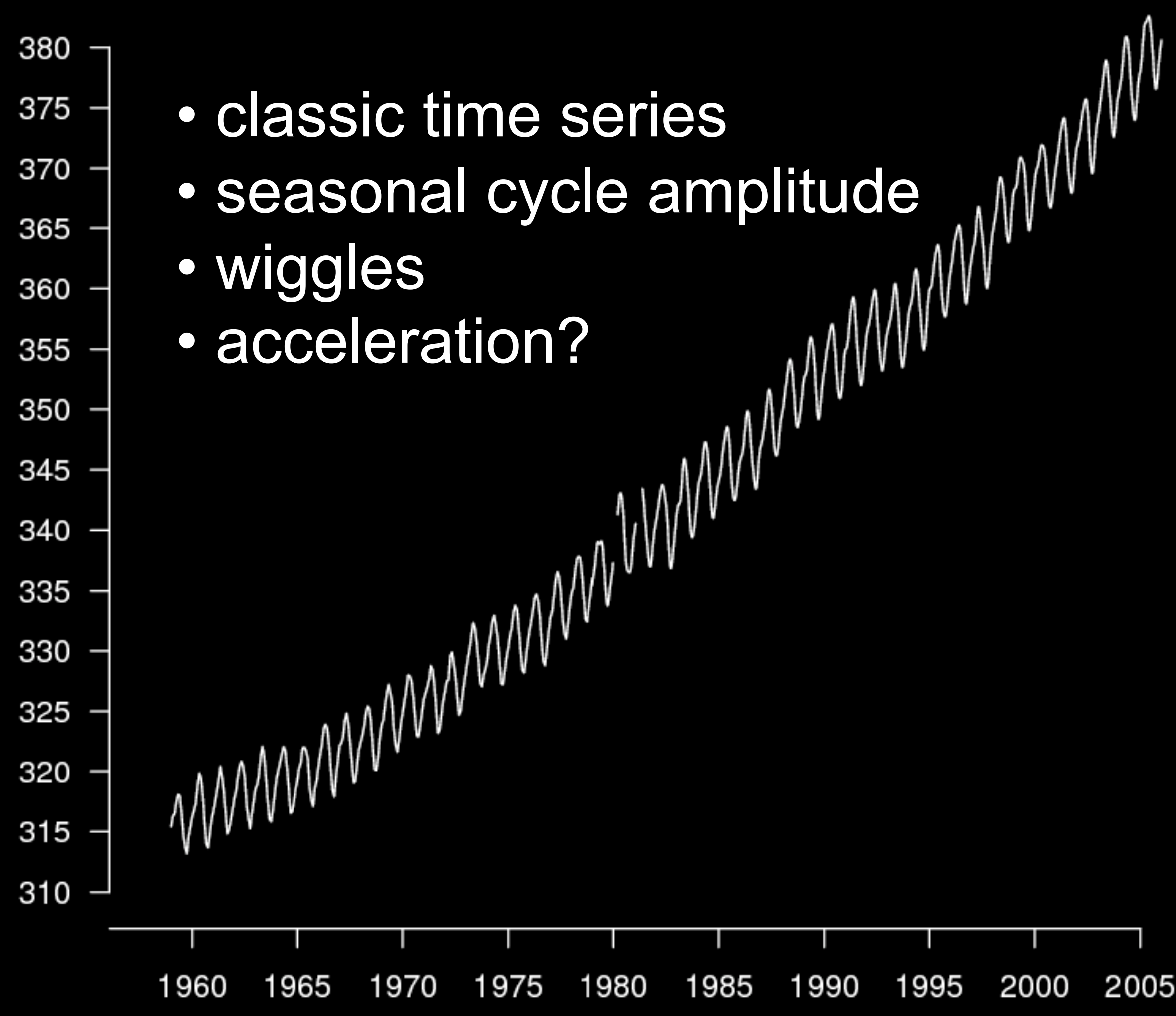
the Mauna Loa record



Data: Scripps CO_2 program

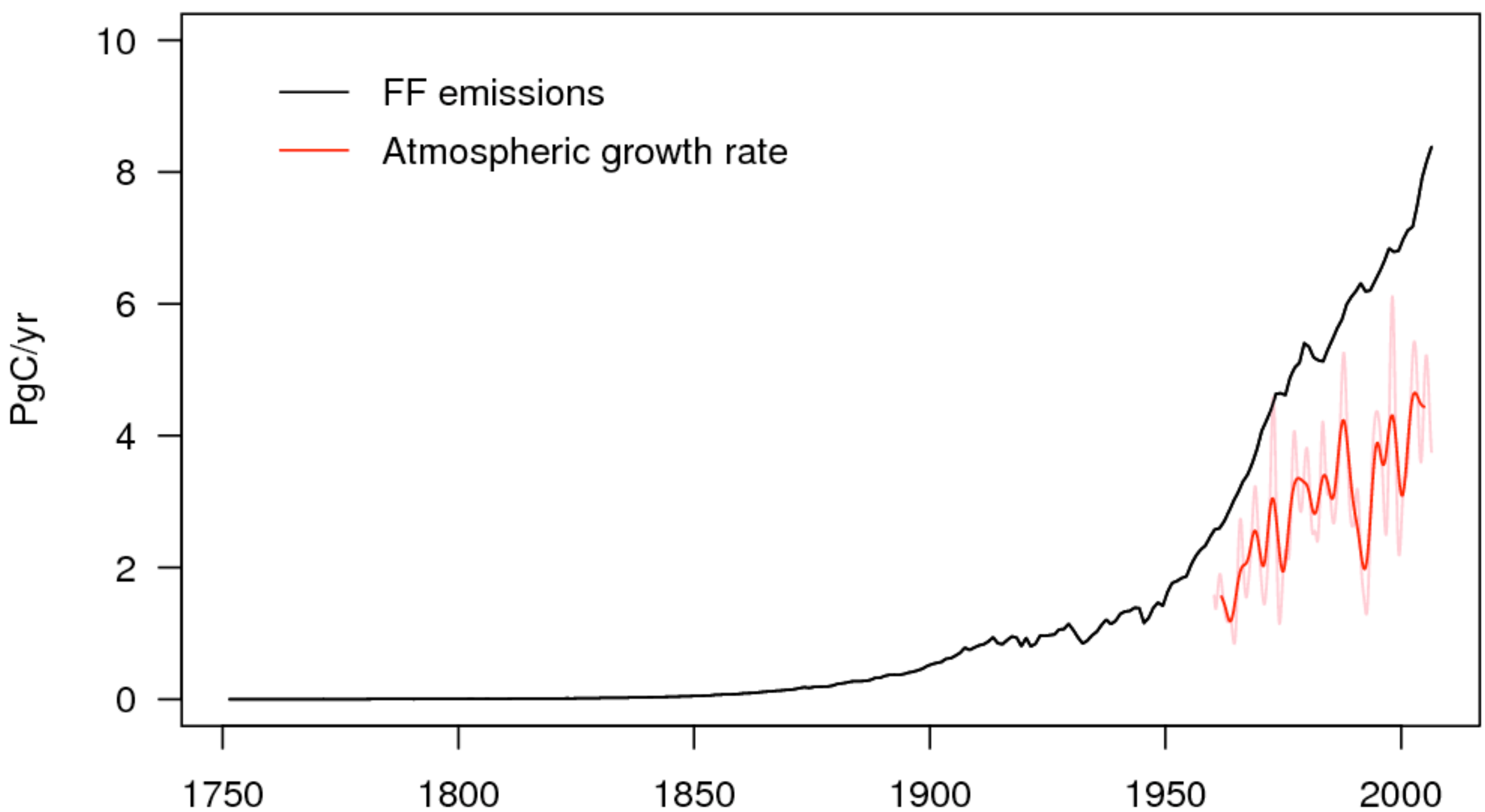
the Mauna Loa record

- classic time series
- seasonal cycle amplitude
- wiggles
- acceleration?



Data: Scripps CO_2 program

Fossil fuel emissions and observed atmospheric growth rate



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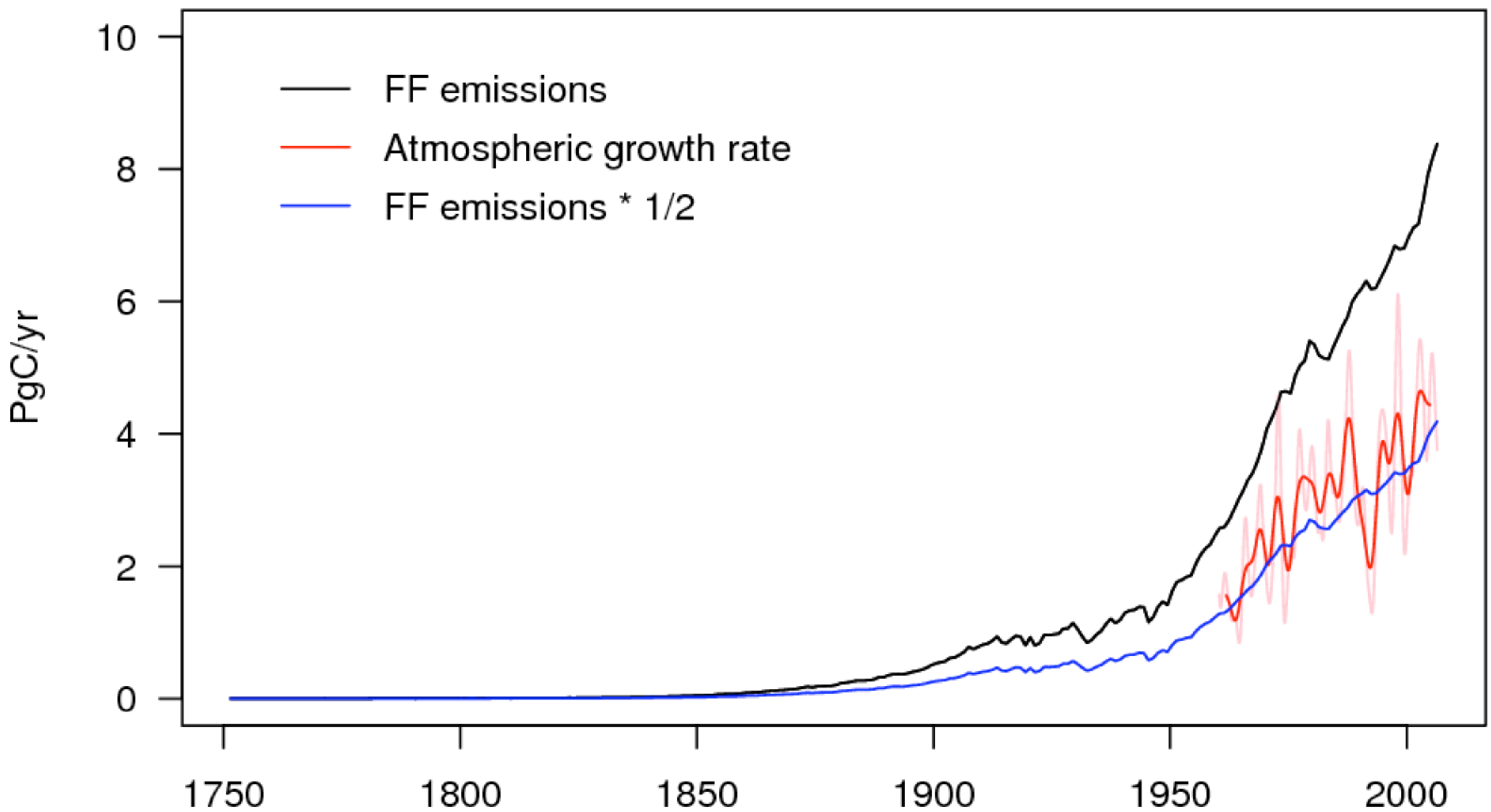
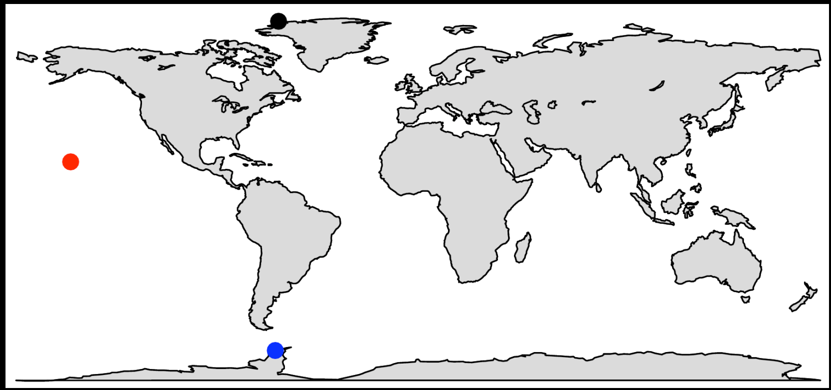
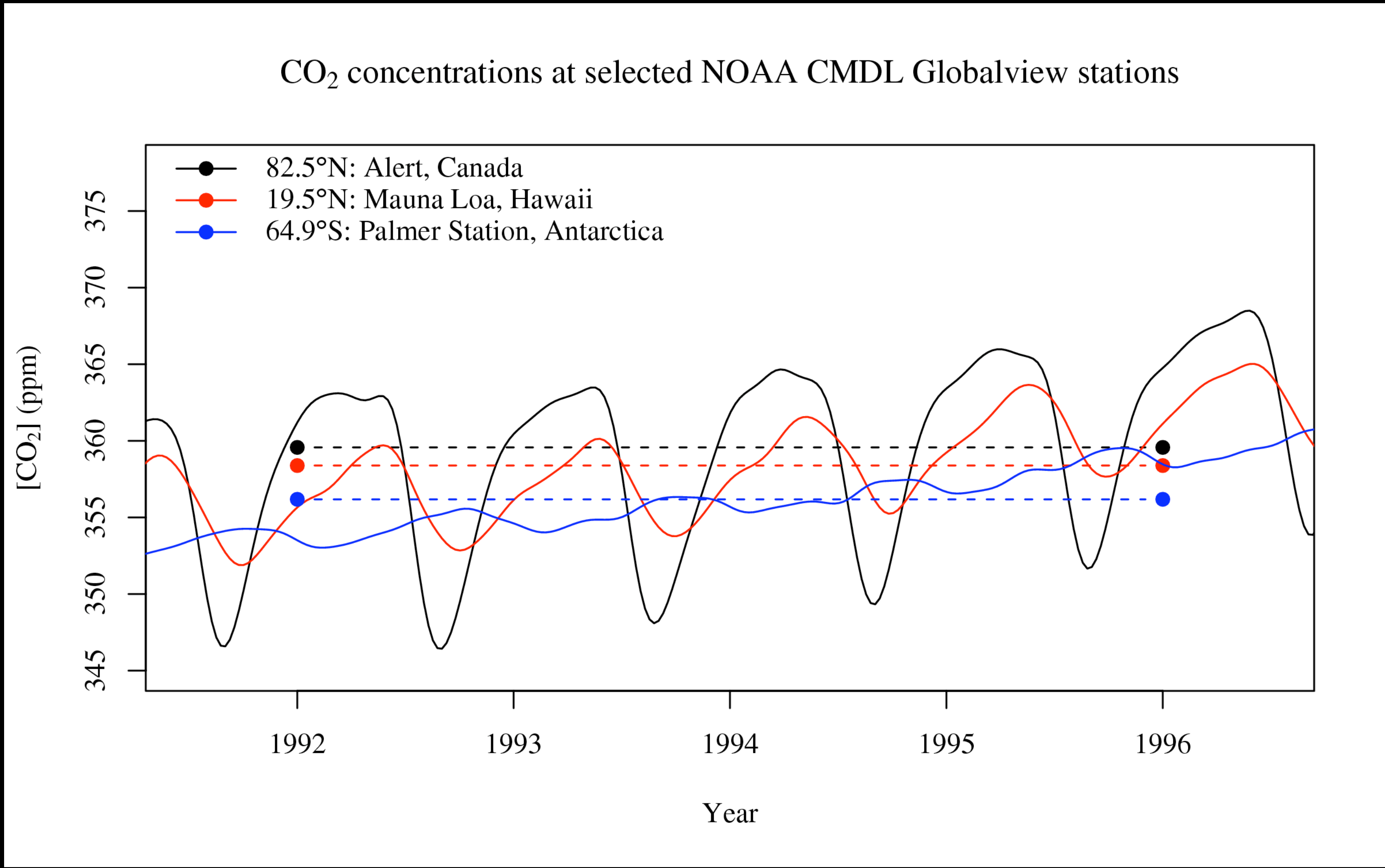
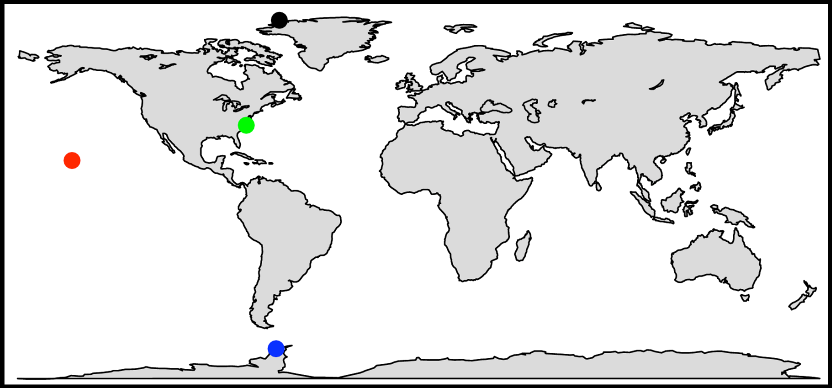


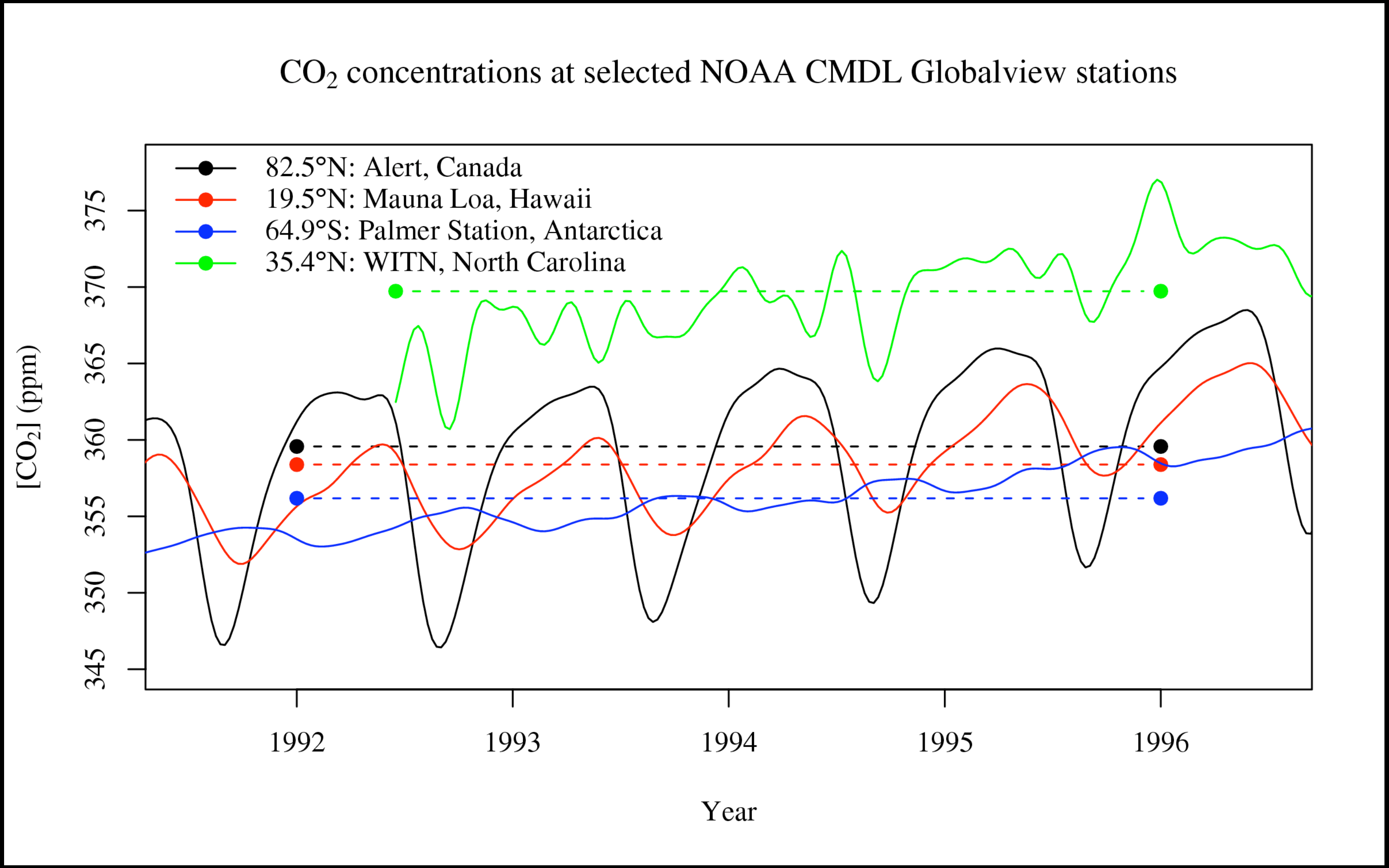
Spatial Gradients of Atmospheric CO_2





Spatial Gradients of Atmospheric CO_2





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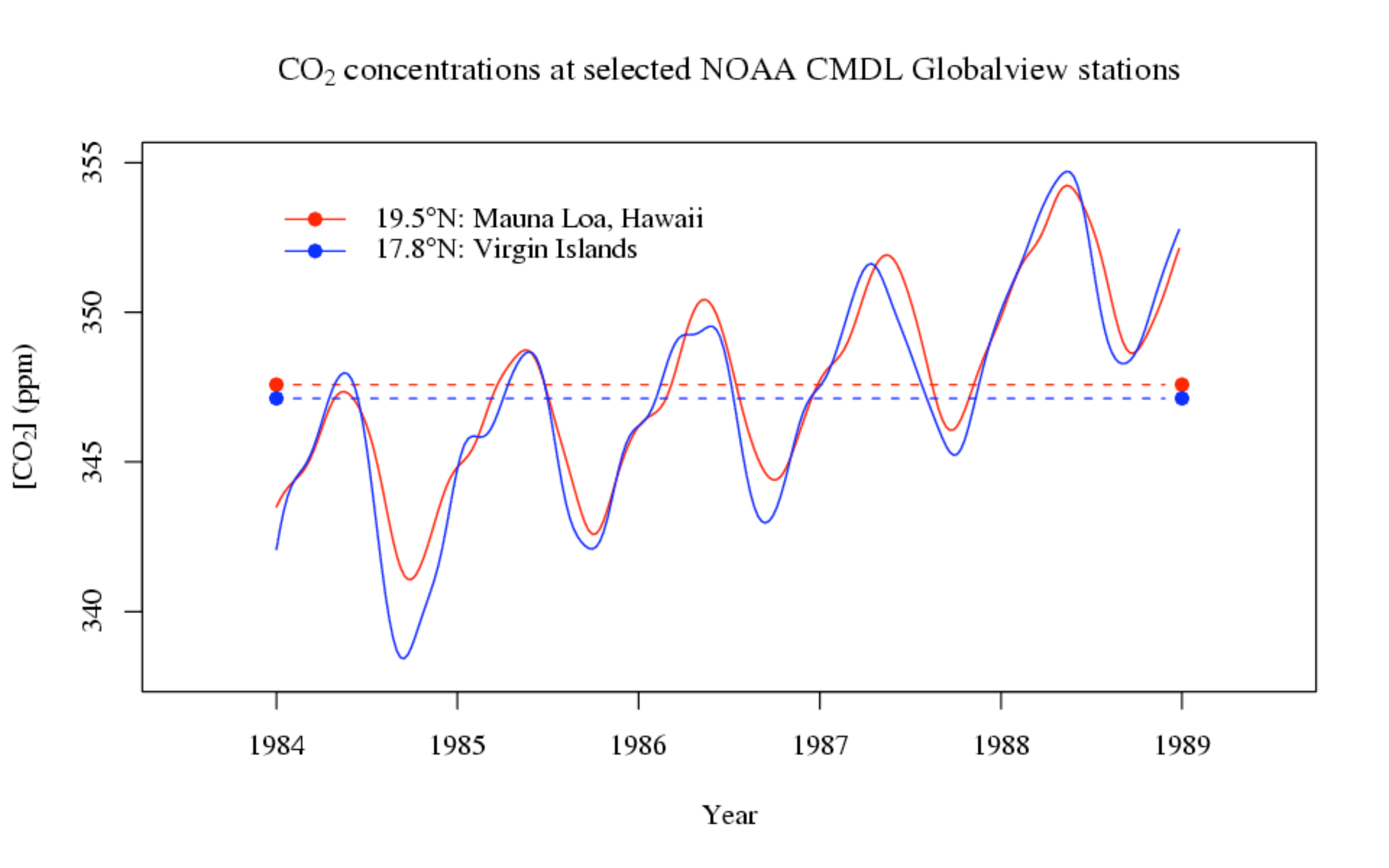
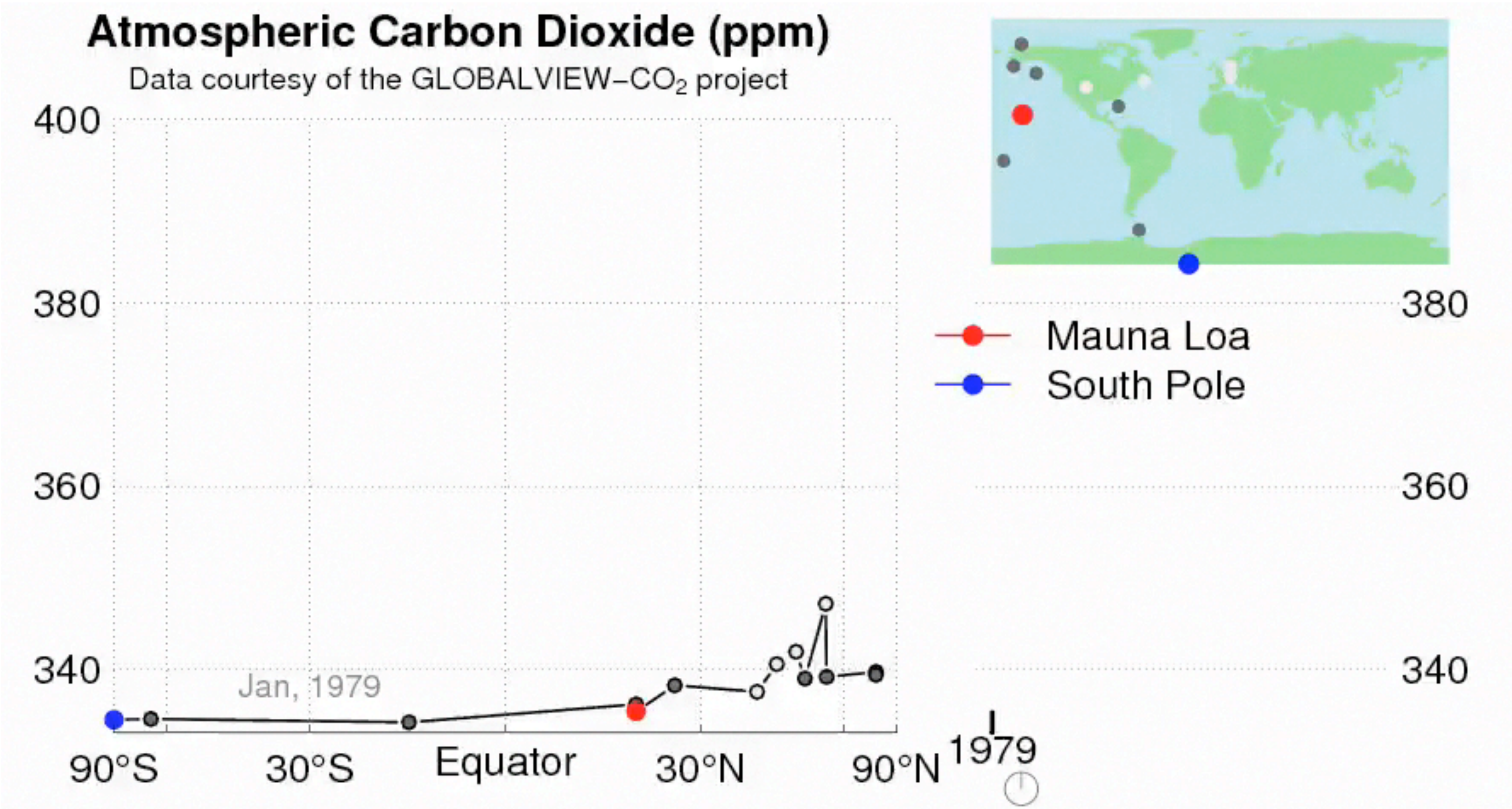




background vs. local stations
most data in northern extratropics
network expanding into continents

Inversion Goal

Find regional fluxes ϕ that agree best with observed concentrations *c*.

$$c = \begin{pmatrix} c_1 \\ c_2 \\ \vdots \\ c_N \end{pmatrix} \quad \Rightarrow \quad \phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \vdots \\ \phi_M \end{pmatrix}$$

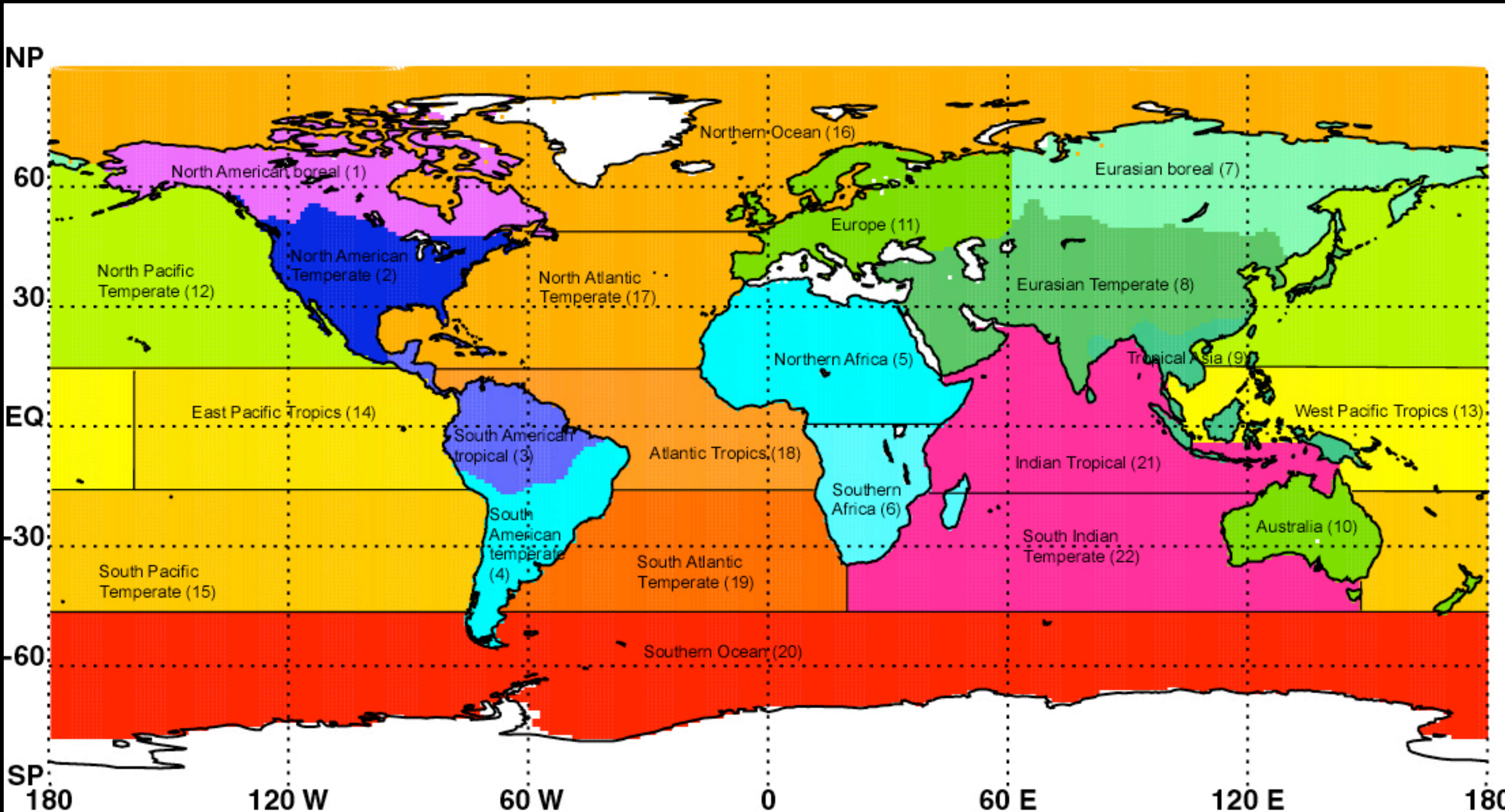
Observations of [CO_2] at *N* locations

N = 76

Fluxes from *M* regions

M = 22

TransCom3 Flux Regions



11 land, 11 ocean

Transport is Estimated by Models

Footprint matrix *A* gives concentrations of **unit** fluxes from each region at each station.

Regions →

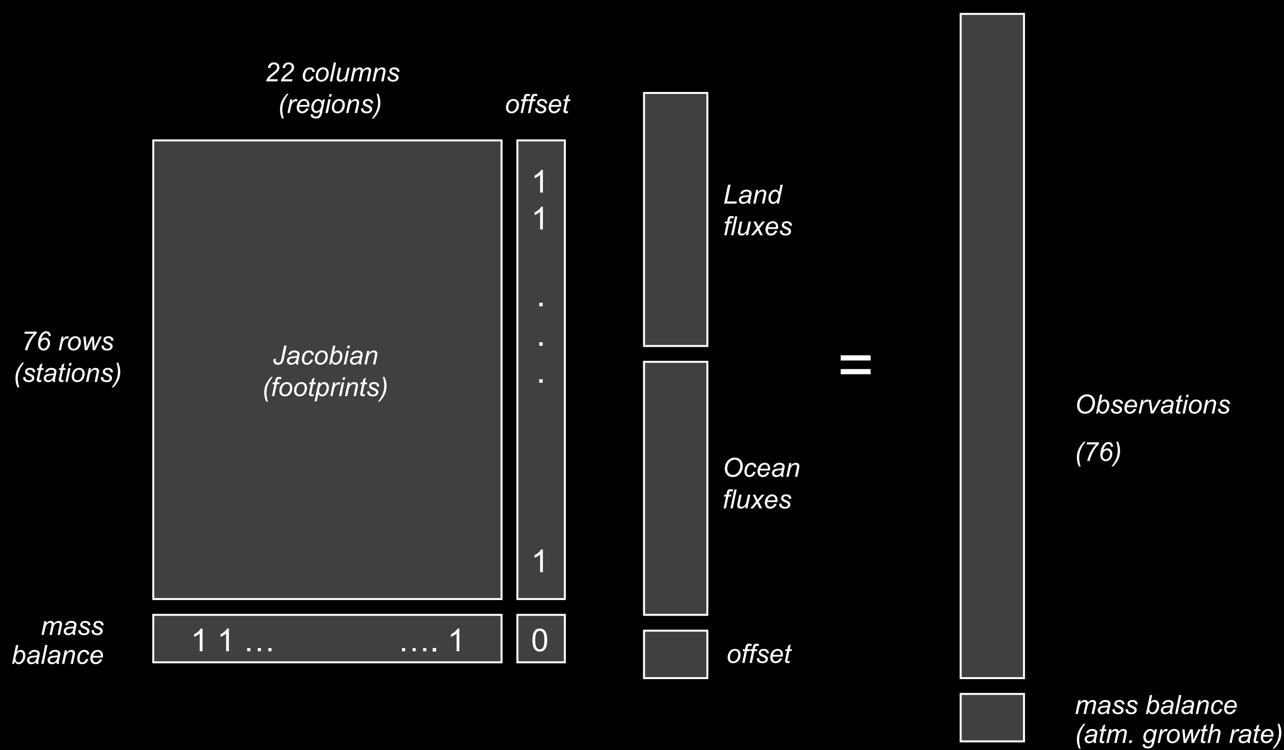
$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1M} \\ a_{21} & a_{22} & \cdots & a_{2M} \\ \vdots & & \ddots & \vdots \\ a_{N1} & \cdots & \cdots & a_{NM} \end{pmatrix}$$

Observations ↓

“Synthesis” Inversion: Forward Model

$$A\phi = c$$

Transport acting on **fluxes** yields **concentrations**



This is multiple linear regression.

"Synthesis" Inversion: Inverse Model

$$A\phi = c$$

→

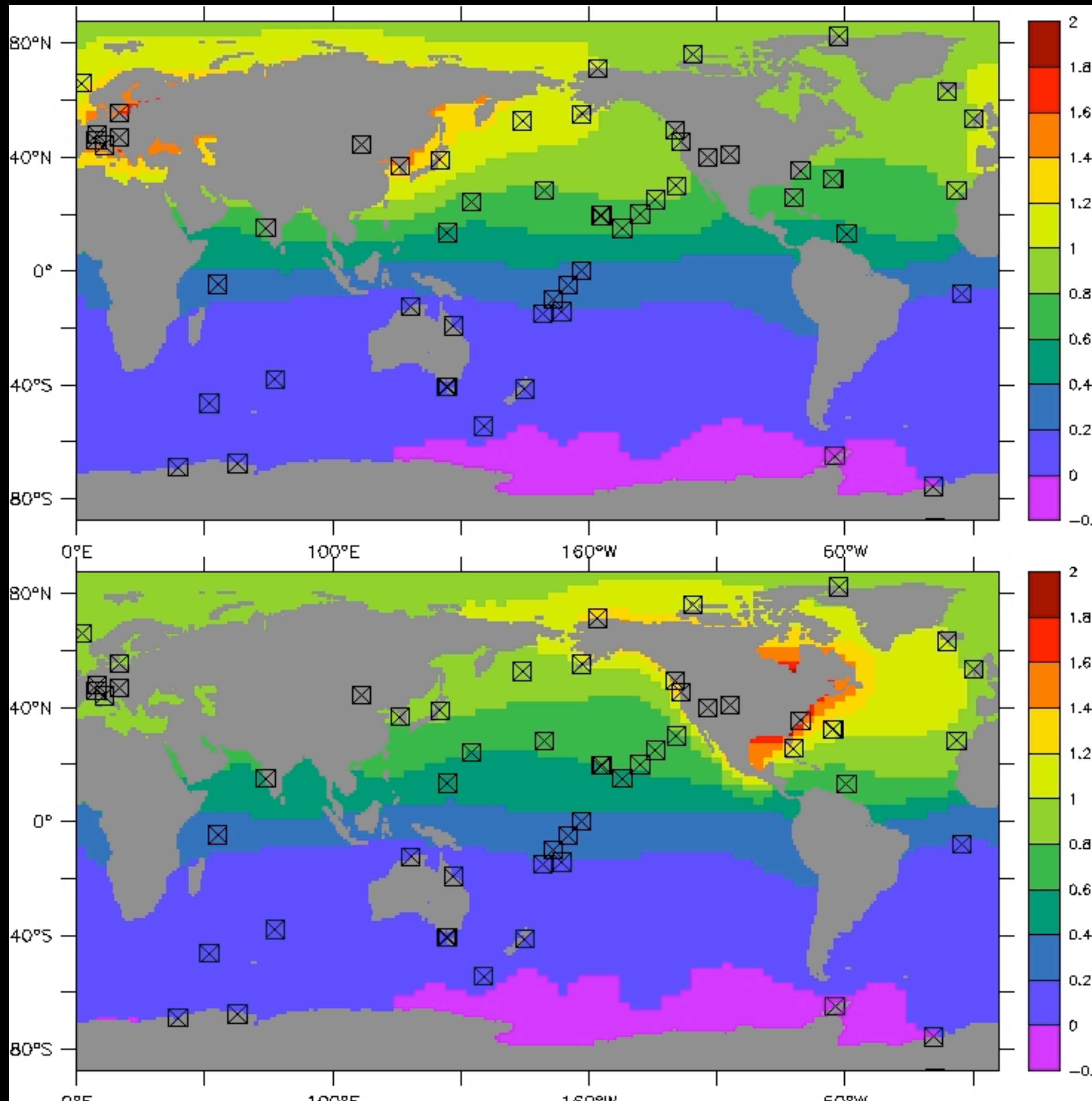
$$\hat{\phi} = A^{-1}c$$

This is multiple linear regression of data *c* onto basis set *A*.

Sample Atmospheric Footprints with TransCom Network

Eurasian NPP

North American NPP



GCTM integrations courtesy of Songmiao Fan, GFDL

A Large Terrestrial Carbon Sink Implied by Atmospheric and Oceanic Carbon Dioxide Data and Models

S. Fan, M. Gloor, J. Mahlman, S. Pacala, J. Sarmiento,
T. Takahashi, P. Tans

16 OCTOBER 1998 VOL 282 SCIENCE www.sciencemag.org

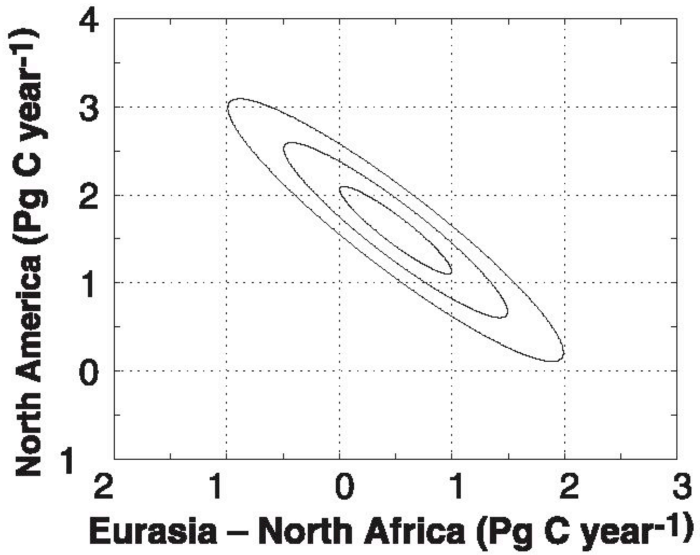


Fig. 2. Inversion uncertainties for North American terrestrial uptake versus Eurasia–North African terrestrial uptake. Ellipses of 1, 2, and 3 SDs are shown.

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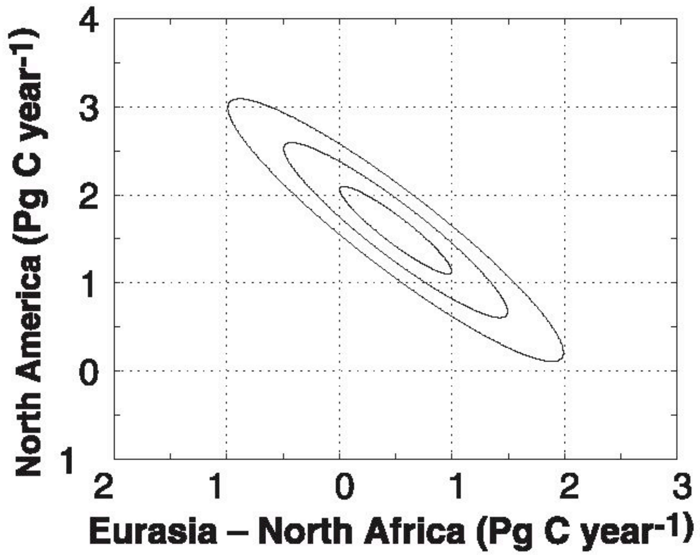

Fig. 2. Inversion uncertainties for North American terrestrial uptake versus Eurasia–North African terrestrial uptake. Ellipses of 1, 2, and 3 SDs are shown.

ESRL Global Monitoring Division – CarbonTracker

http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/ | noaa tall tower program

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- Overview
- FAQ

Results
- Executive Summary
- View
  - Flux Maps
  - Flux Time Series
  - CO_2 Weather
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CarbonTracker

What is CarbonTracker?

A system to keep track of carbon dioxide uptake and release at the Earth's surface over time. [read more]

Who needs CarbonTracker?

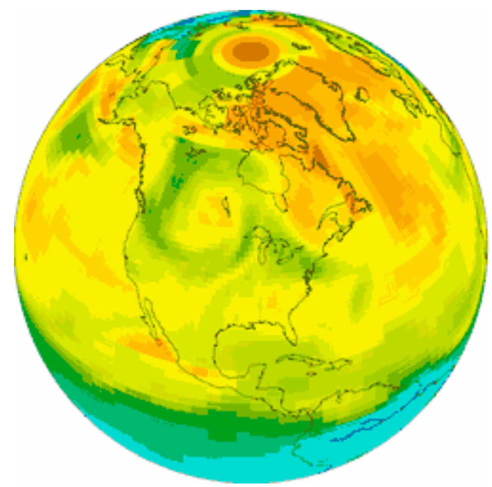
Policy makers, industry, scientists, and the public need CarbonTracker information to make informed decisions to limit greenhouse gas levels in the atmosphere. [read more]

What does CarbonTracker tell us?

North America is a source of CO_2 to the atmosphere. The natural uptake of CO_2 that occurs mostly East of the Rocky Mountains removes only ~30% of the CO_2 released by the use of fossil fuels. [read more]

What's new in this release of CarbonTracker? NEW!

The 2009 release of CarbonTracker ("CT2009") includes observations and flux estimates



CarbonTracker CO_2 weather for June–July, 2008. Warm colors show high atmospheric CO_2 concentrations, and cool colors show low concentrations. As the summer growing season takes hold, photosynthesis by forests and crops draws concentrations CO_2 down, opposing the general increase from fossil fuel burning. The resulting high- and low-CO_2 air masses are then moved around by weather systems to form the patterns shown here. [More on CO_2 weather]

Transferring data from www.esrl.noaa.gov... 0:19

CarbonTracker

structure

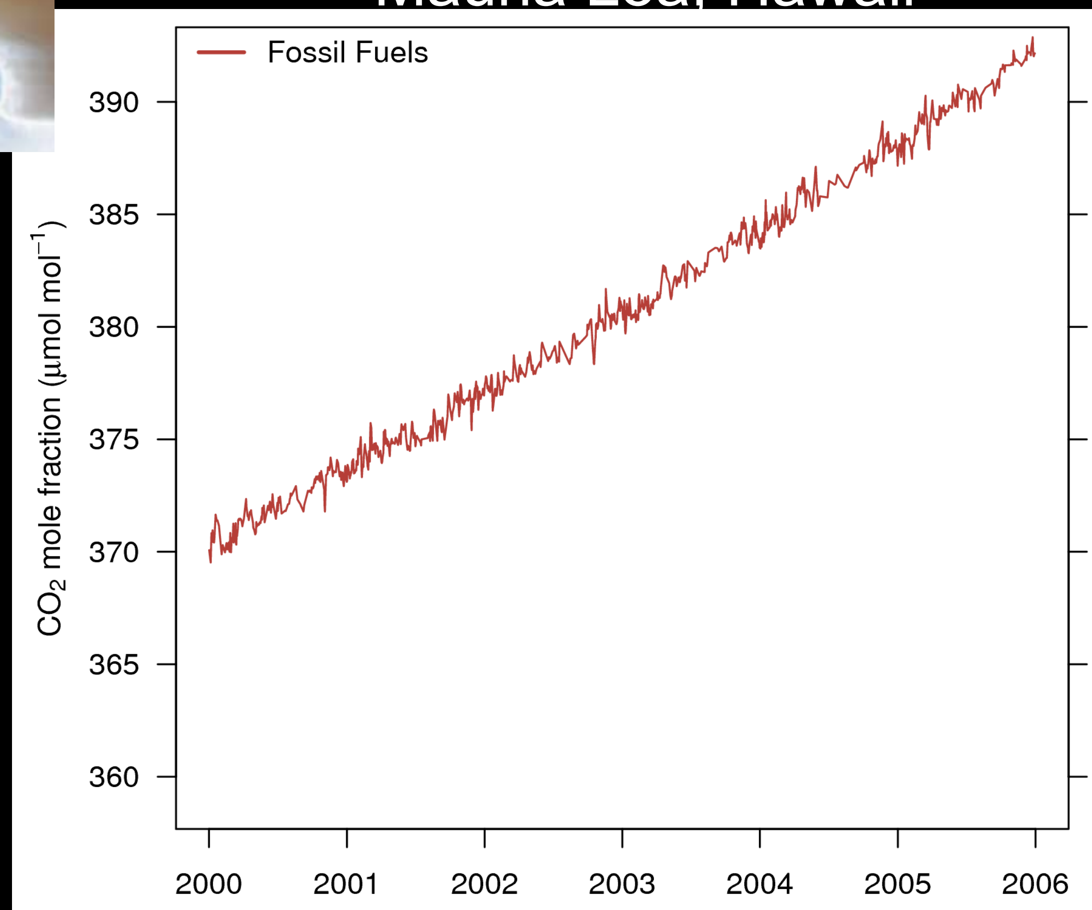
Fossil Fuel emissions: John Miller, from EDGAR, BP, CDIAC

CarbonTracker

structure

Transport: offline model (TM5) driven by ECMWF analyses, postprocessed to conserve mass.

Mauna Loa, Hawaii

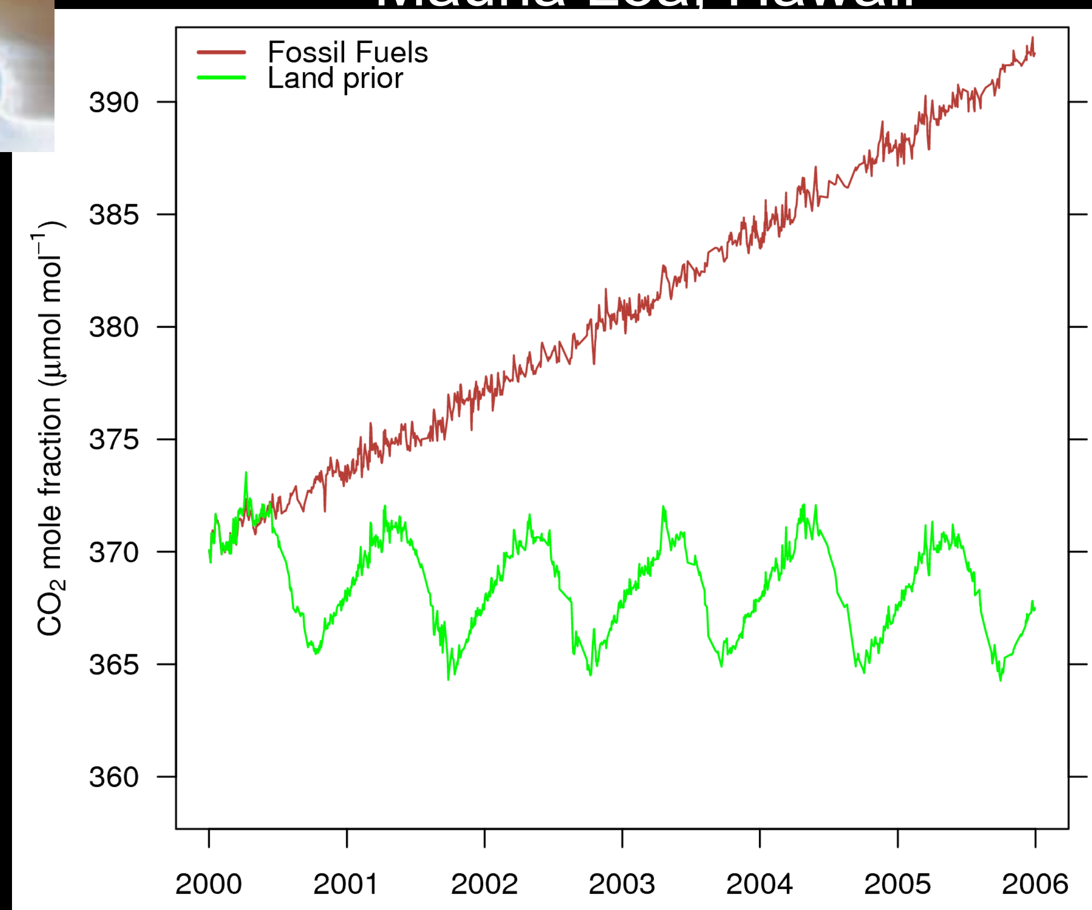


CarbonTracker

structure

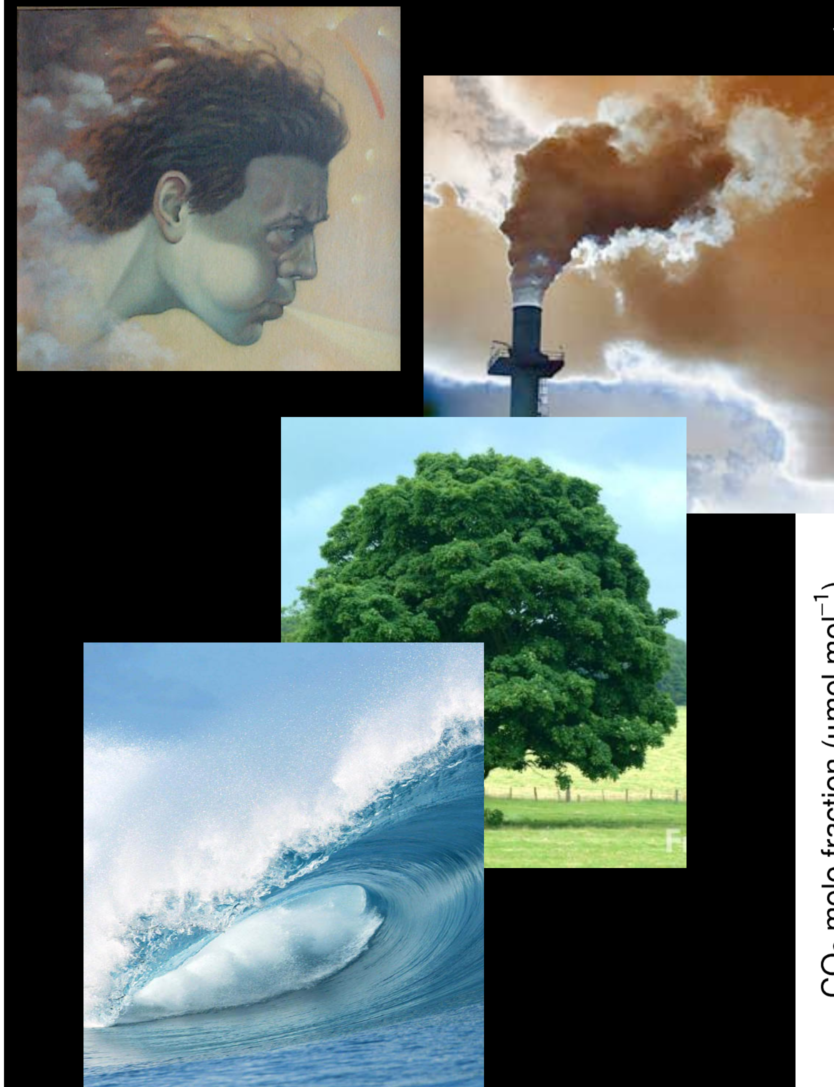
Terrestrial biosphere: satellite fire counts acting on NDVI-driven "CASA" model (from GFED2 of van der Werf et al.)

Mauna Loa, Hawaii



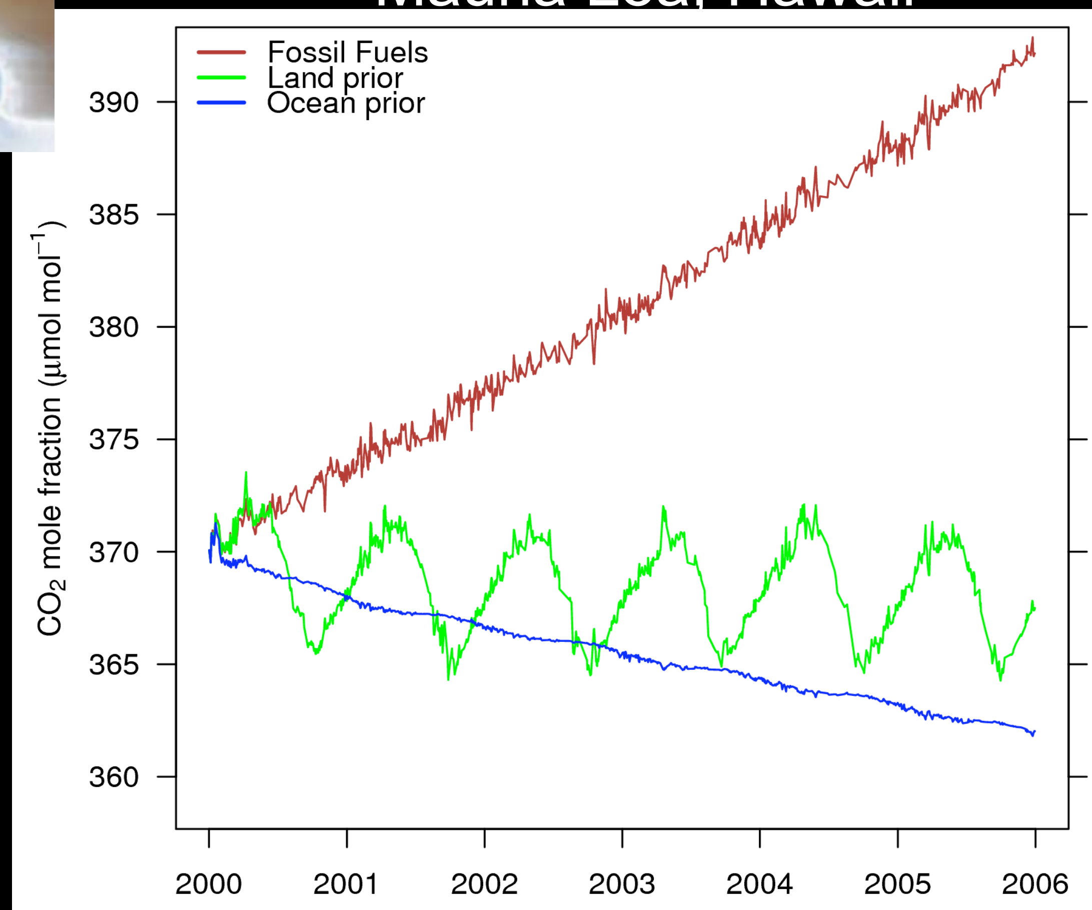
CarbonTracker

structure



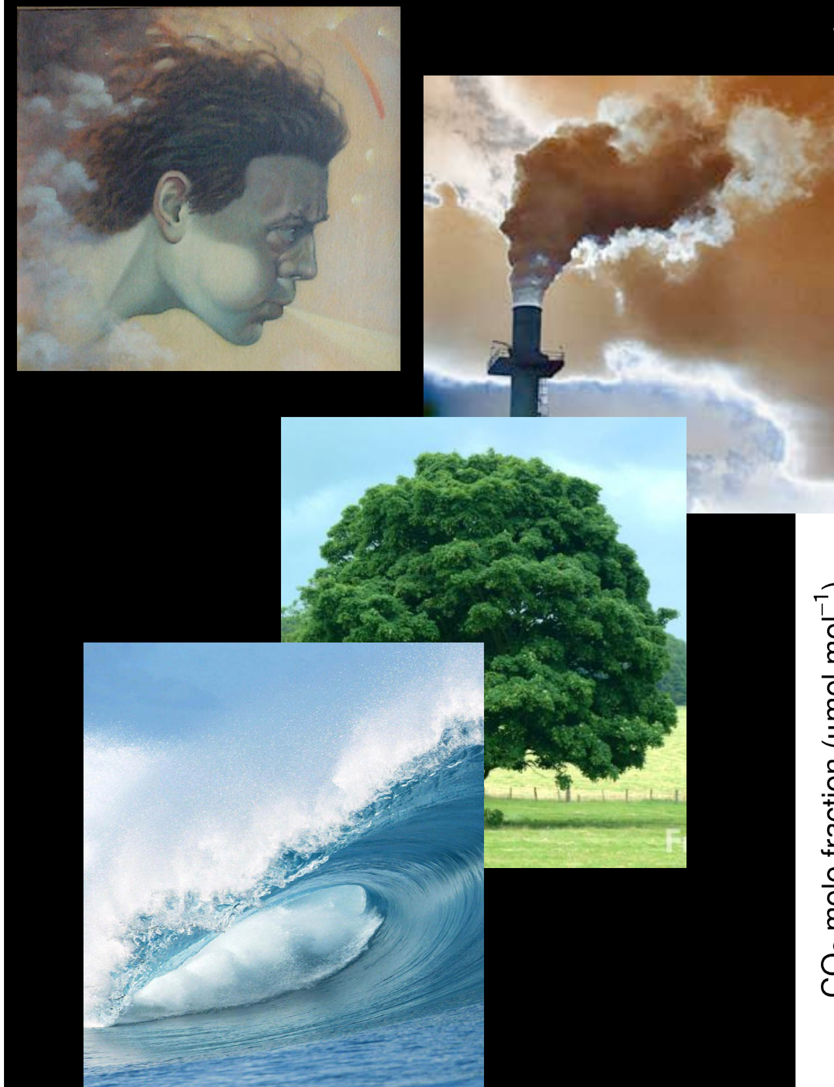
Air-sea fluxes: ocean interior inversions of Jacobson et al. (2007)

Mauna Loa, Hawaii

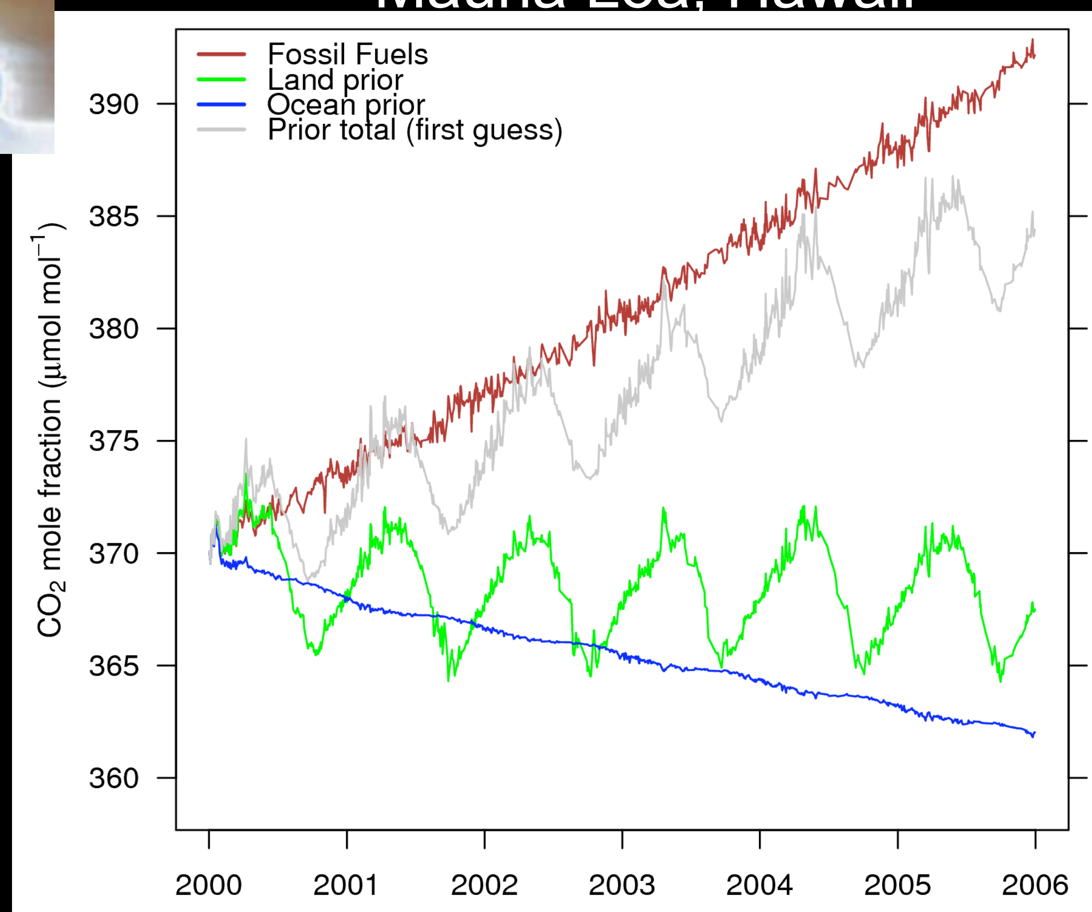


CarbonTracker

structure

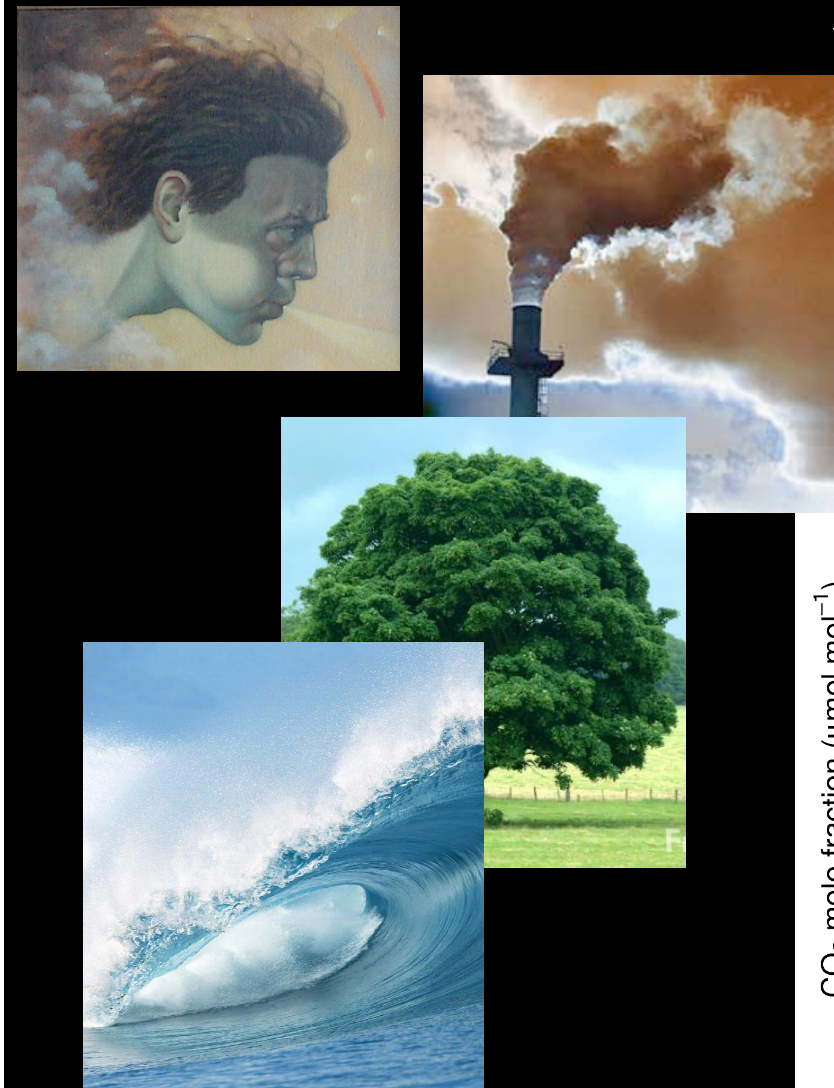


Mauna Loa, Hawaii



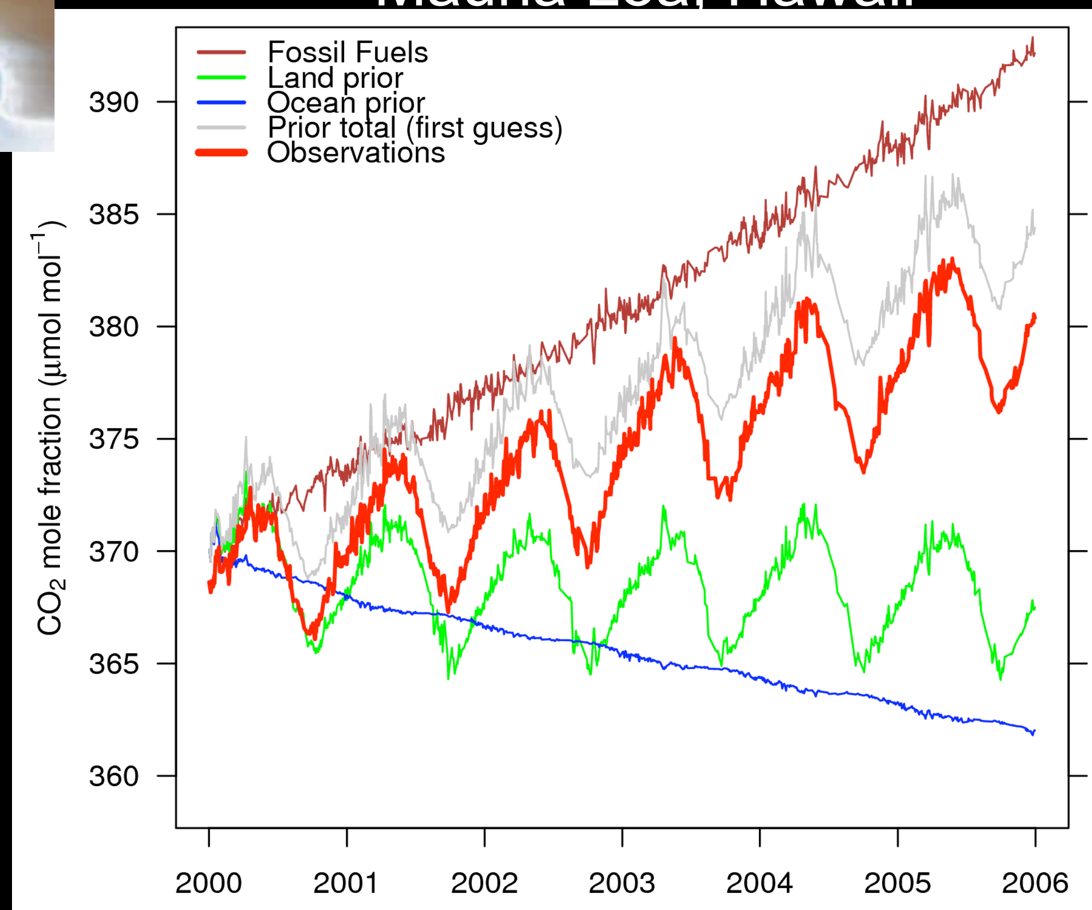
CarbonTracker

structure

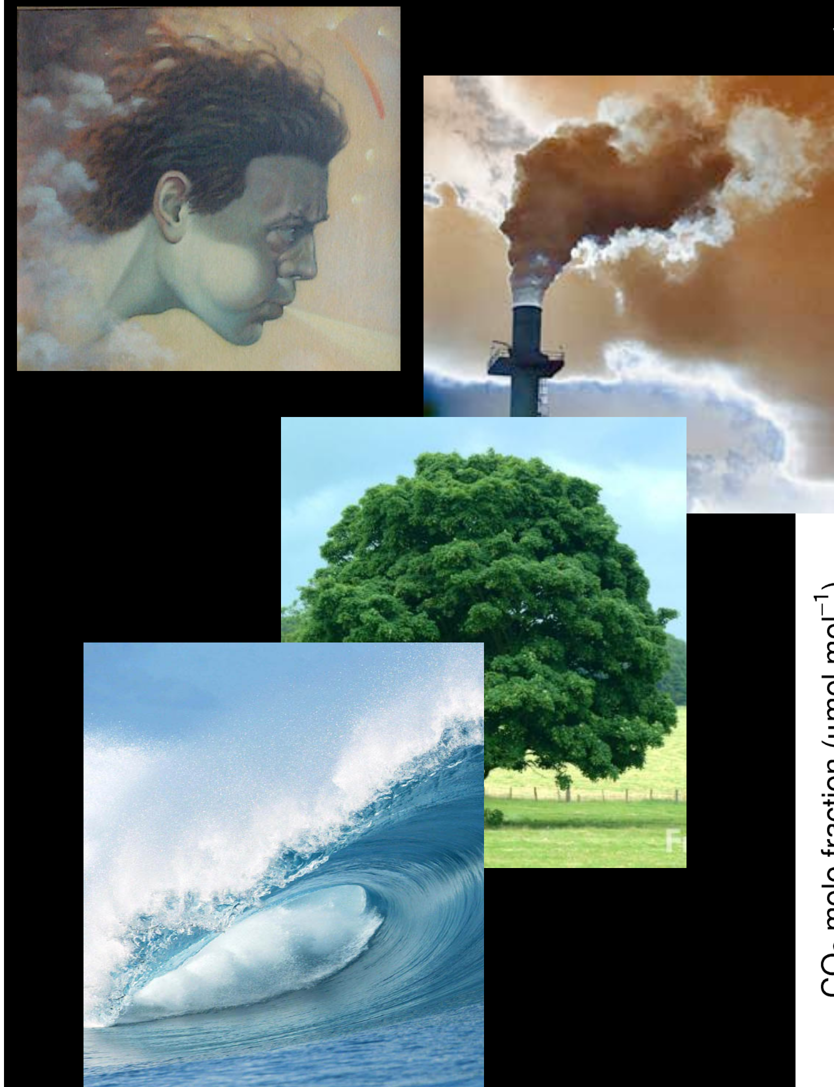


Observations: GMD, EC, NCAR, CSIRO, …

Mauna Loa, Hawaii

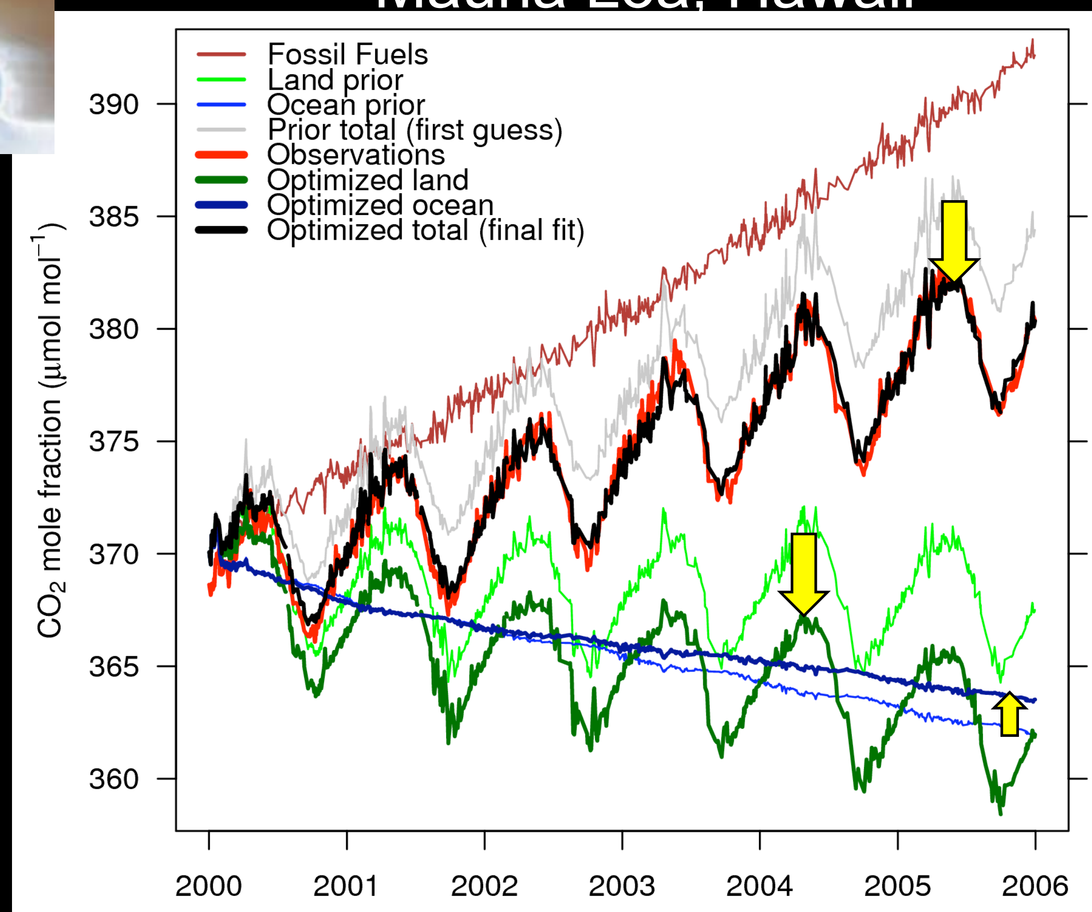


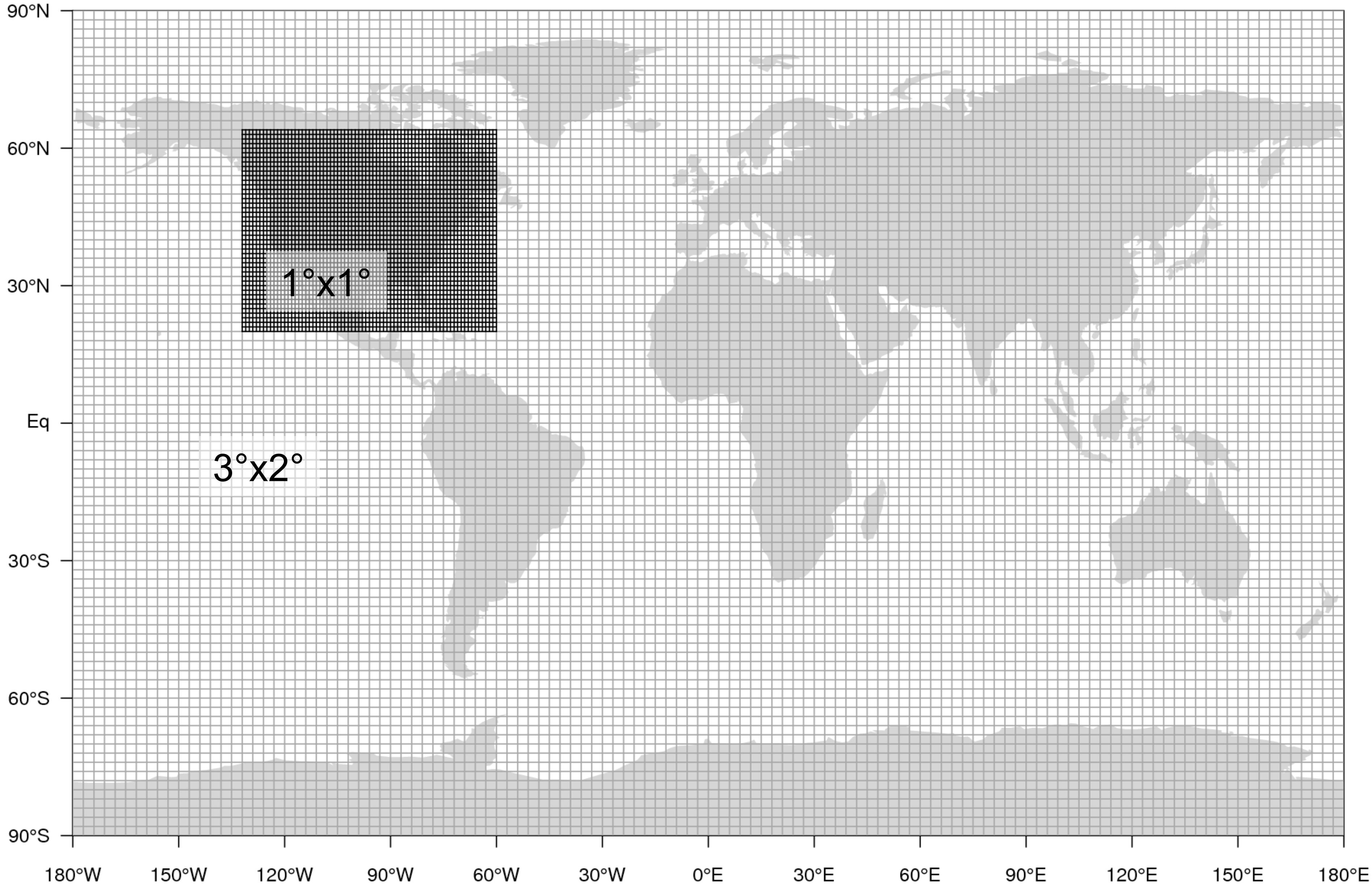
CarbonTracker
structure



Optimization: EnSRF of Whitaker and Hamill (2002)

Mauna Loa, Hawaii




90°N
60°N
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Eq
30°S
60°S
90°S
180°W
150°W
120°W
90°W
60°W
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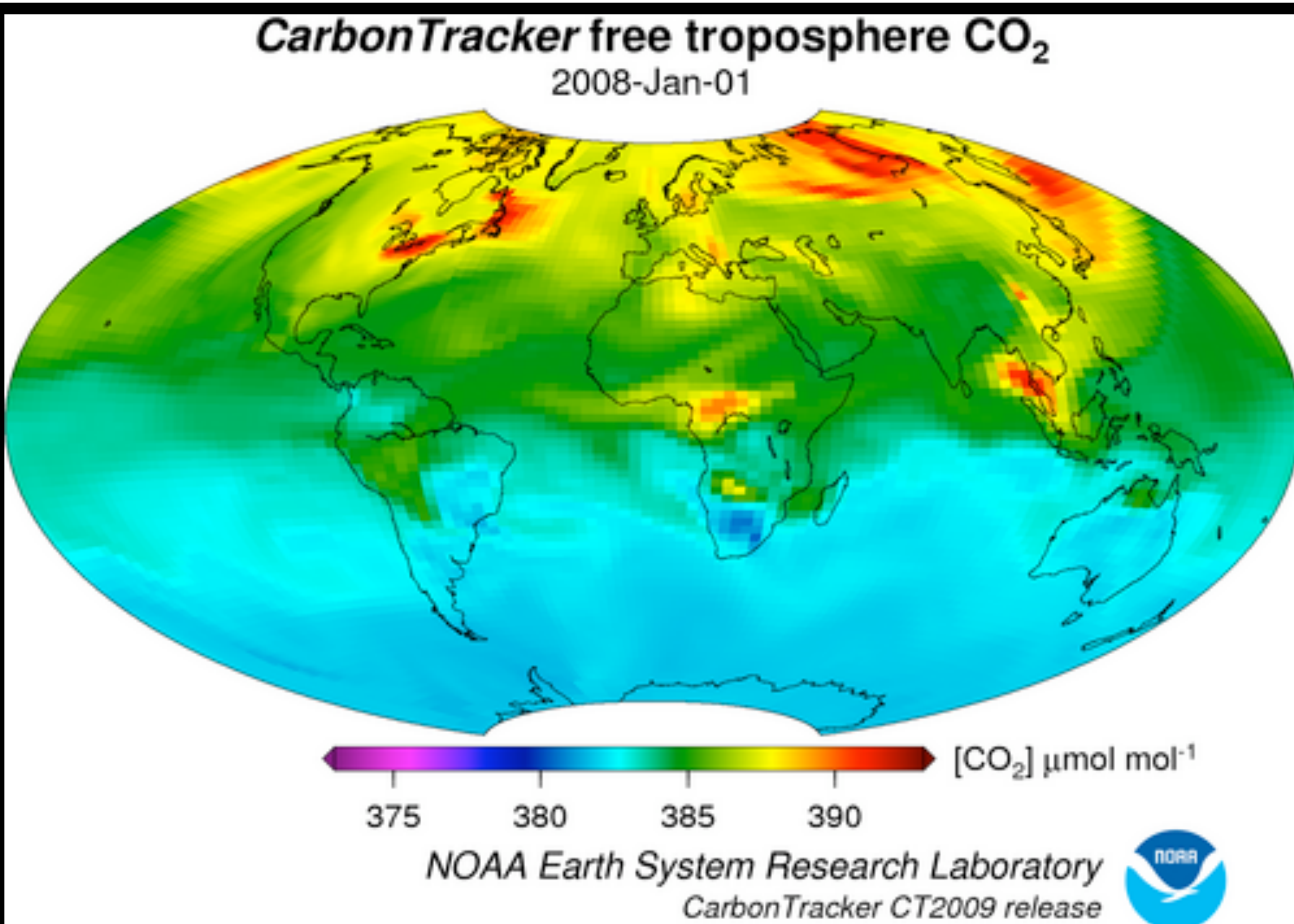
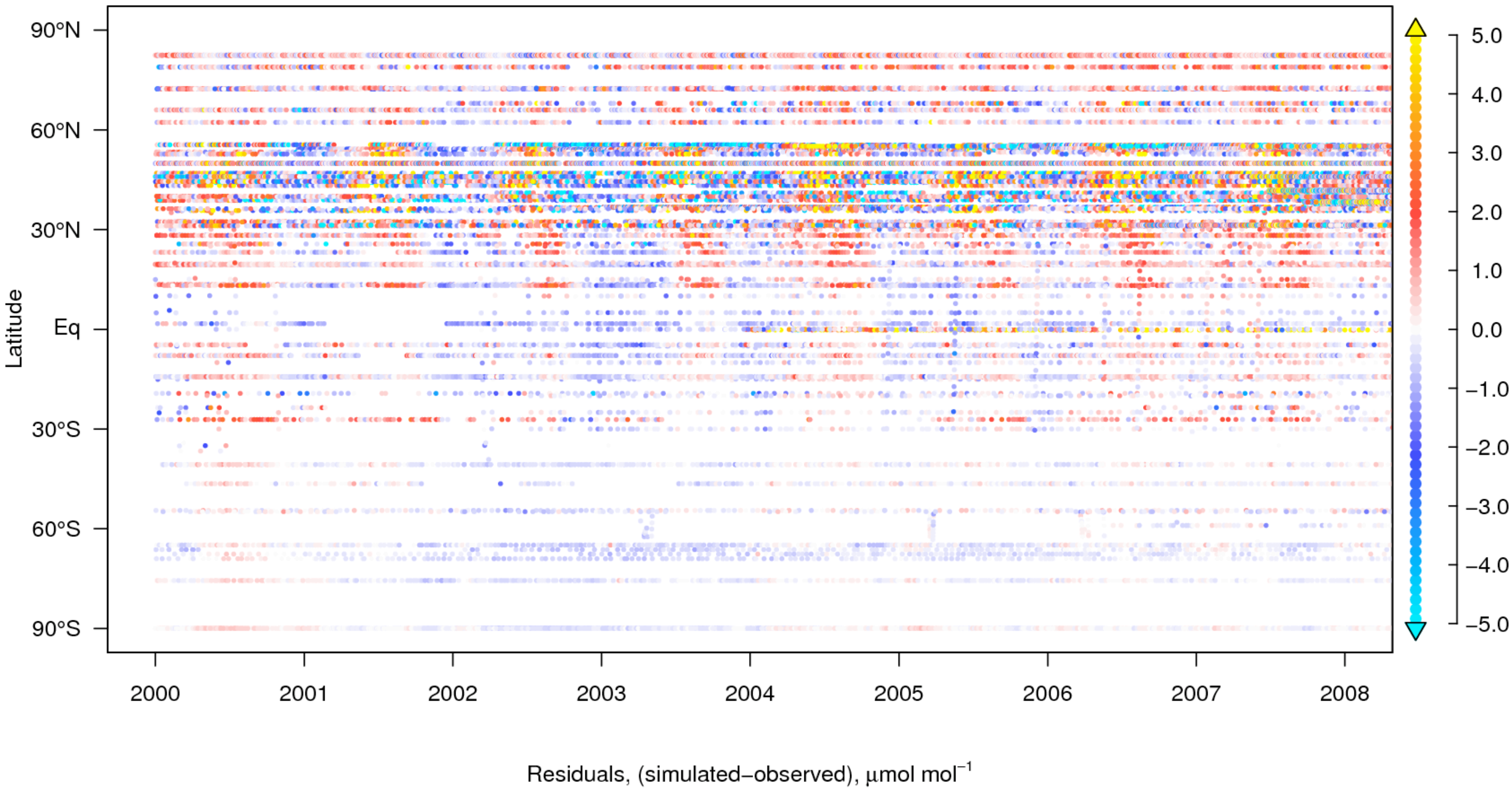
1°x1°
3°x2°



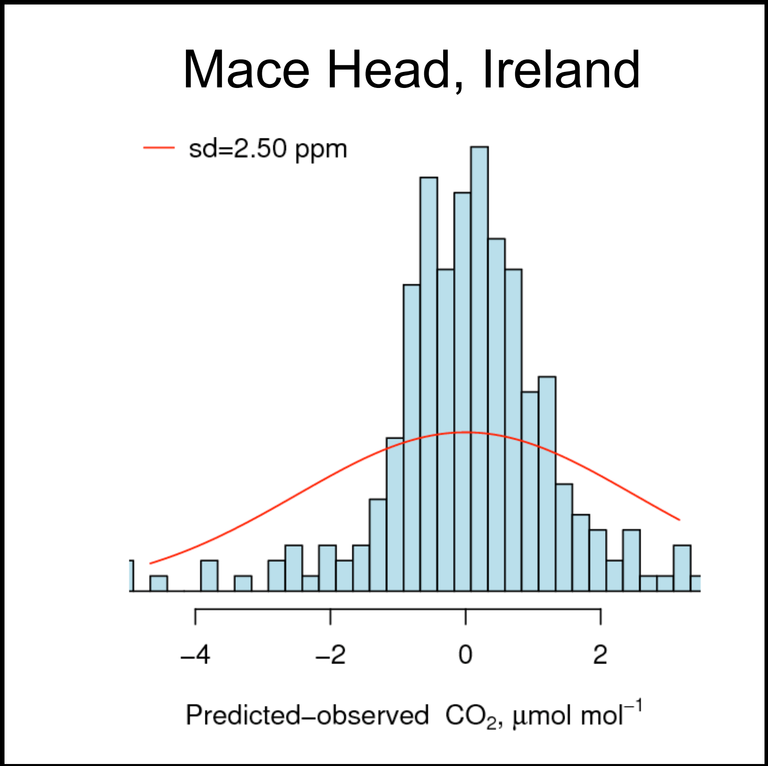
carbontracker.noaa.gov

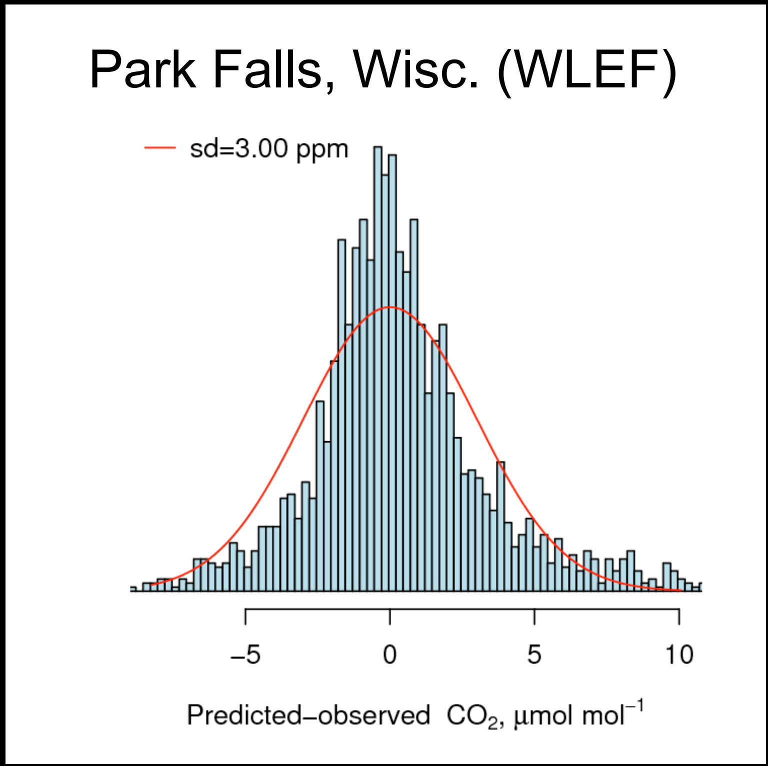
CT2009 Residuals (excludes aircraft obs, assimilated data only)



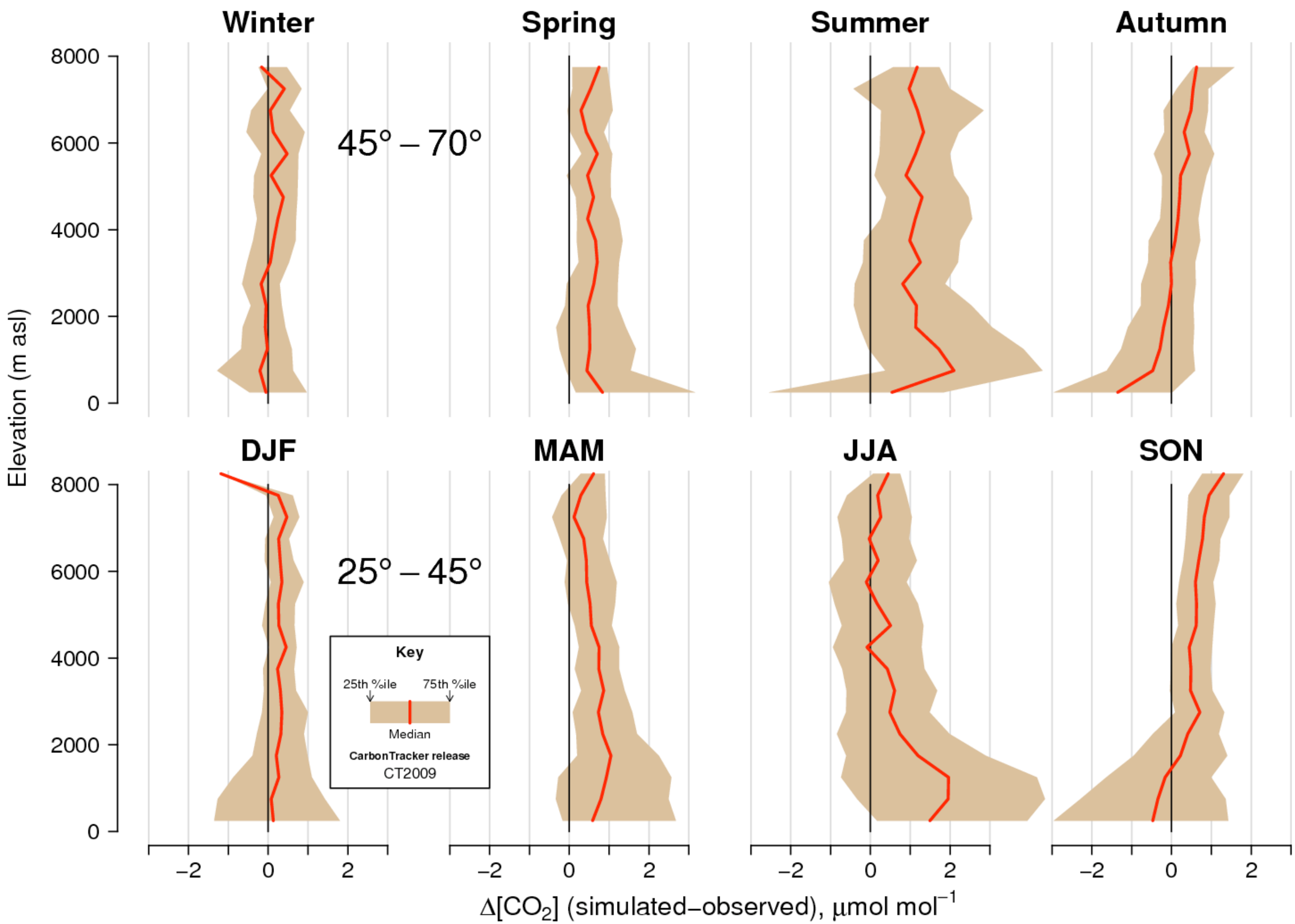
Inversion core research

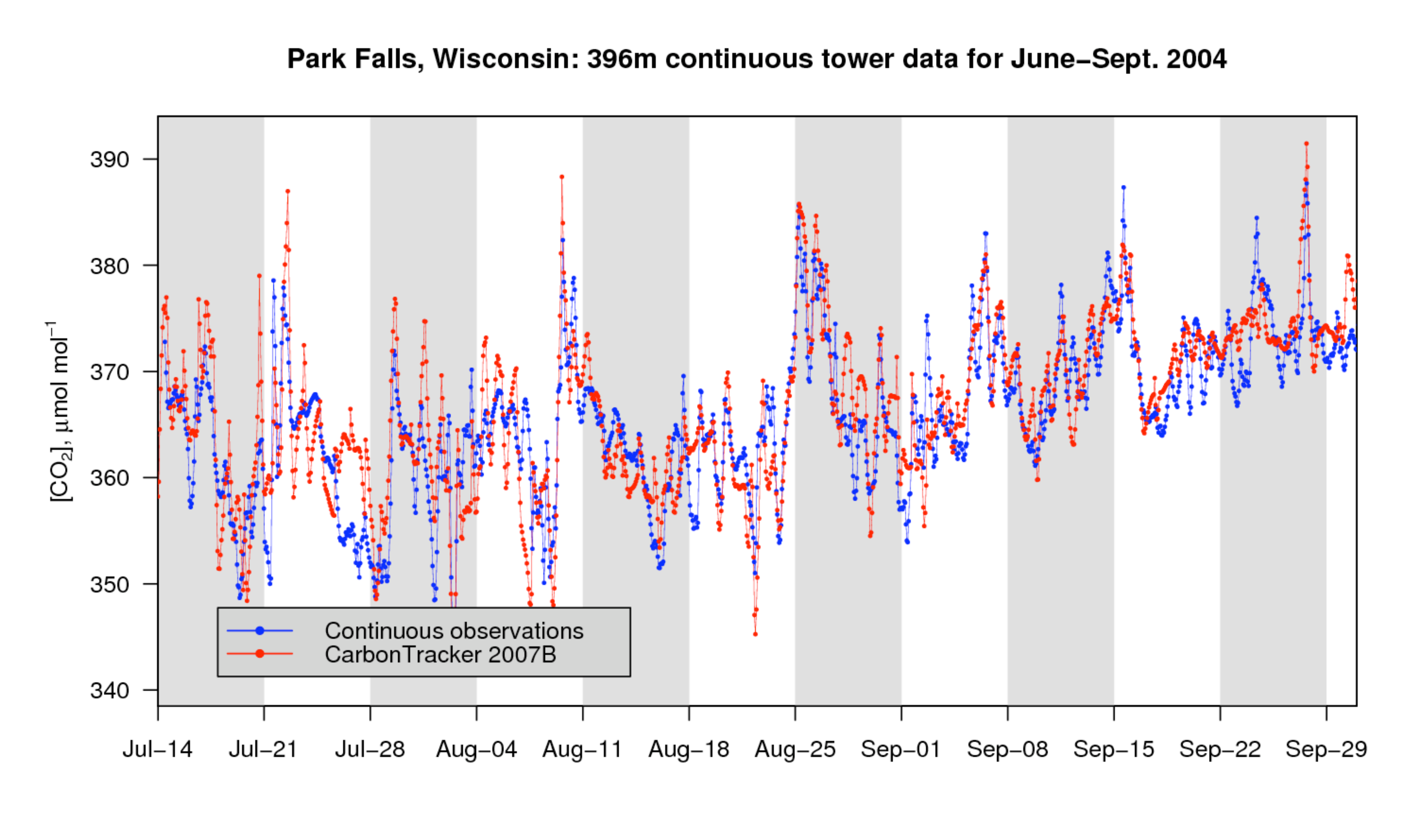
large / small deviations given too much / little significance



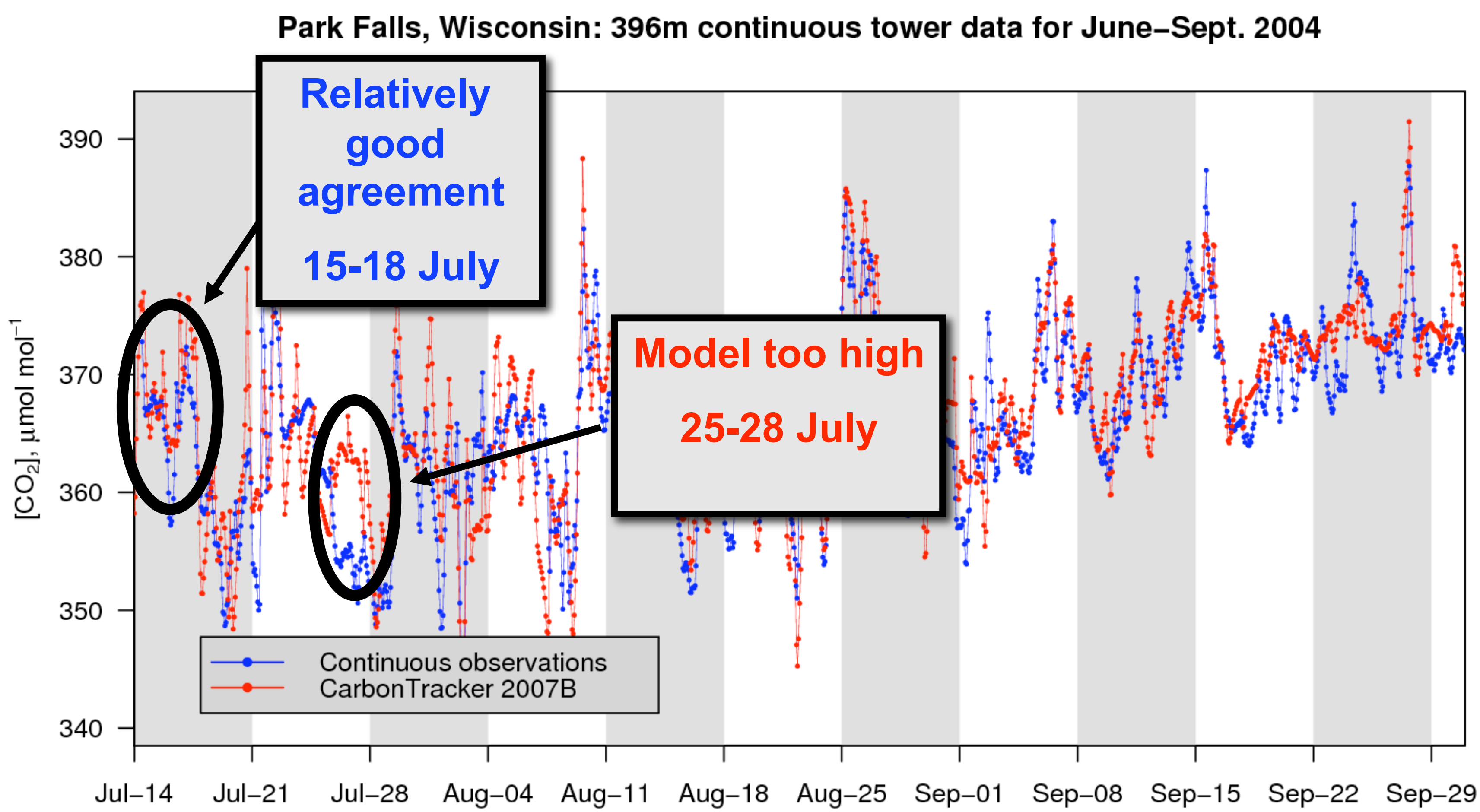


leptokurtic residuals - sharp peak and long tails modeled with an overly large Gaussian variance


Winter
Spring
Summer
Autumn
DJF
MAM
JJA
SON
45° – 70°
25° – 45°
Elevation (m asl)
8000
6000
4000
2000
0
−2
0
2
Key
25th %ile
75th %ile
Median
CarbonTracker release
CT2009
Δ[CO2] (simulated−observed), µmol mol−1



Data: NOAA tall towers program

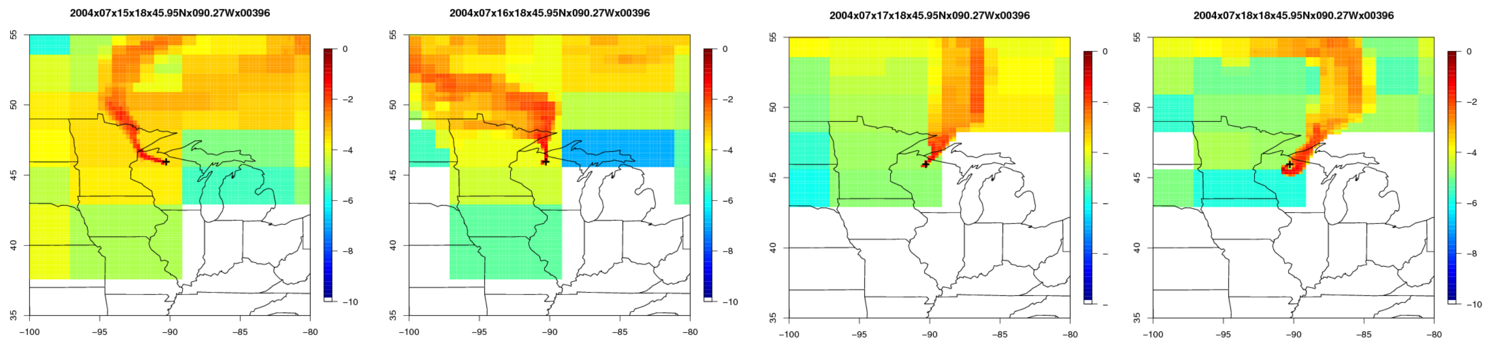


Data: NOAA tall towers program

STILT footprints for WLEF 396m afternoon averages

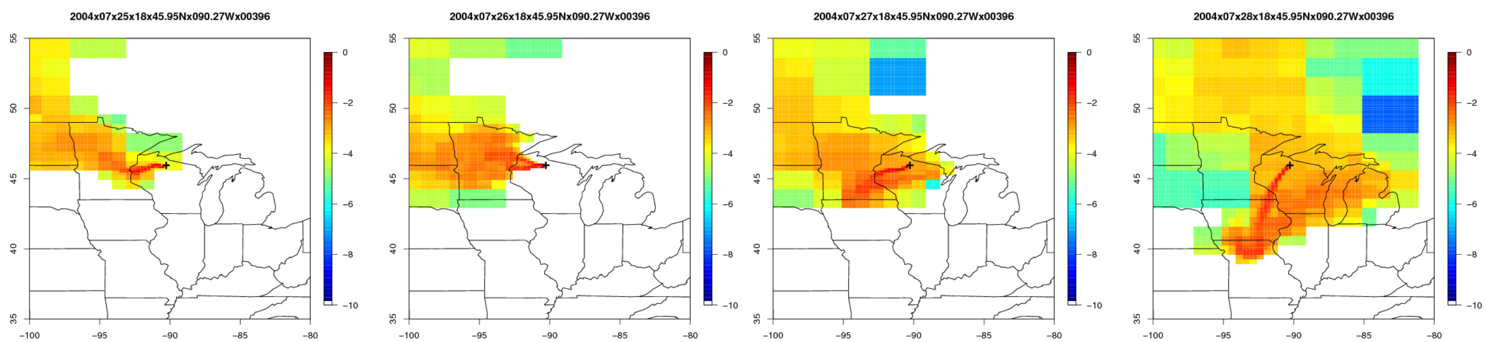
Relatively good agreement

15-18 July



Model too high

25-28 July

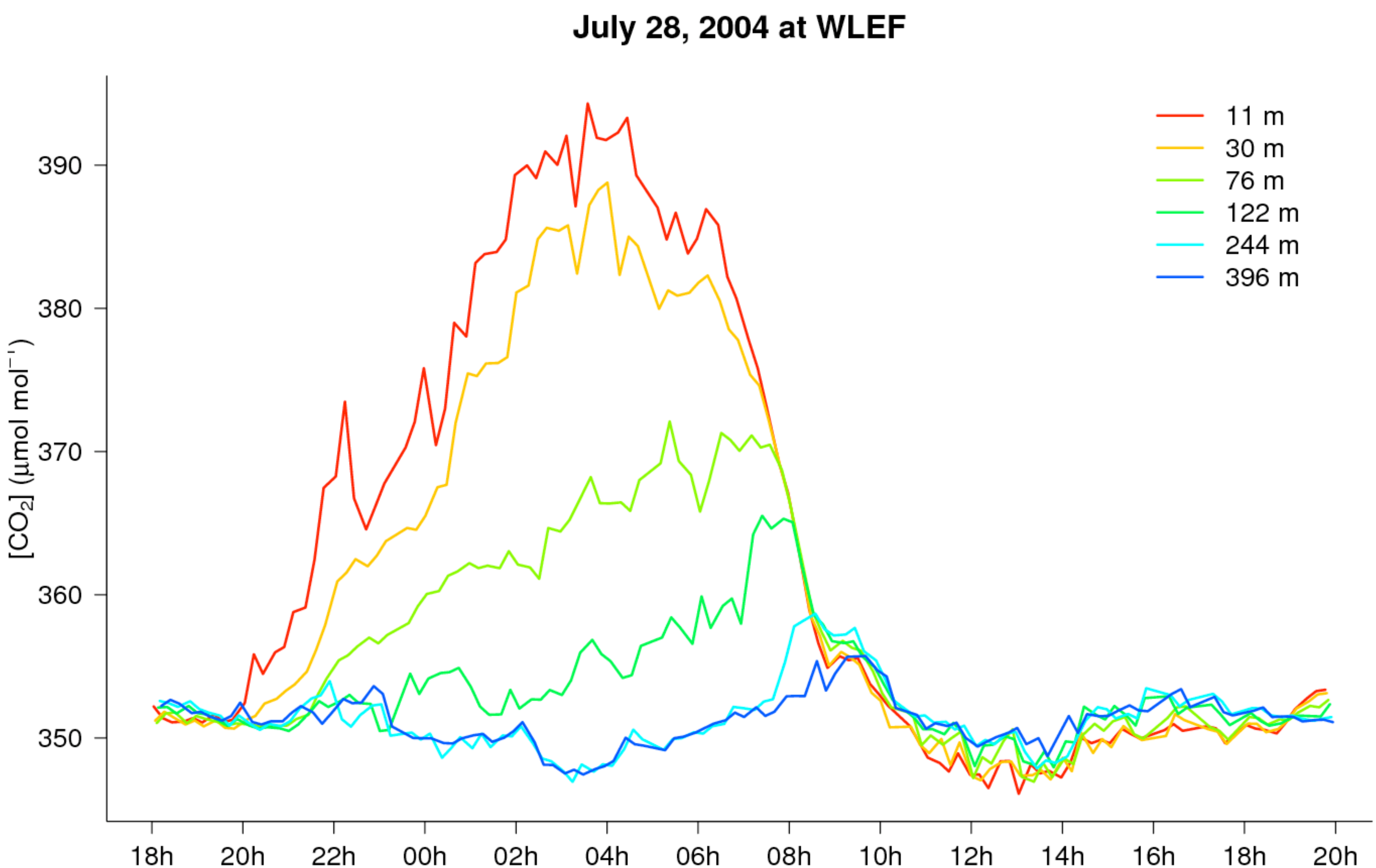


FIgures courtesy of Arlyn Andrews, NOAA

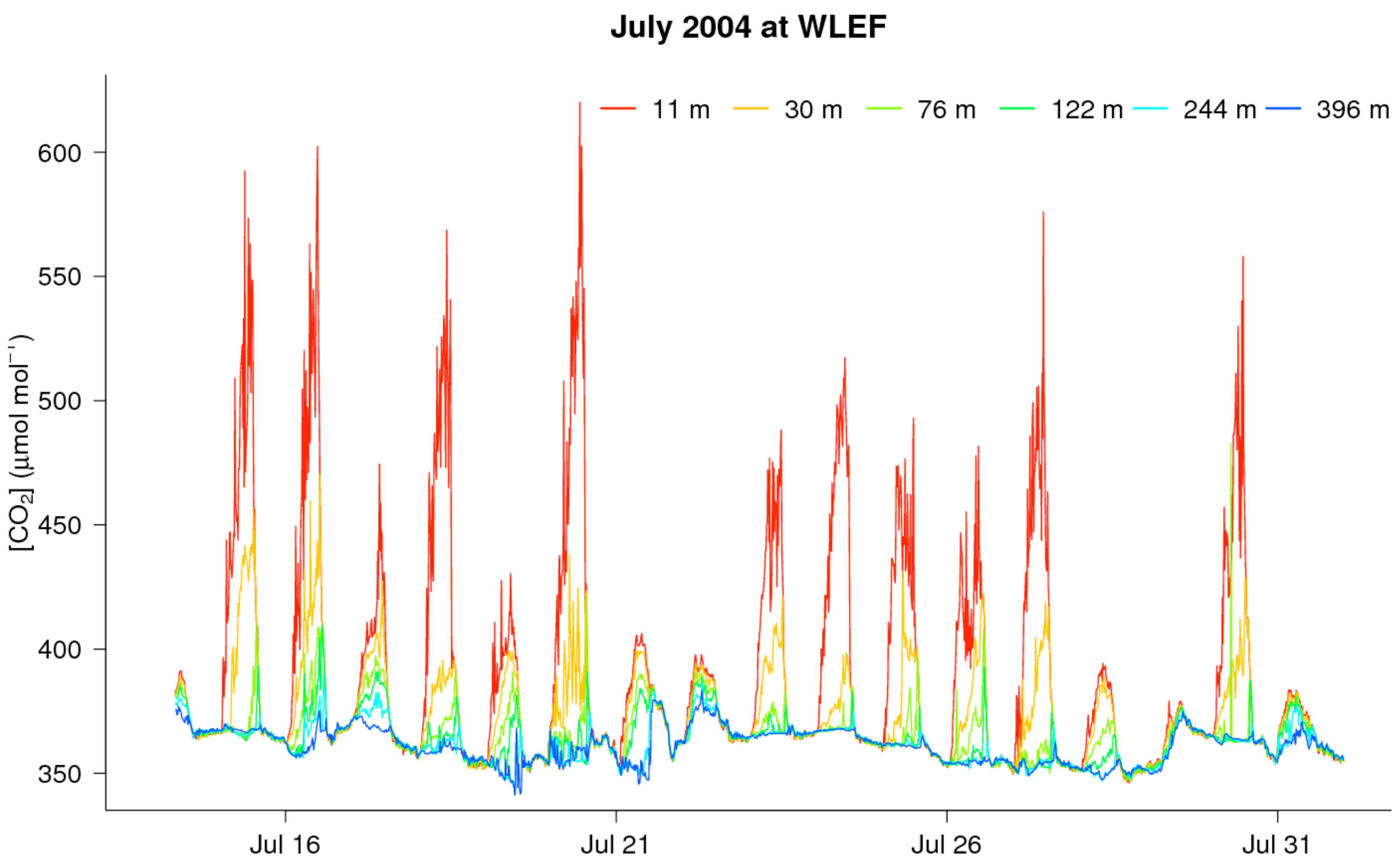
Orbiting Carbon Observatory

477m tall, observations begun in 1994
Sampling at 11, 30, 76, 122, 244, 396 m AGL

Photo: NOAA tall towers program

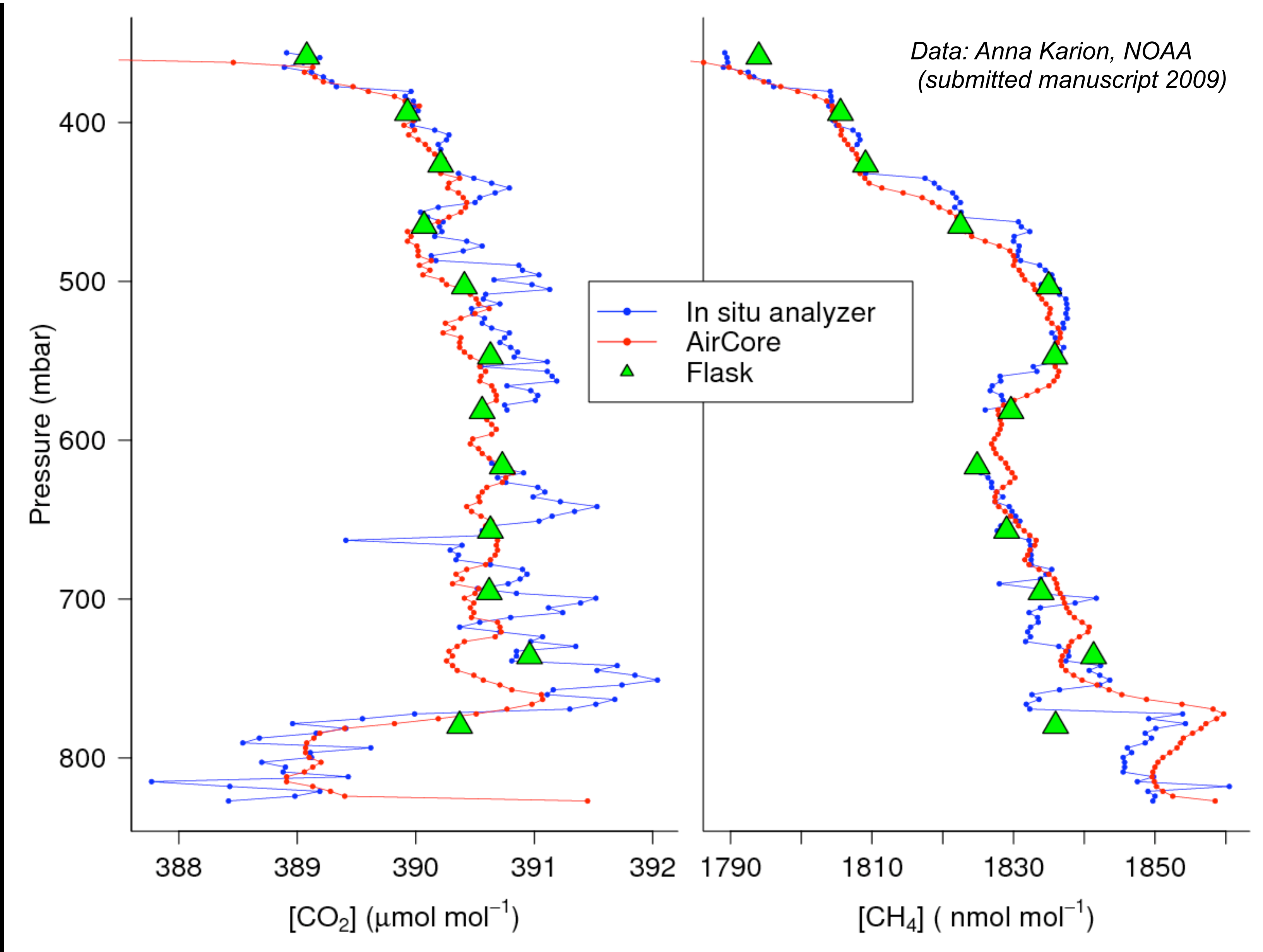


Data: NOAA tall towers program



Data: NOAA tall towers program

RMS diffusive length scale 3.2m/day for CO_2
yields ~47 independent obs in 150m coil
weight about 15 lbs



AirCore test on aircraft flight of May 7, 2009

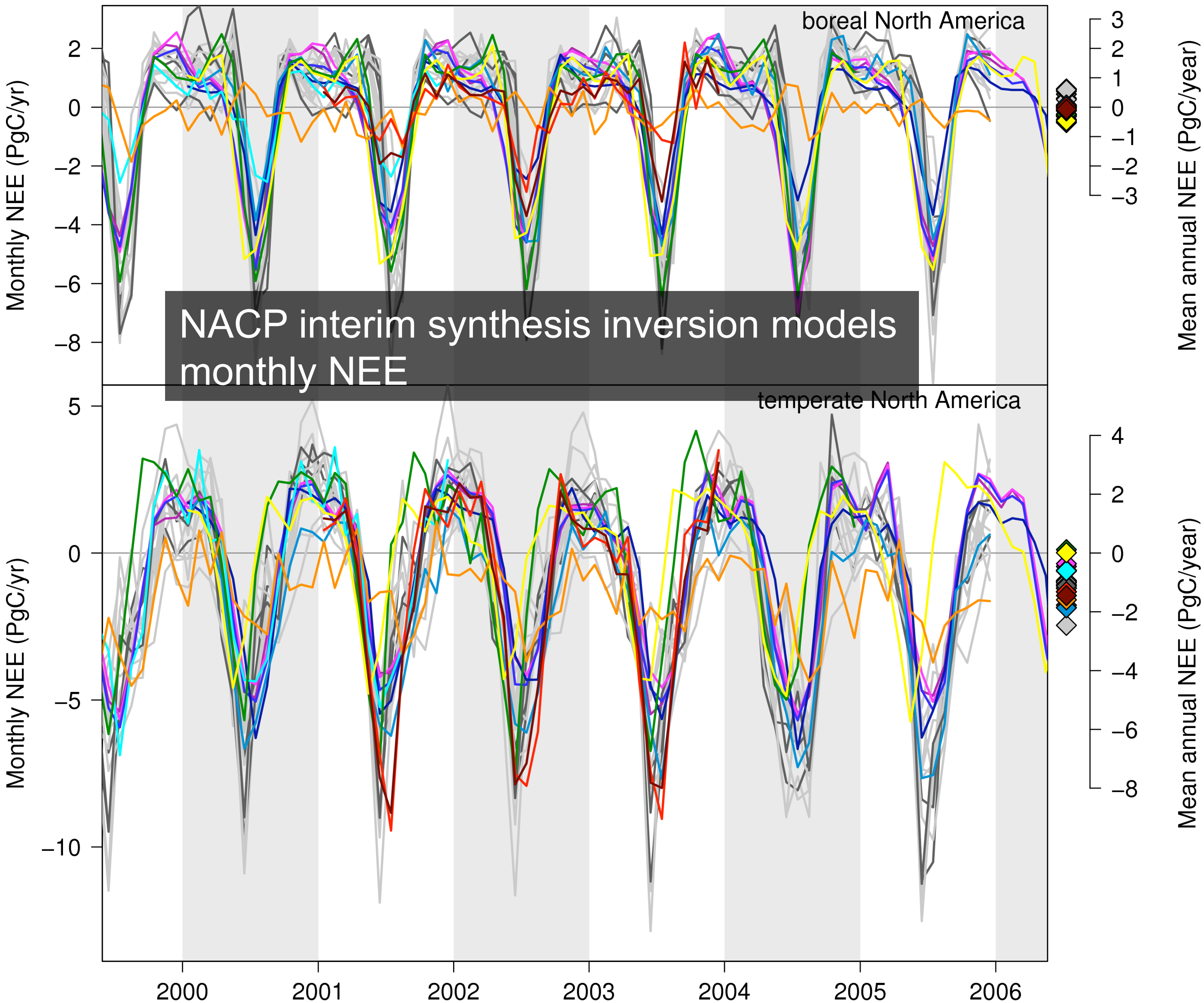
n.b. Some variability of in-situ data due to lateral sampling

Summary stats for NEE over North America
North American Carbon Program Interim Synthesis

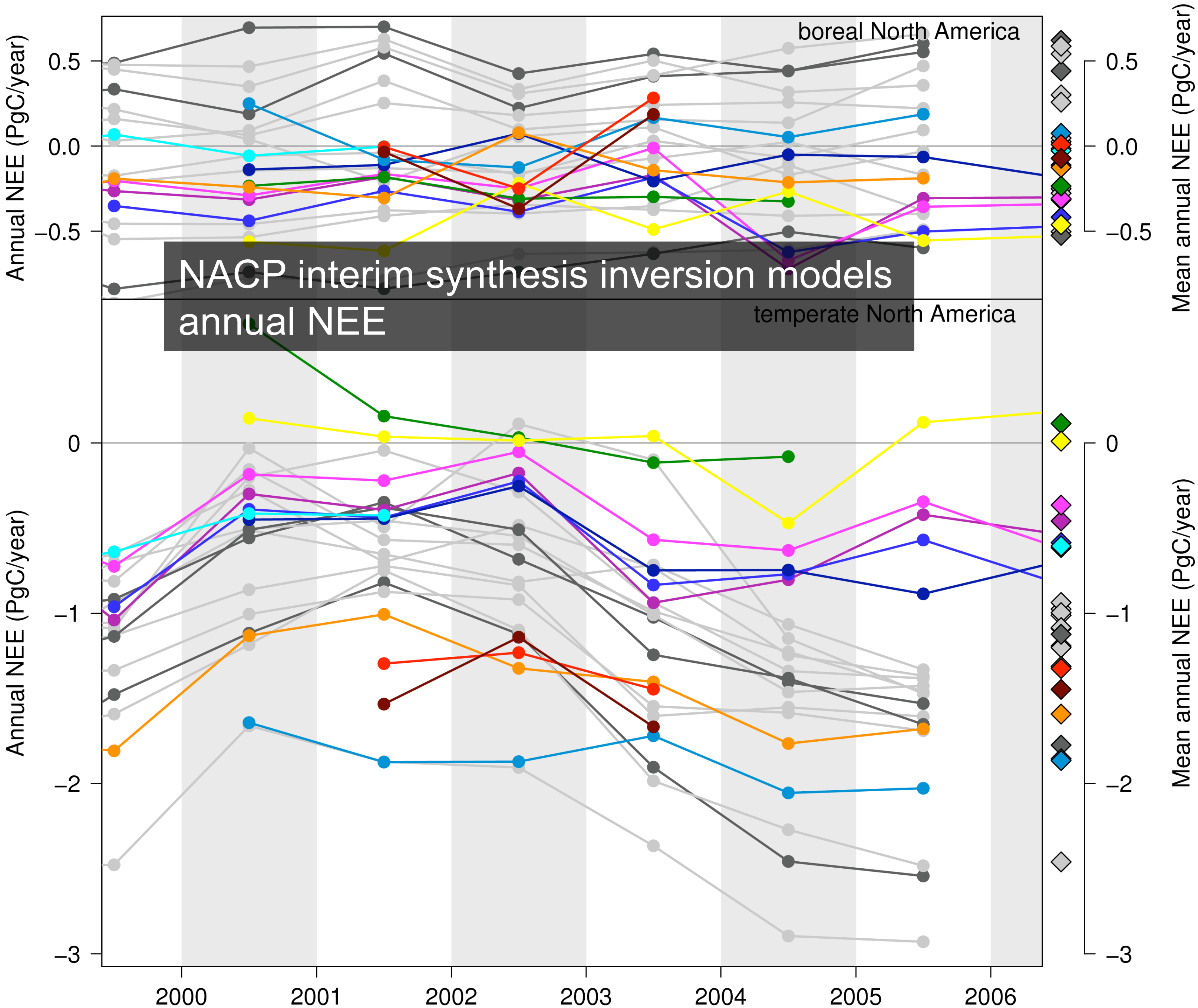
Inversions	25th percentile	Central	75th percentile
Uptake	0.6	1.1	1.4
IAV peak-peak	0.7	1.1	1.5
IAV (sd)	0.2	0.3	0.4

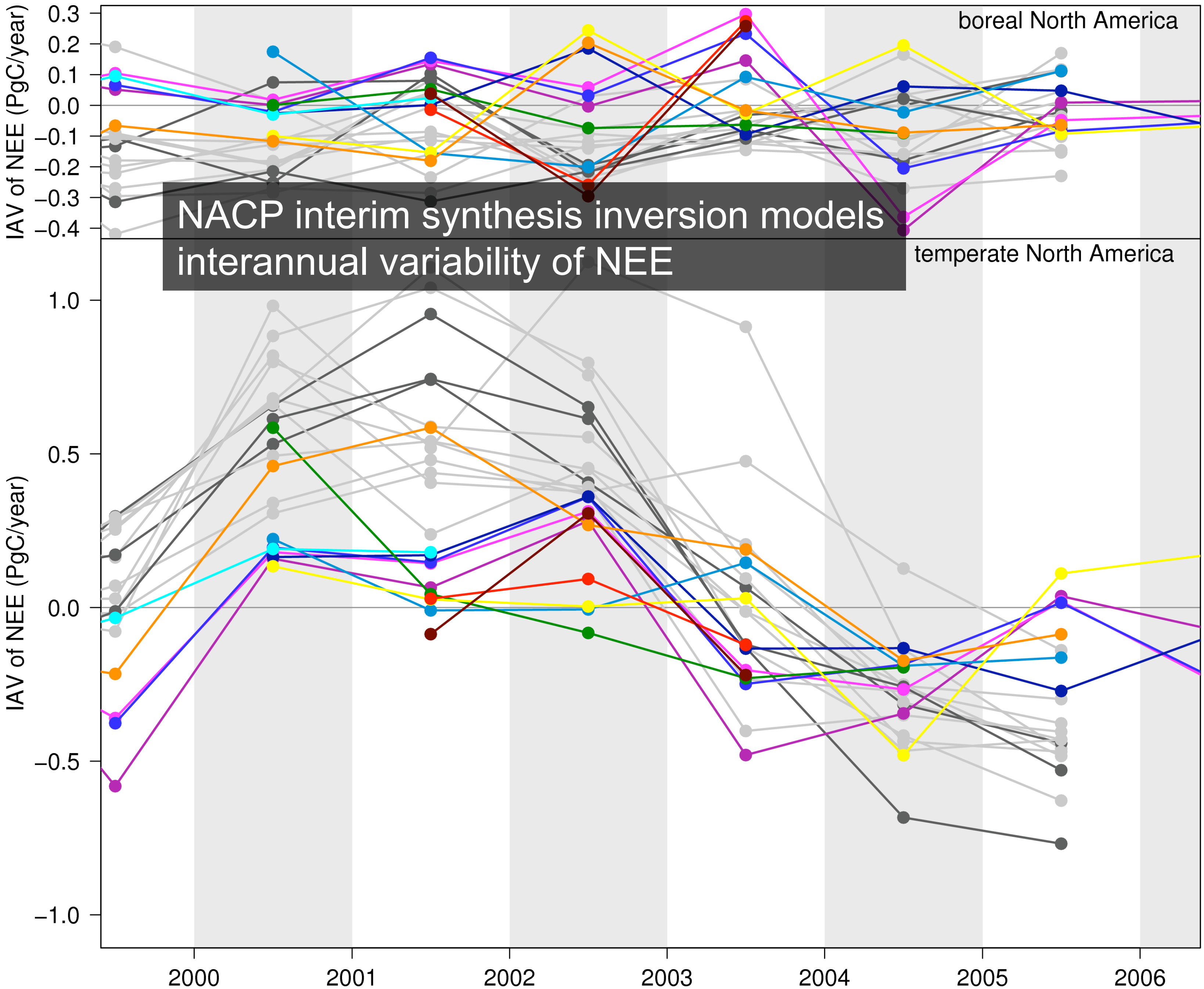
Forward models	25th percentile	Central	75th percentile
Uptake	0.1	0.3	0.8
IAV peak-peak	0.3	0.6	0.8
IAV (sd)	0.1	0.2	0.3

NACP interim synthesis inversion models monthly NEE



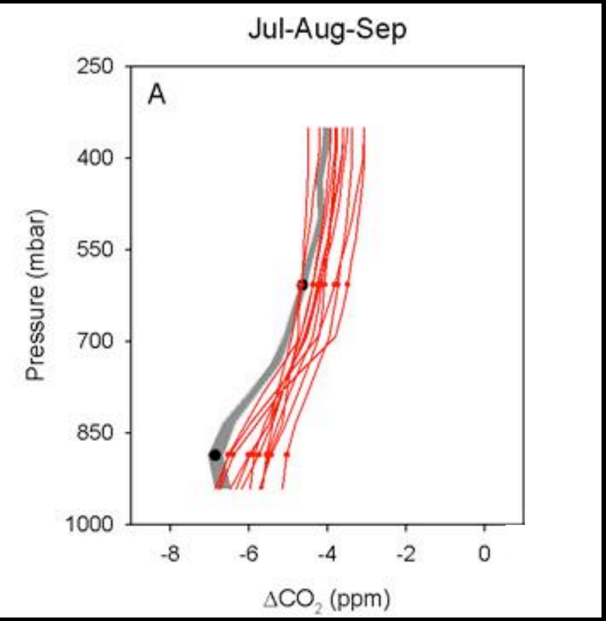
NACP interim synthesis inversion models annual NEE




NACP interim synthesis inversion models
interannual variability of NEE
boreal North America
temperate North America
IAV of NEE (PgC/year)
IAV of NEE (PgC/year)
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
1.0
0.5
0.0
−0.5
−1.0
2000
2001
2002
2003
2004
2005
2006

Northern Hemisphere Vertical CO_2 Gradients

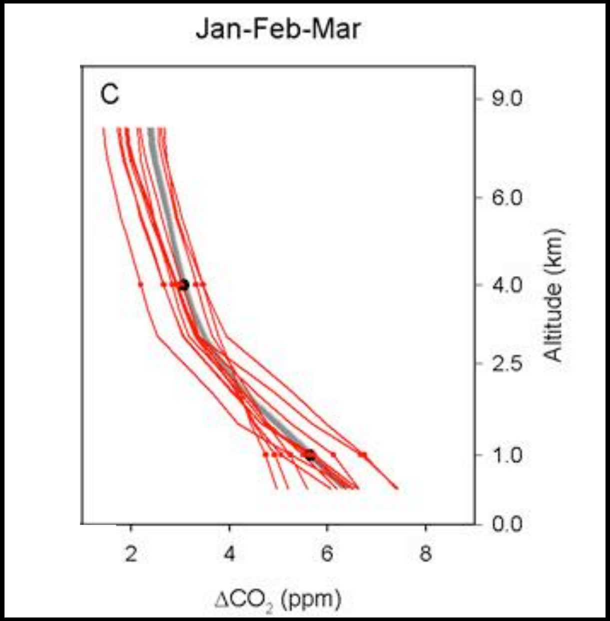
Figure courtesy of Britt Stephens



Summer

models underpredict gradient (too much diffusion).

Inversion requires greater uptake.



Winter

models overpredict gradient (too little diffusion).

Inversion requires less of a source.

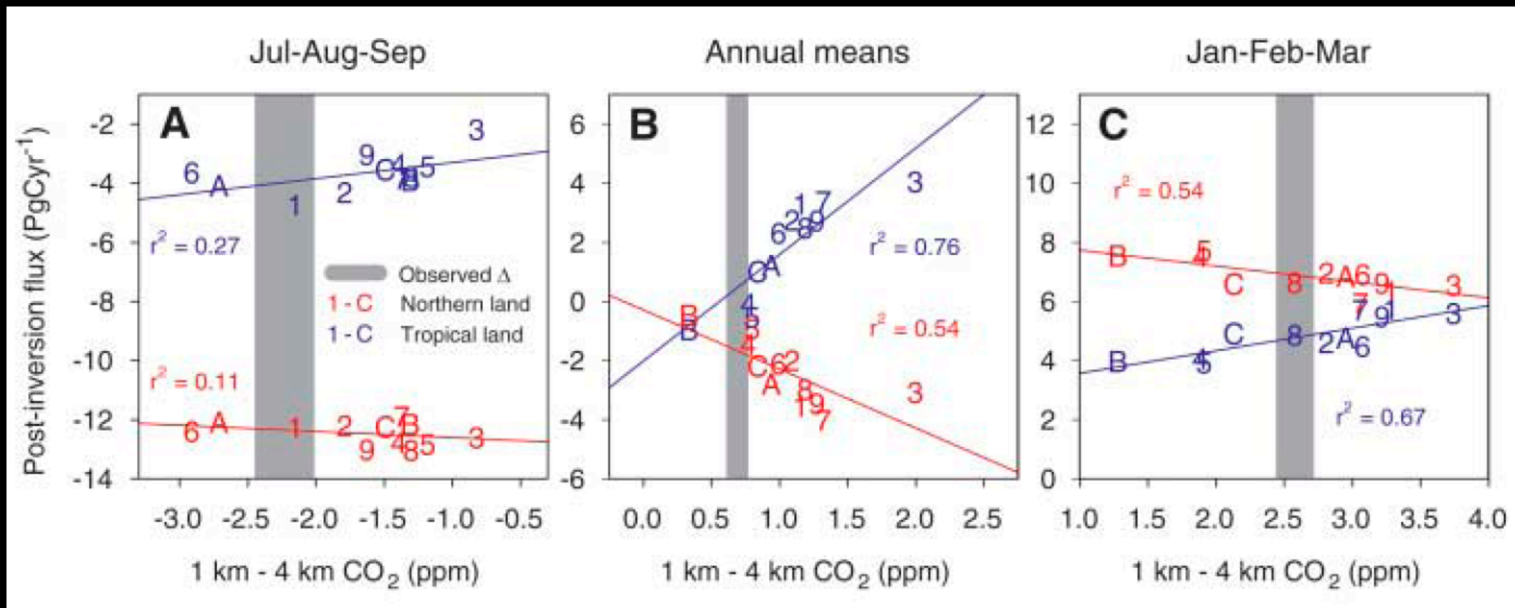


Figure courtesy of Britt Stephens

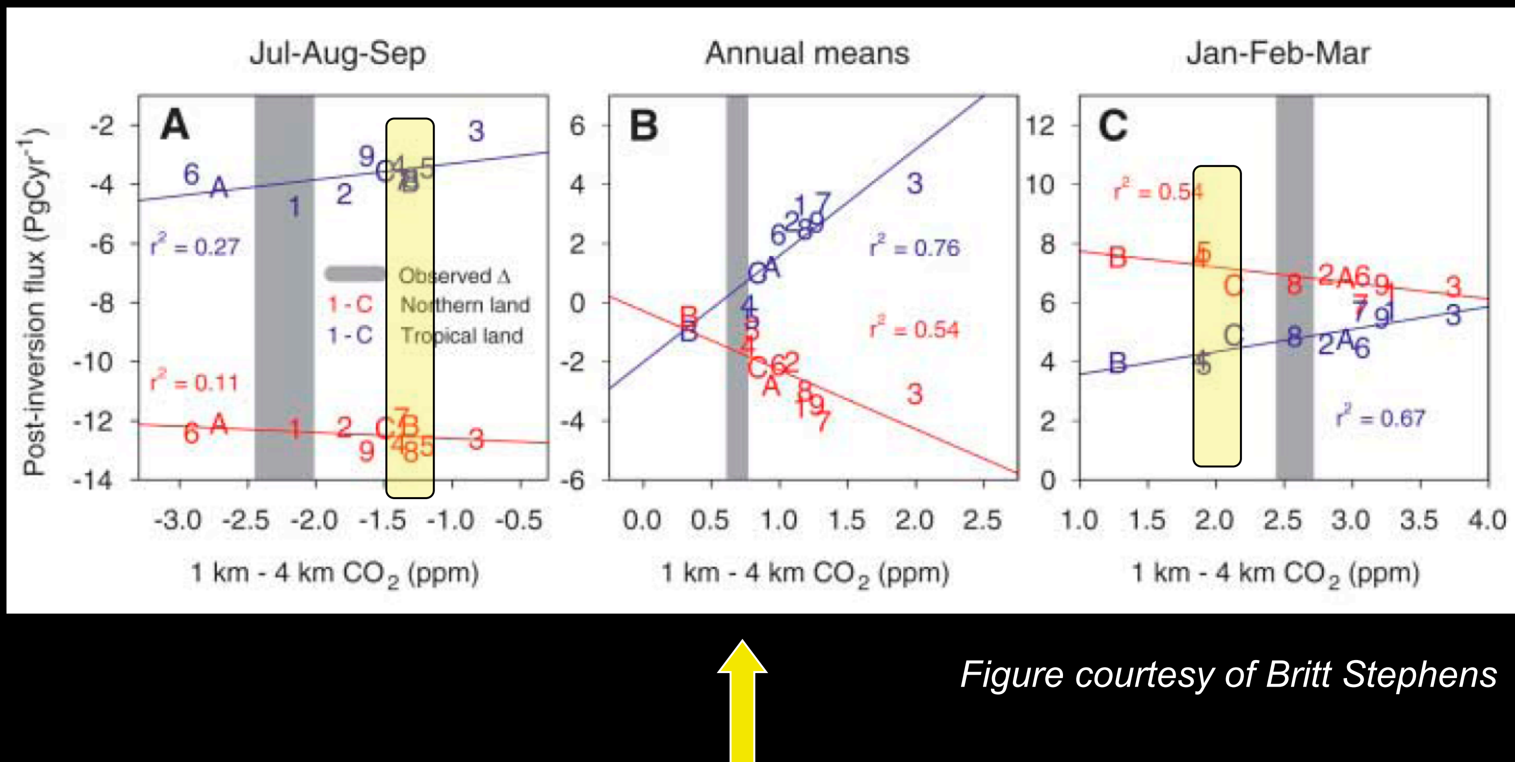
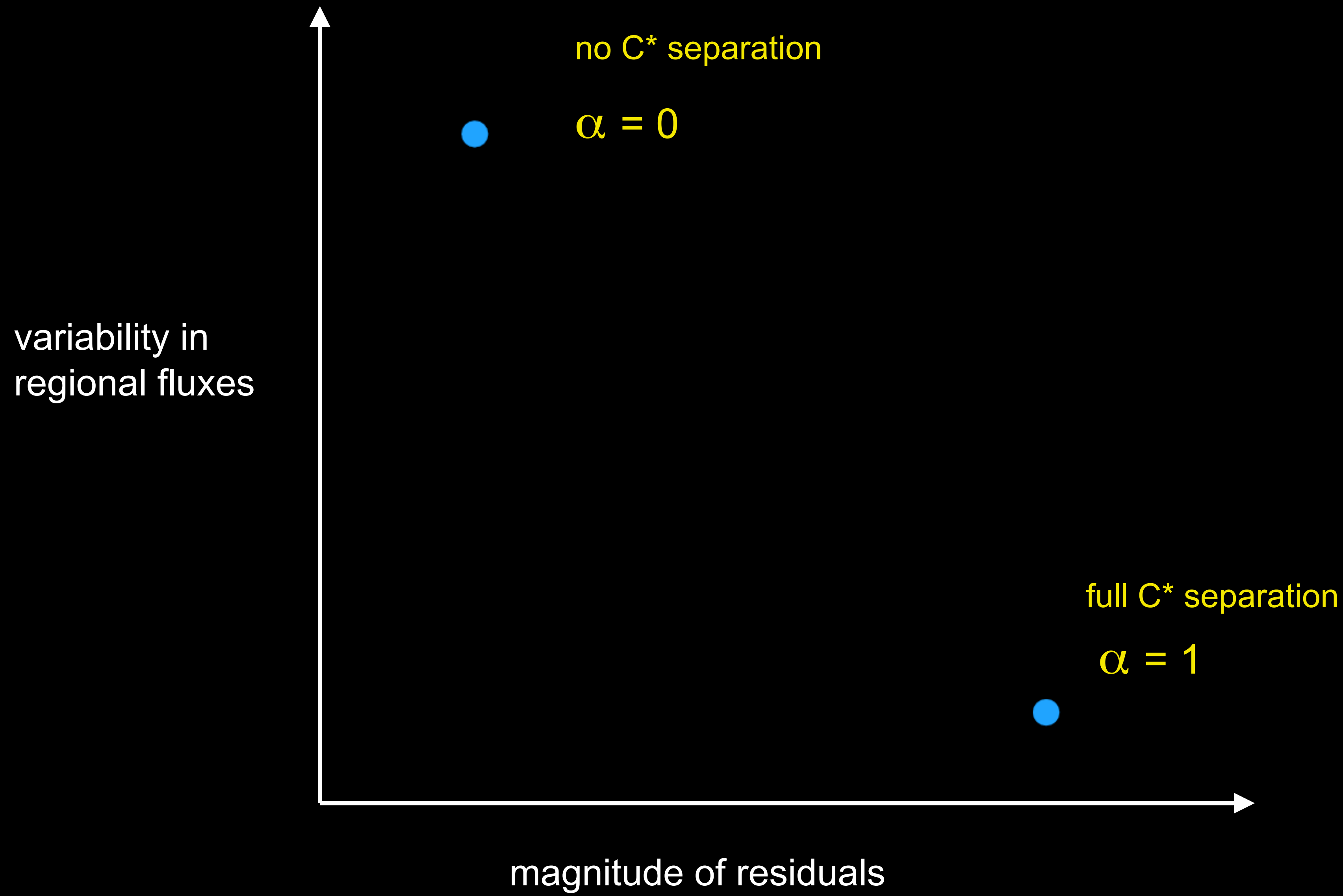
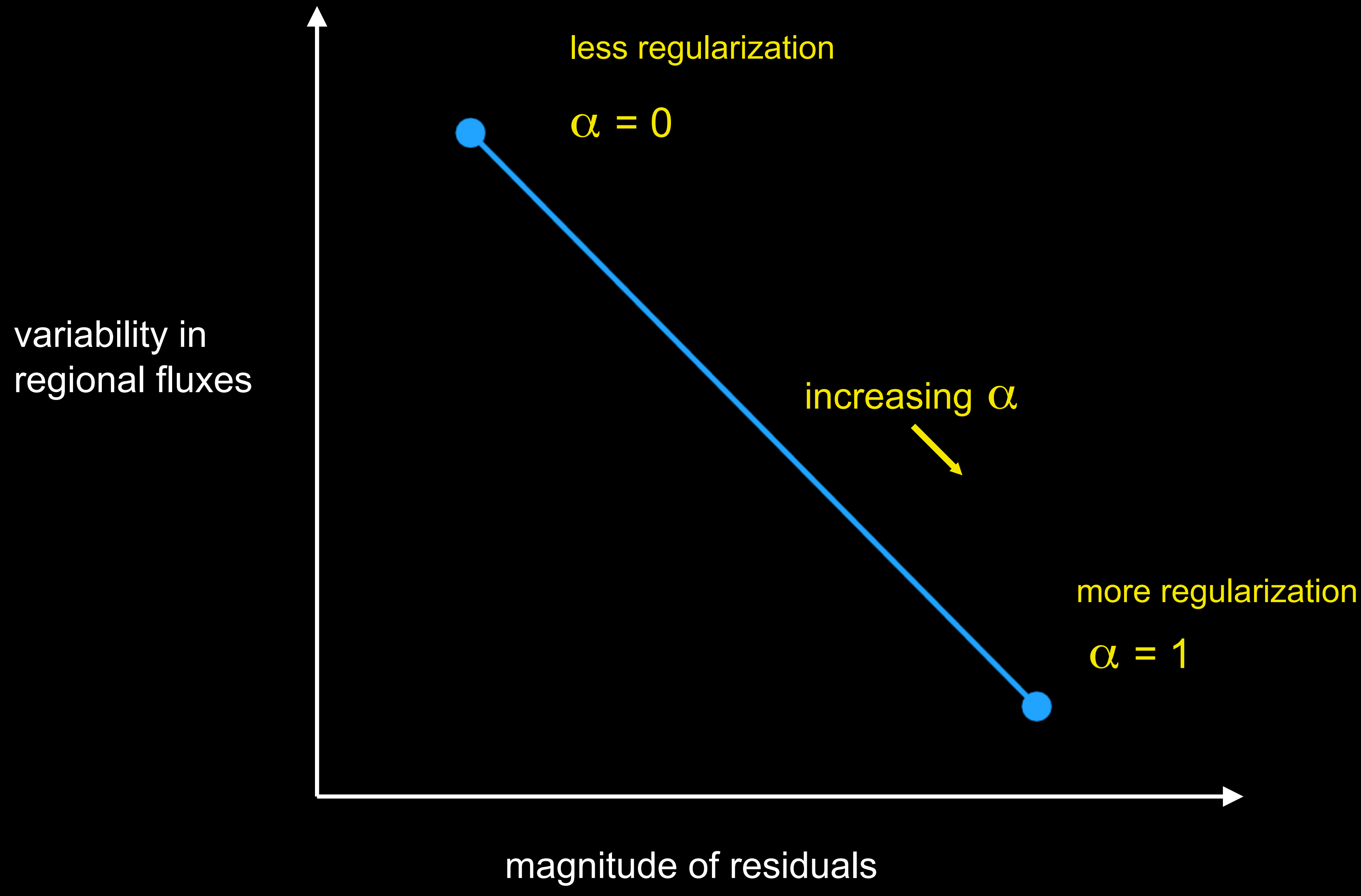
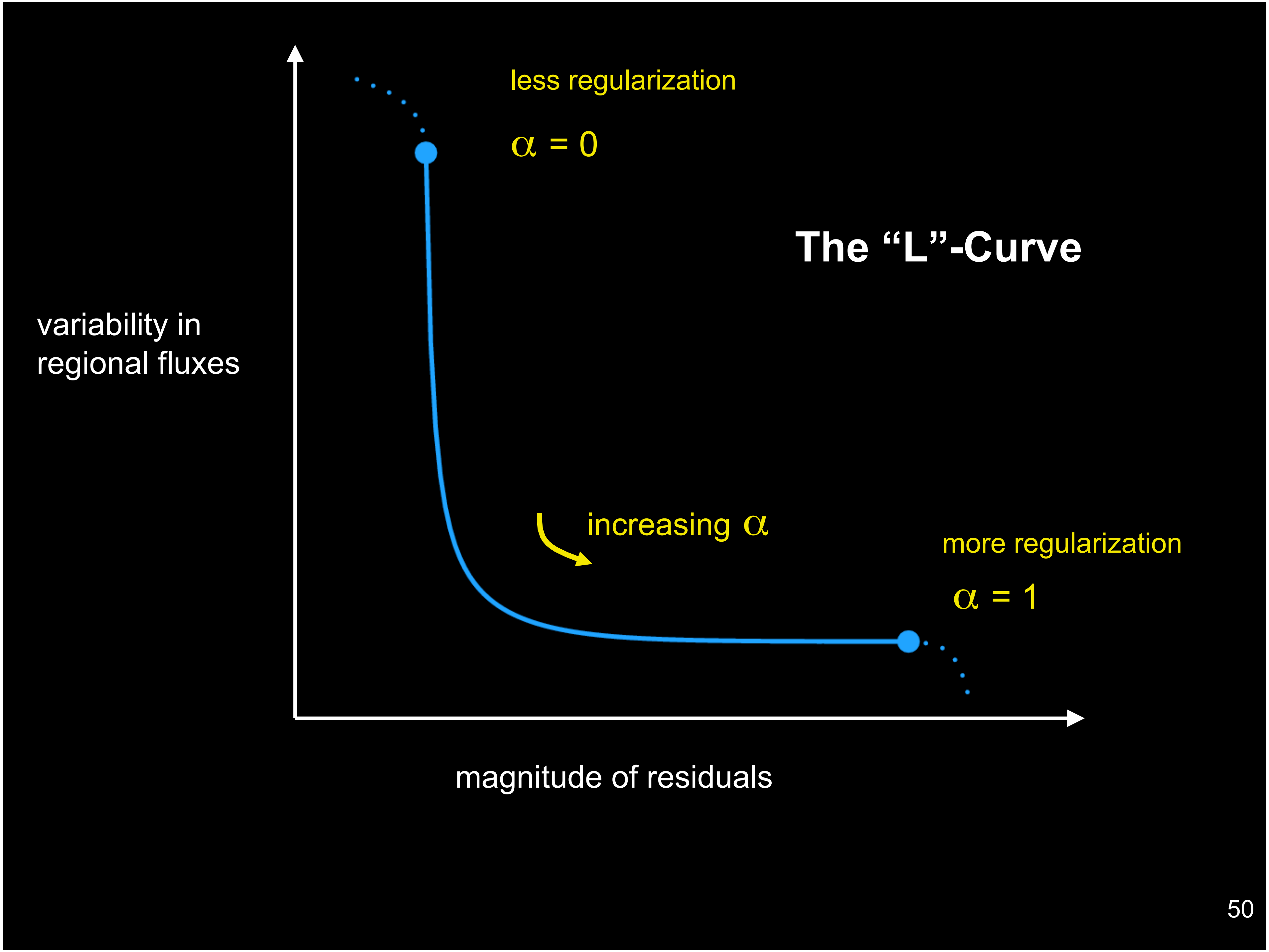


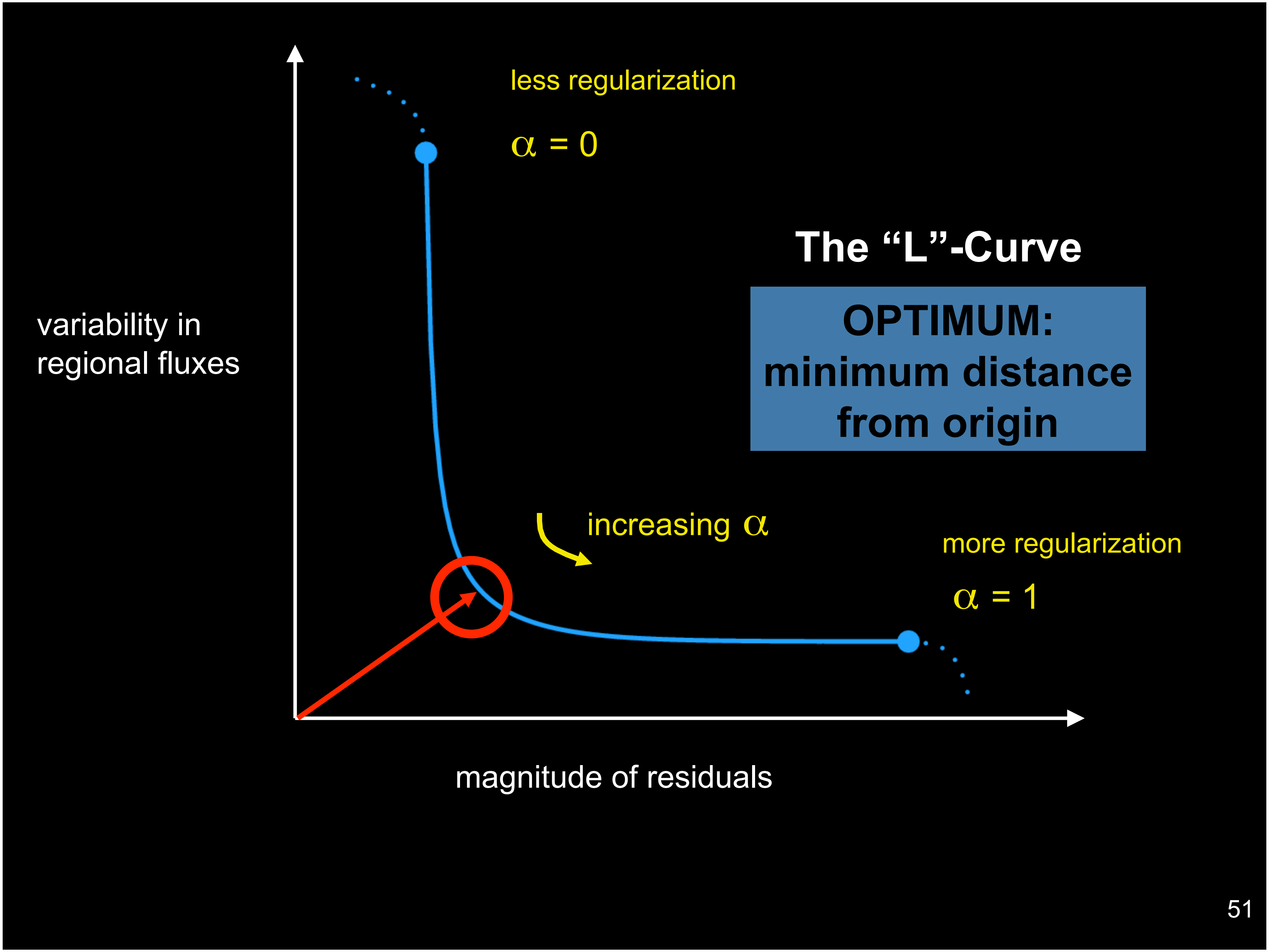
Figure courtesy of Britt Stephens


no C* separation
α = 0
variability in regional fluxes
full C* separation
α = 1
magnitude of residuals

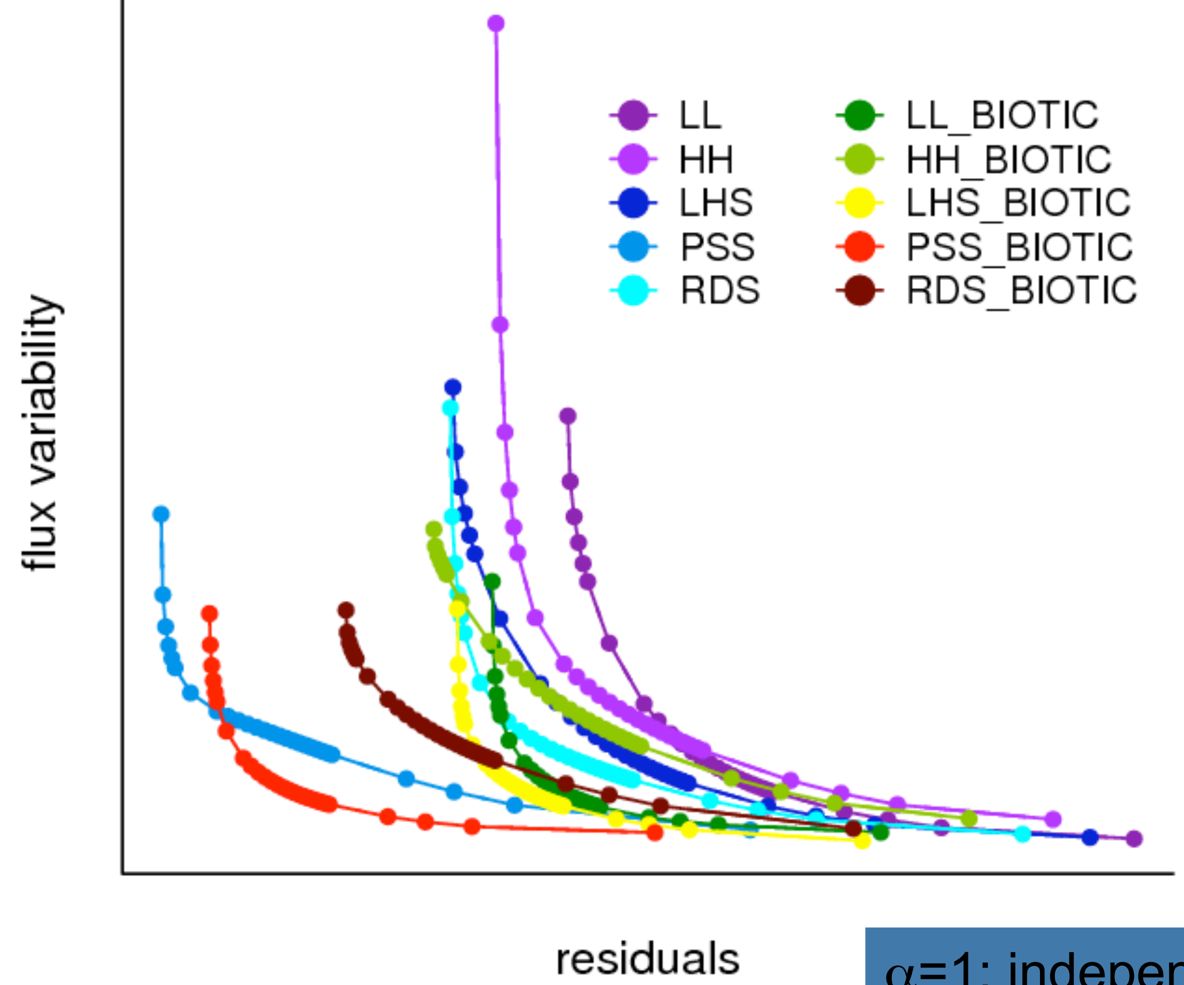

less regularization
α = 0
variability in
regional fluxes
increasing α
more regularization
α = 1
magnitude of residuals



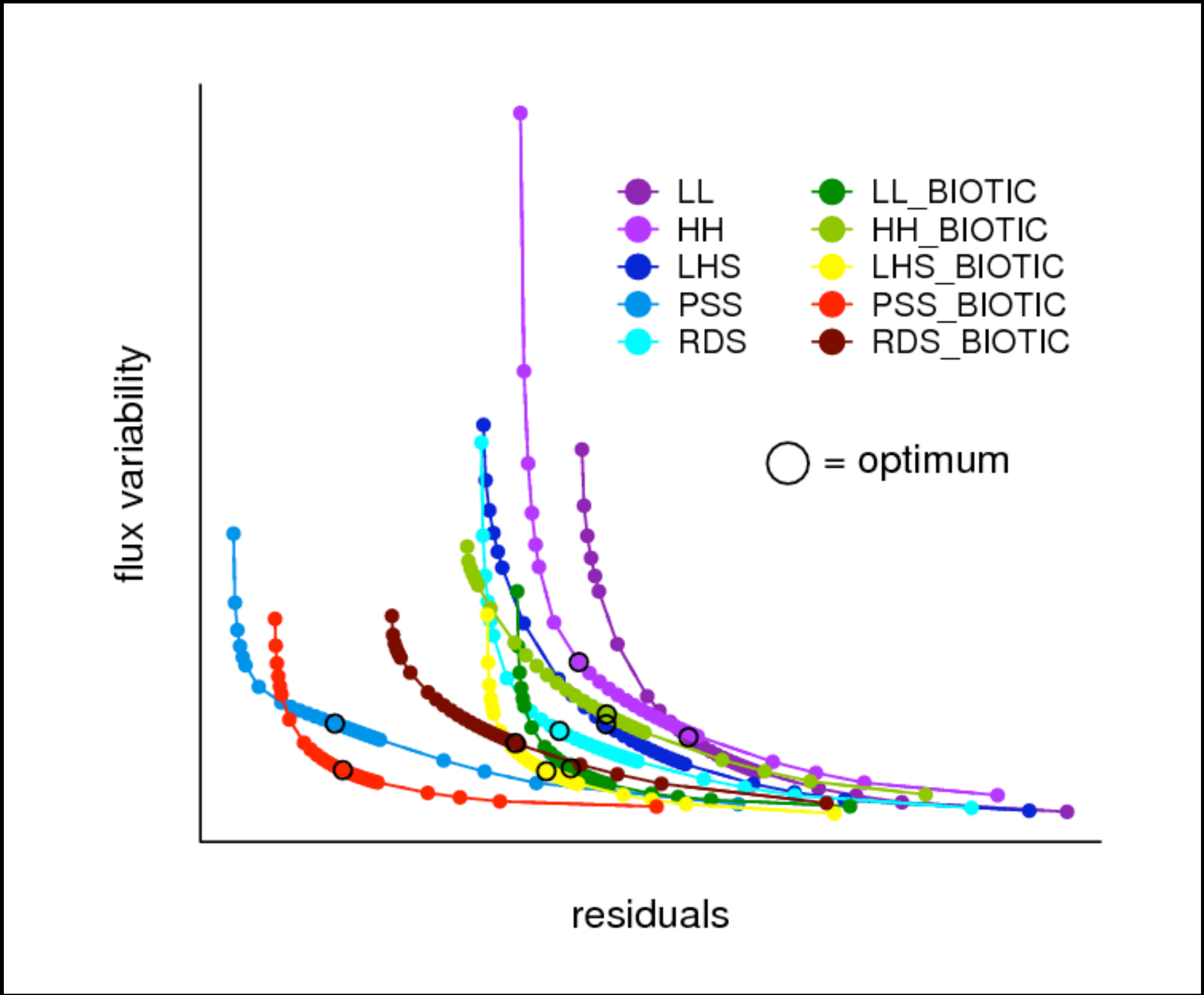
less regularization
α = 0
The "L"-Curve
variability in regional fluxes
increasing α
more regularization
α = 1
magnitude of residuals


less regularization
α = 0
The "L"-Curve
OPTIMUM:
minimum distance
from origin
variability in
regional fluxes
increasing α
more regularization
α = 1
magnitude of residuals

α=0: no ΔC_{ant} information



α=1: independent ΔC_{ant}, ΔC_{gasex} inversions



LL
HH
LHS
PSS
RDS
LL_BIOTIC
HH_BIOTIC
LHS_BIOTIC
PSS_BIOTIC
RDS_BIOTIC
= optimum
flux variability
residuals

Perspectives for the future

1. Treaty verification – societal need is at small scales
2. Remote sensing
3. Direct assimilation into carbon models
4. Joint meteo-carbon analysis
5. Online models, non-Gaussianity, ...

Topics

1. What conclusions are robust?
2. Use of biased models & MIPs
3. Rich, interesting dataset!
4. Footprint of an observation – scale of analysis
5. How best to reconcile models and data