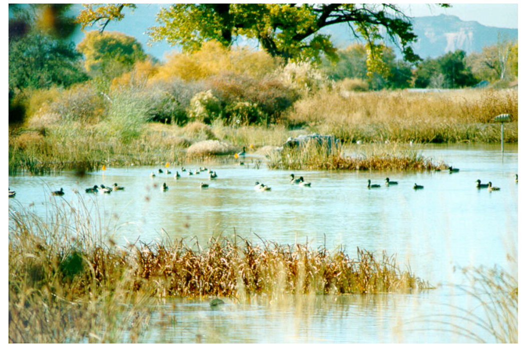
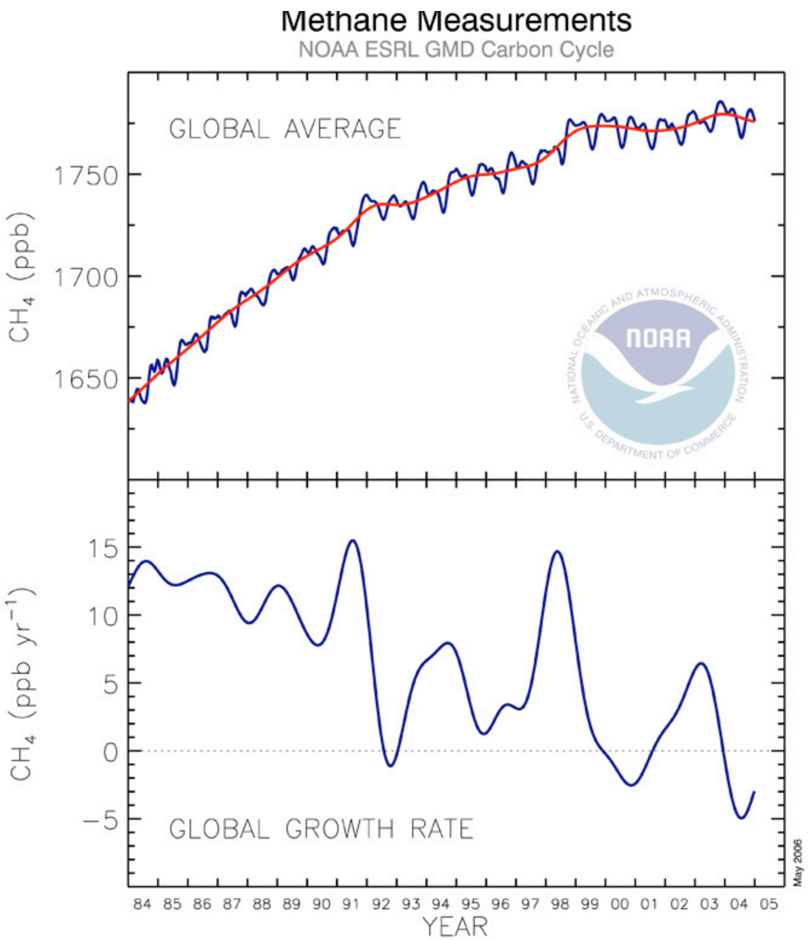



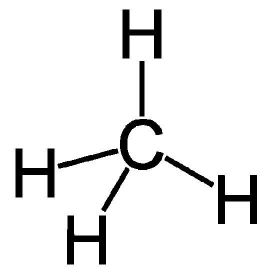

Inverse Modeling of Methane Emission Fluxes

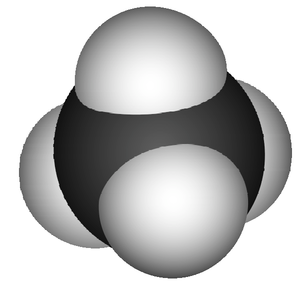
Lisa Neef, Michiel van Weele, Peter van Velthoven
Royal Netherlands Meteorological Institute (KNMI)

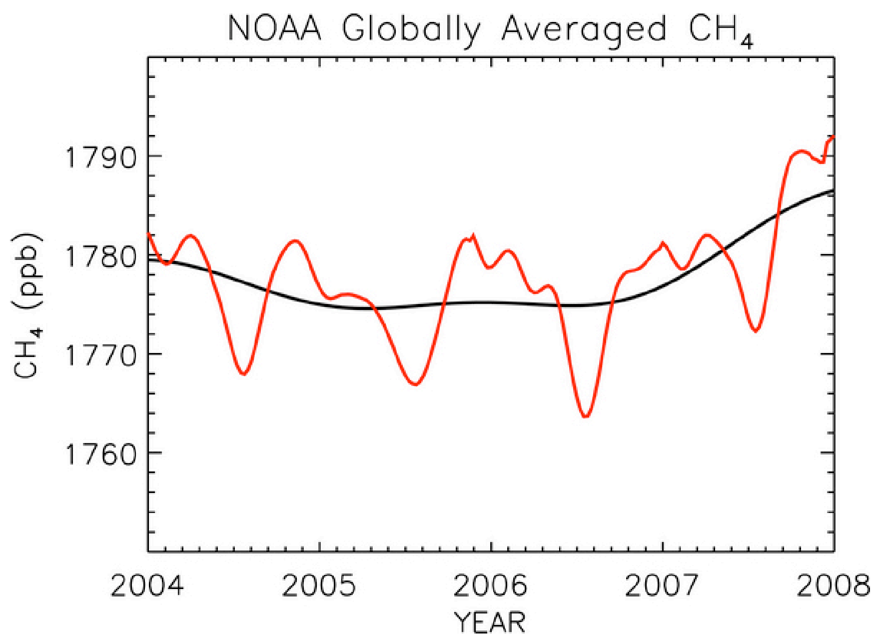
Methane : #2 Anthropogenic Greenhouse Gas



Top: Global average atmospheric methane mixing ratios (blue line) determined using measurements from the GMD cooperative air sampling network. The red line represents the long-term trend. Bottom: Global average growth rate for methane. Contact: Dr. Ed Dlugokencky, NOAA ESRL GMD Carbon Cycle, Boulder, Colorado, (303) 497-6228 (ed.dlugokencky@noaa.gov, http://www.cmdl.noaa.gov/ccgg).

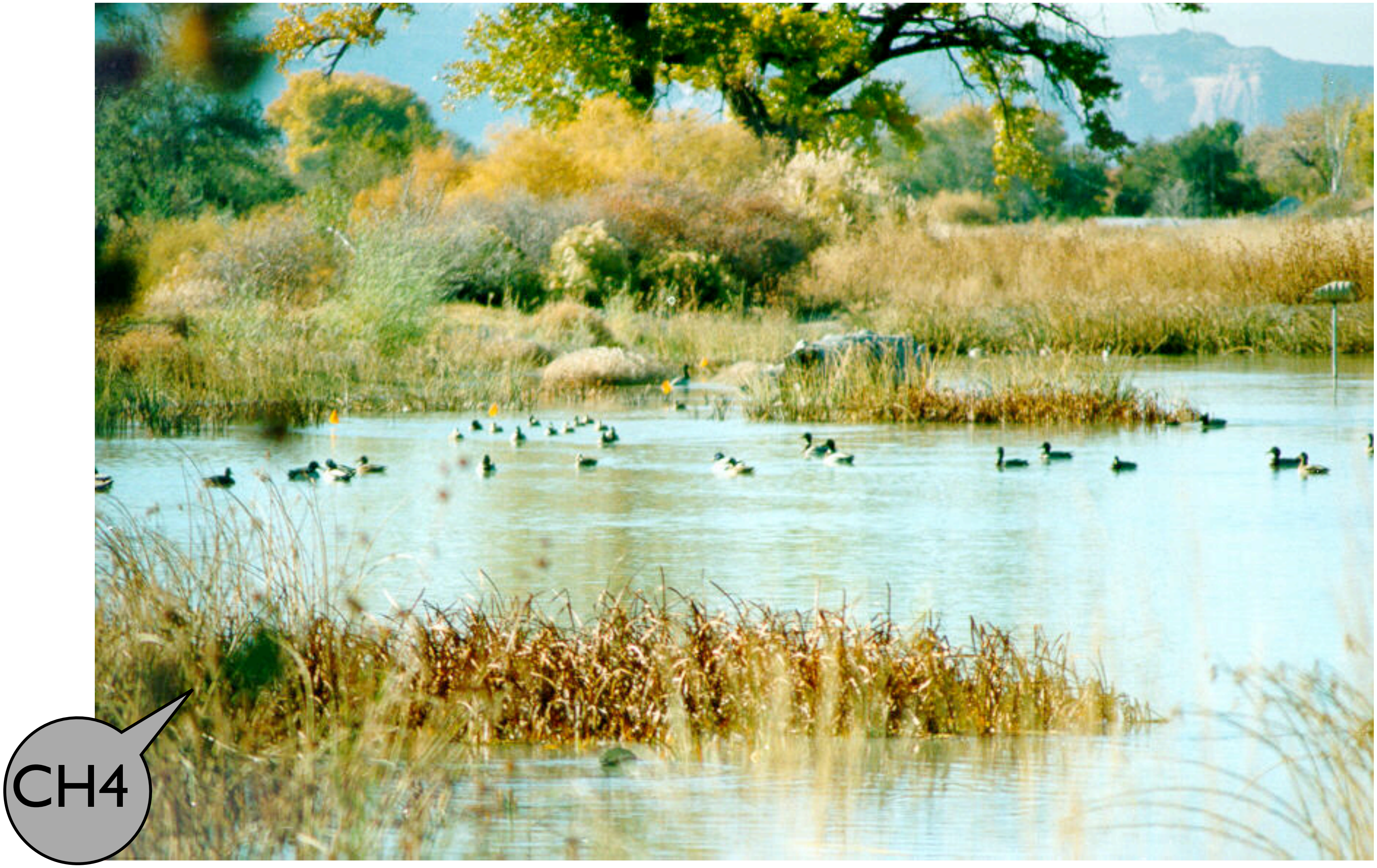






Sources of Methane

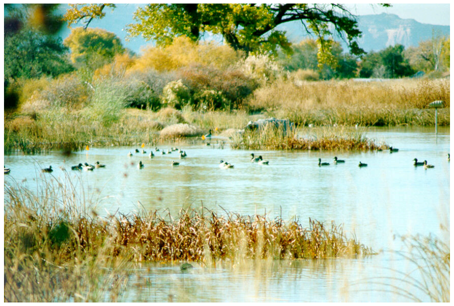
Sources of Methane



Sources of Methane

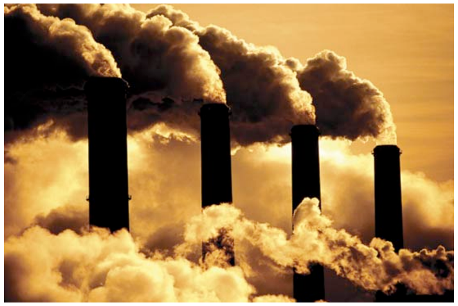
Sources of Methane

Wetlands (32%) [-56‰]



Ruminants (17%) [-62‰]

Fossil Fuels (16%) [-40‰]



Waste (12%) [-61‰]

Rice (9%) [-63‰]

Geol. Seepage (6%) [-40‰]

Burning (3%) [-22‰]

Termites (3%) [-57‰]

Hydrates (??) [??]

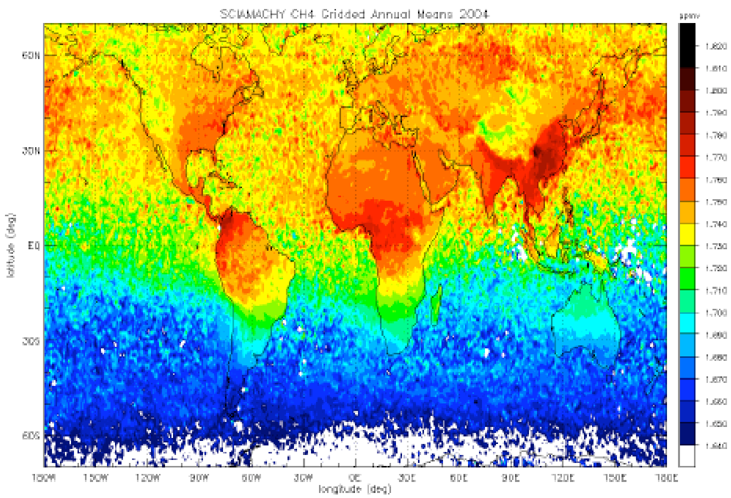
Some Unknowns about Methane

- Why did the growth rate slow down in the early 2000's?
- Why has it increased again?
- What are the relative roles of wetland and biomass burning emissions?
- How important is geological seepage?

We need to understand emissions

But what we measure is concentration

This Calls for Fancy Data Assimilation!



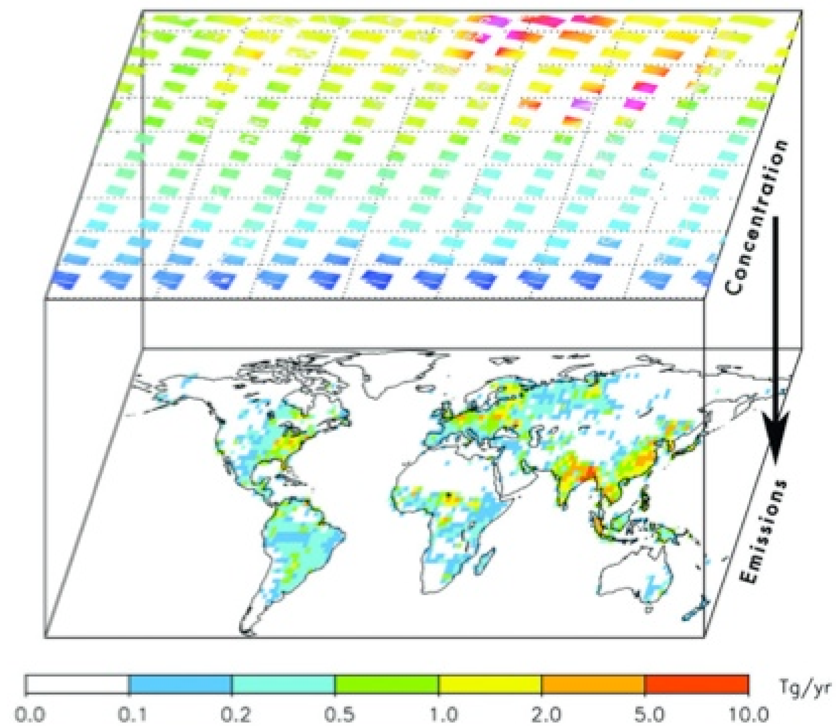
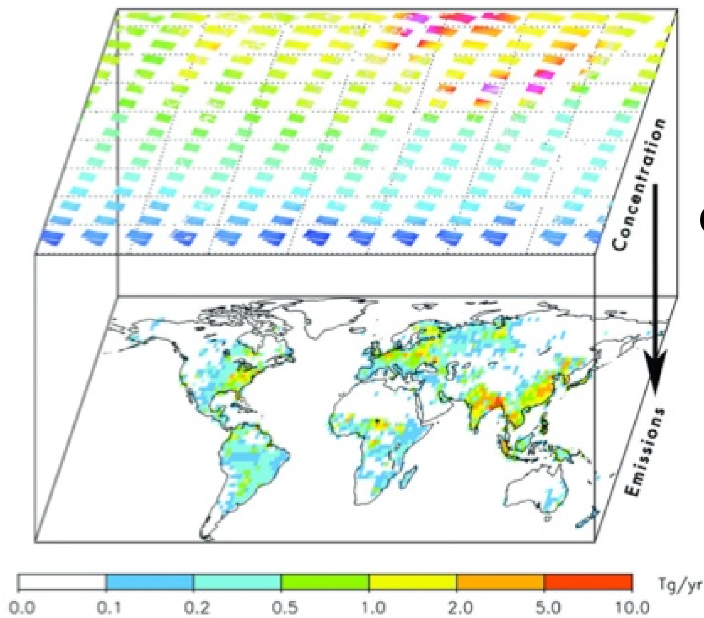


figure courtesy of J.F. Meirink

We search for the optimal emissions (per month per process) to fit the observed concentration

Connect emissions to concentrations using a transport model and assimilation algorithm

Methane Inversion Using 4D-Var



Observed surface concentration or column-averaged

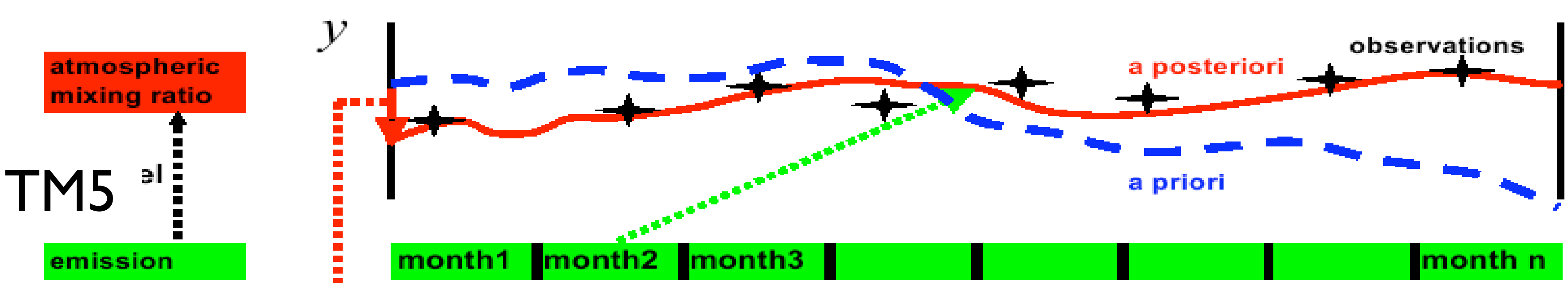
"observation operator" = transport model (TM5)

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x} - \mathbf{x}_b)^{\mathrm{T}} B^{-1} (\mathbf{x} - \mathbf{x}_b) + \frac{1}{2}[y - H(\mathbf{x})]^{\mathrm{T}} R^{-1} [y - H(\mathbf{x})]$$

Prior estimate of emissions: flux per gridcell per source type

Methane Inversion using 4D-Var

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}_b)^{\mathrm{T}}B^{-1}(\mathbf{x}-\mathbf{x}_b) + \frac{1}{2}[y-H(\mathbf{x})]^{\mathrm{T}}R^{-1}[y-H(\mathbf{x})]$$

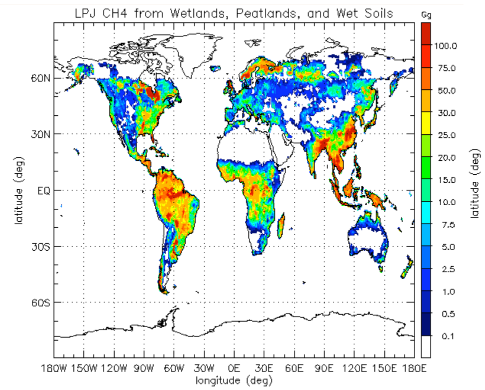


$$x = \begin{bmatrix} x_{\mathrm{INI}} \\ x_{\mathrm{EMIS}} \\ x_{\mathrm{PARA}} \end{bmatrix}$$

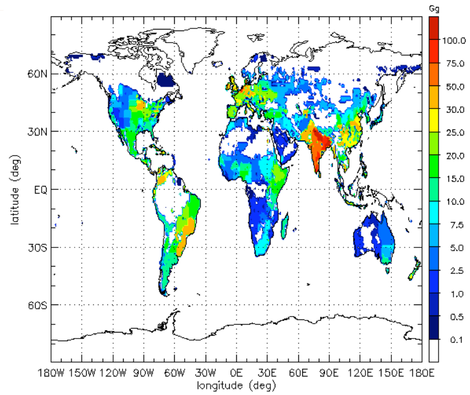
* Initial [CH4] field
* Emissions per month per cell per process
* satellite bias parameters

figure courtesy of J.F. Meirink

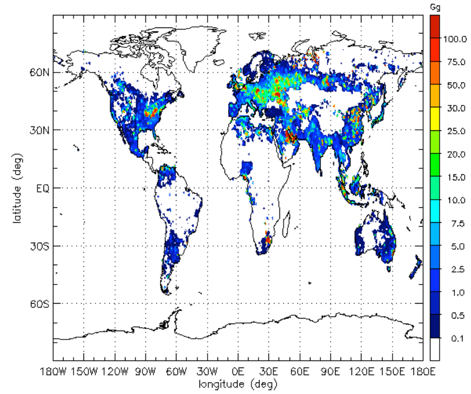
A Priori Methane Source Estimates



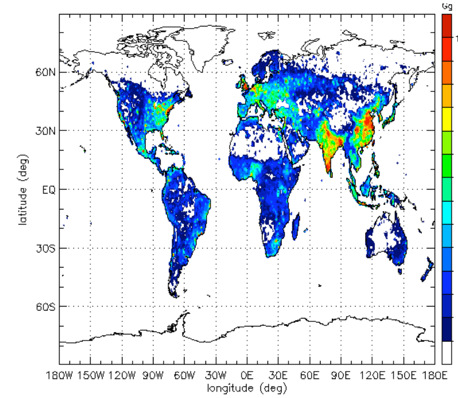
Wetlands



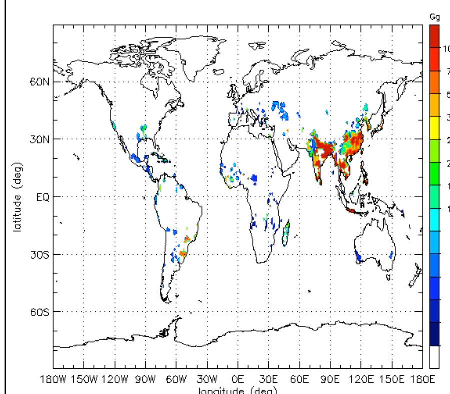
Domestic Ruminants



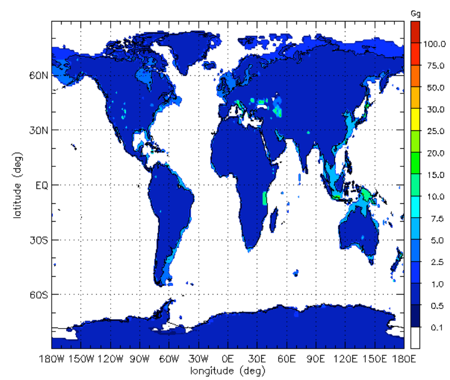
Coal mining, Oil & Gas



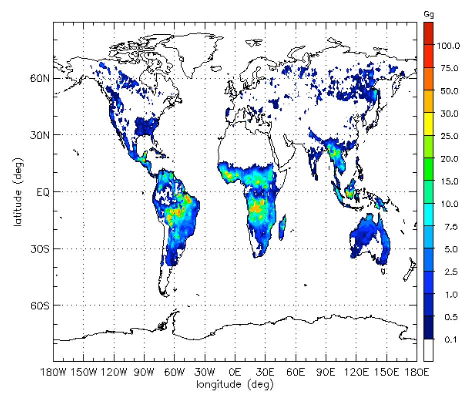
Waste



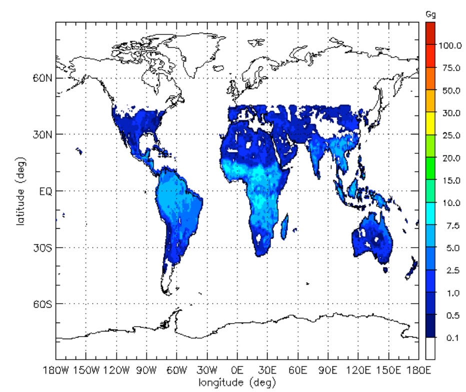
Rice Agriculture



Geological Seepage



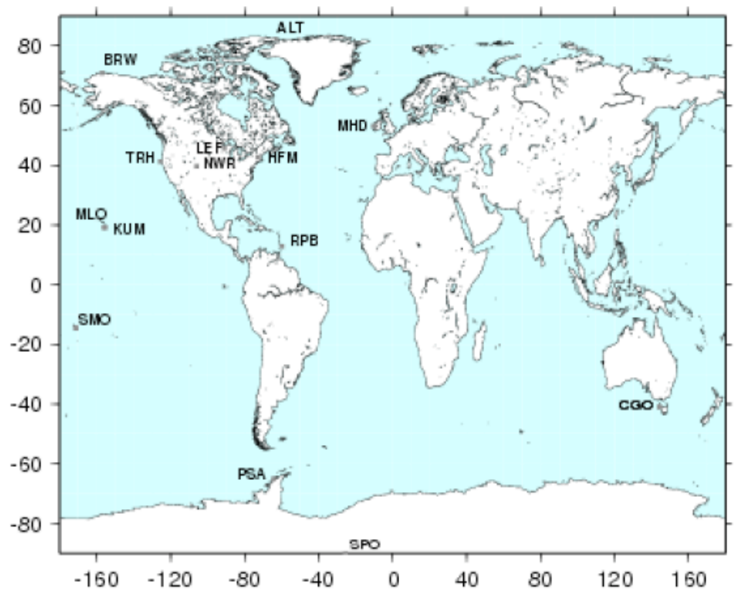
Biomass Burning

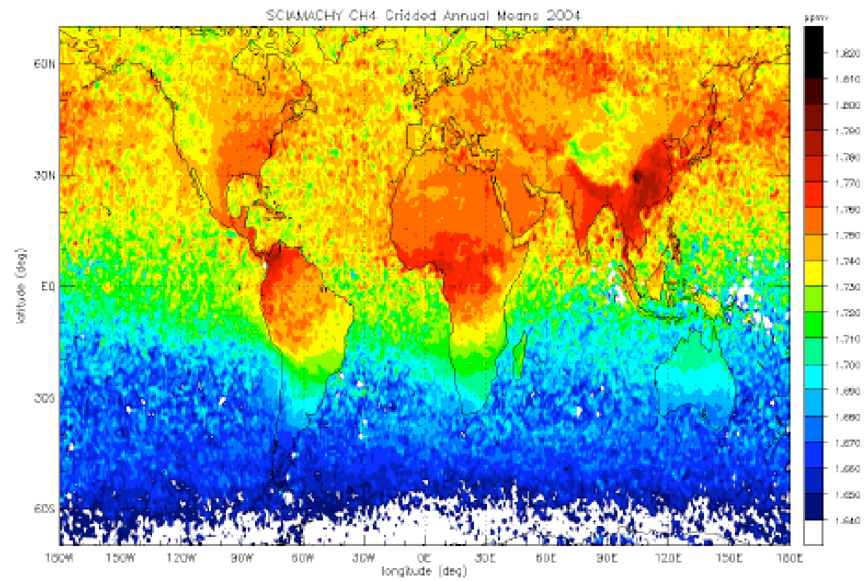


Termites

Different inventories form the building blocks of the prior emission vector.

Observations: CH4 Concentration





58 Stations
+ Measure surface concentration
+ In-situ
+ Accurate
- Sparse

SCIAMACHY
+ Column-average mixing ratios
+ Dense
- Possibly strong latitudinal bias
- 2004 only

Details: 4D-Var Inversion at KNMI

Control Vector (x)

Dimension = 10 Categories x 2700 grid cells x 12 months + Initial Concentration = 326,000

* Can simplify the number of categories.

Observations (y)

NOAA surface network

SCIAMACHY (new)

obs vector dimension ~10^5

Covariance Matrix (B)

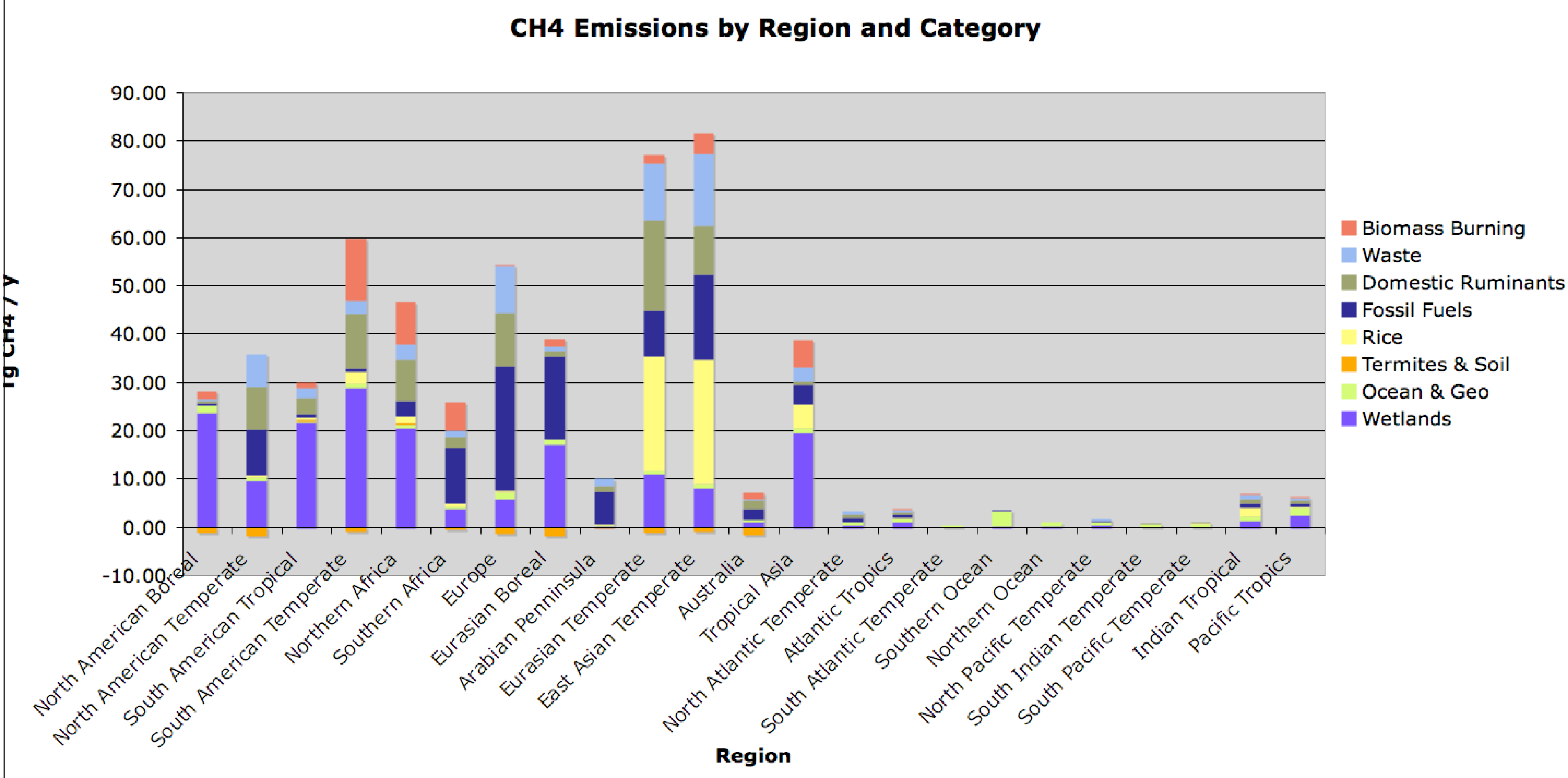
- 0 correlation between processes
- gaussian spatial correlations with decorrelation length L ~ 500 km
- exponential temporal correlation between months (for some processes

Forward Model (H)

TM5

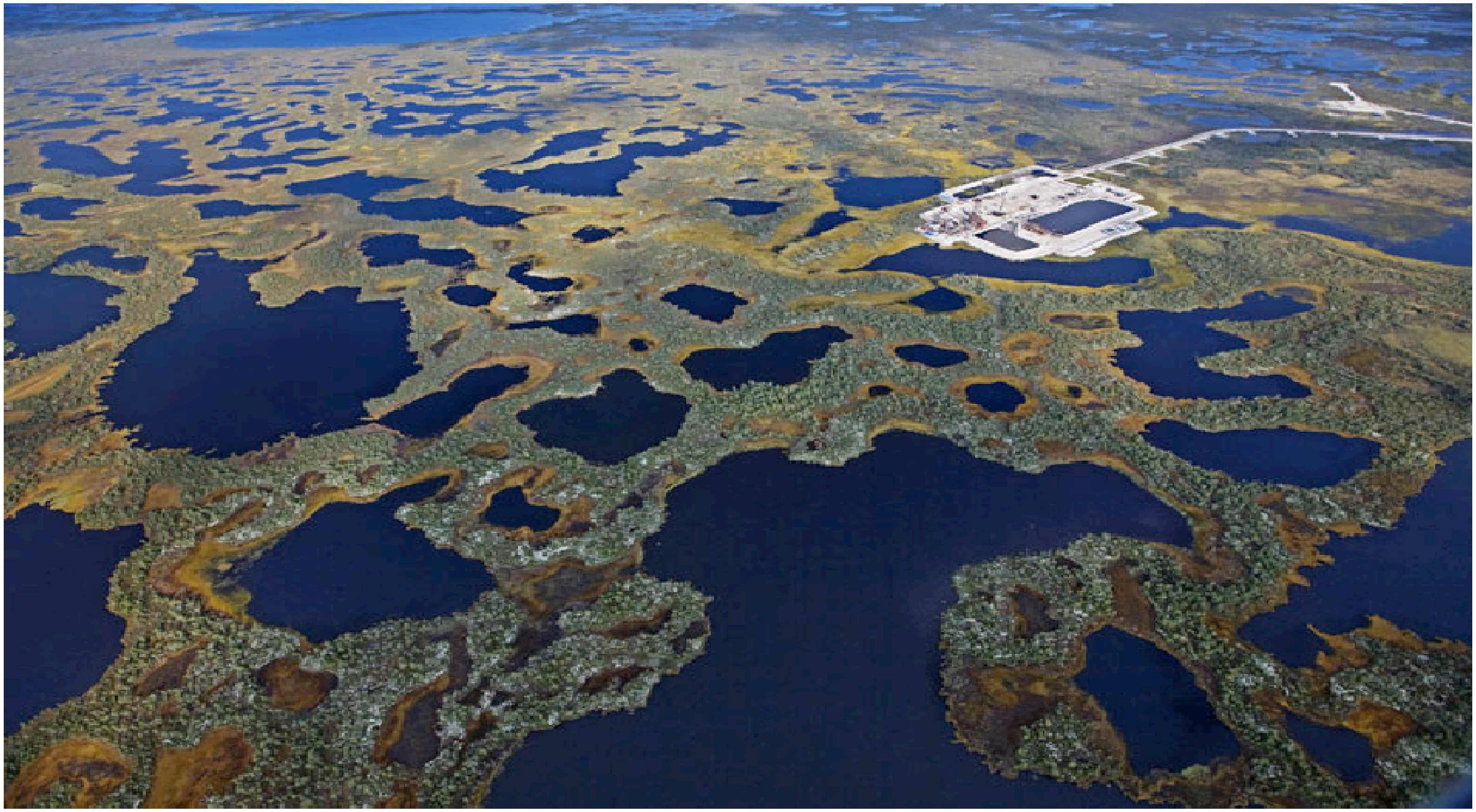
6° x 4° resolution

Spatial Structure of CH4 Sources



It’s a ruminant in a rice paddy...

...or an oil drillpad in the Siberian wetlands.



Photograph by Gerd Ludwig

A drill pad built on top of fragile wetlands probes for new oil reserves. Technology imported from the West is helping Russia's oil industry modernize, but Soviet-era spills and pipeline breaks have contaminated much of the region.

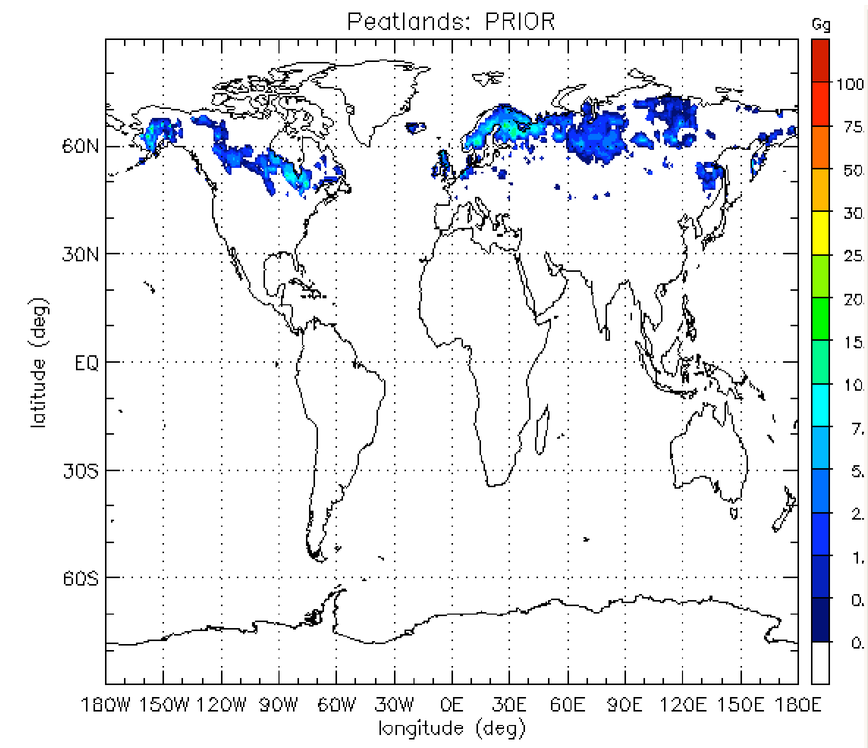
From National Geographic, June 2008
(via L. Bruhwiler, NOAA)

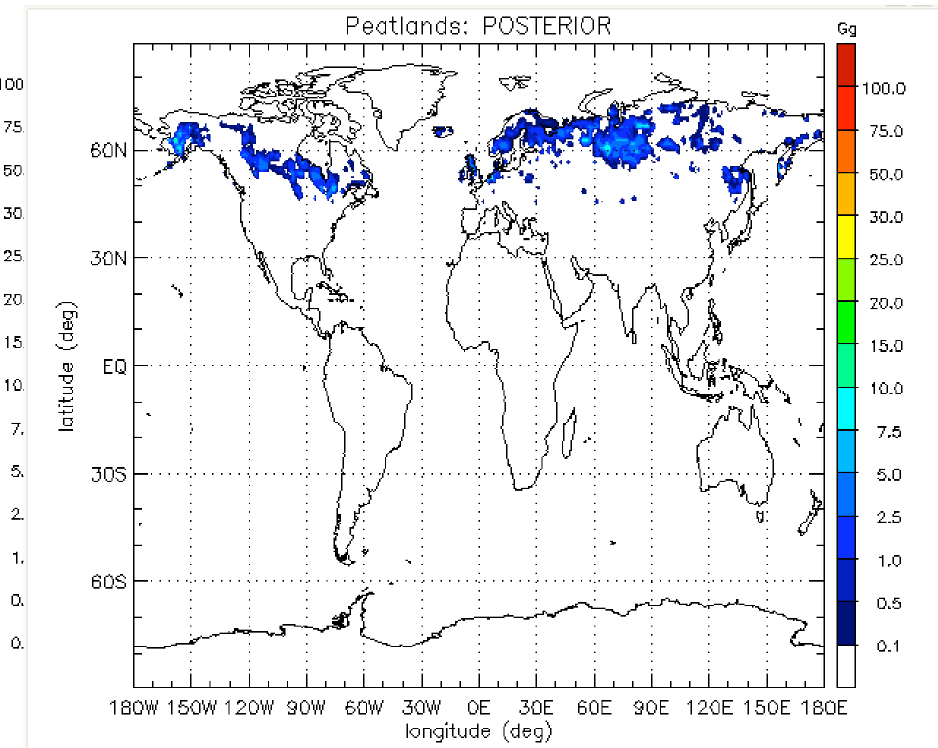
A Sample Inversion

	Prior →	Posterior	% change
Wetlands & Rice	213	221	+4%
Termites	19	25	+27%
Geological	17	14	-18%
Biomass Burning	24	28	+17%
Coal, Oil, Gas	75	68	-10%
Waste	68	64	-5%
Ruminants	99	117	+18%
Soil Consumption	-38	-30	-20%

→ Shift from NH to more tropical sources.

Adjustment of LPJ Wetland Components



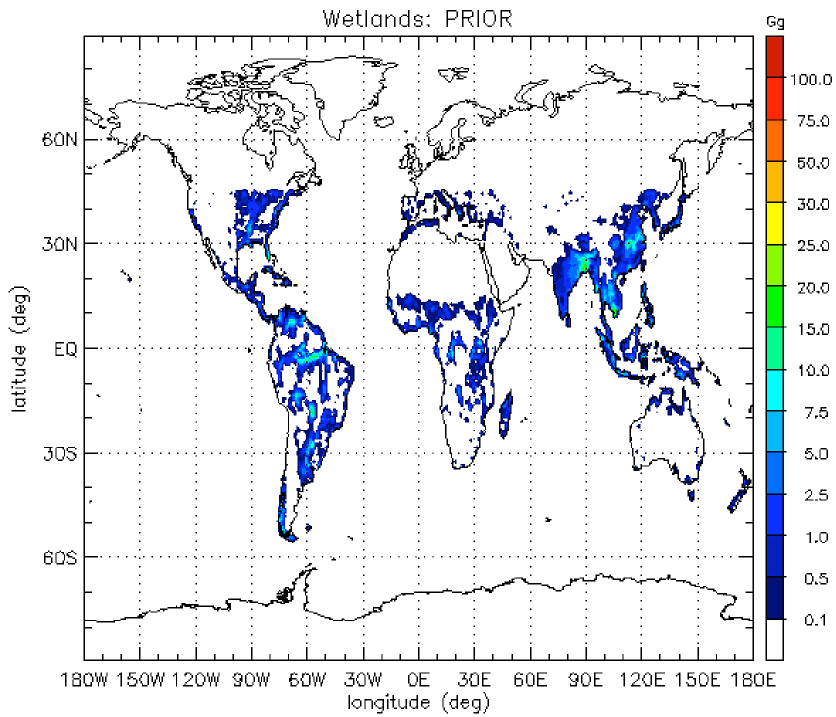


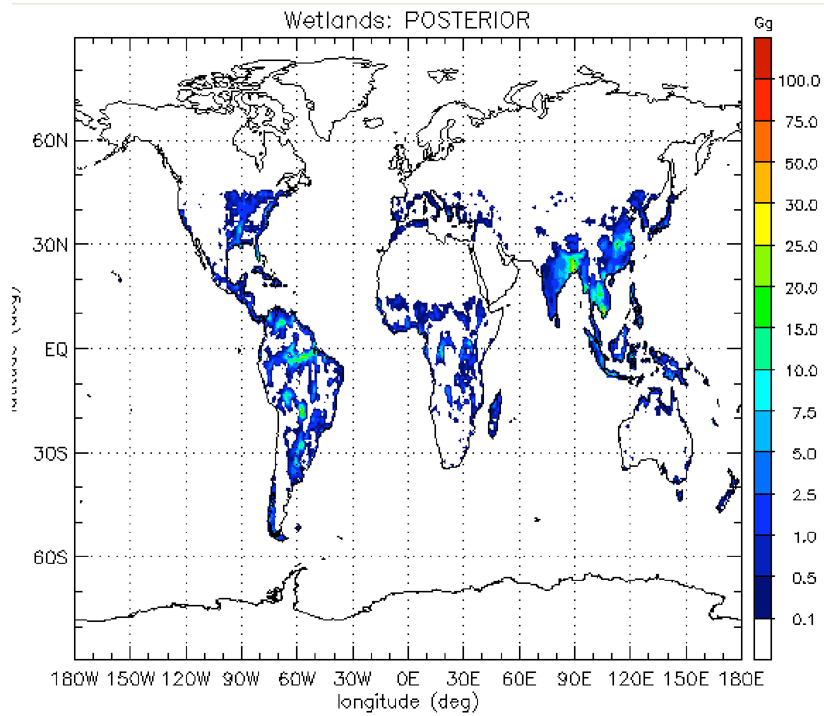
39 Tg / y

26 Tg / y

Northern Hemisphere Peatlands strongly decreased.

Adjustment of Wetland Components



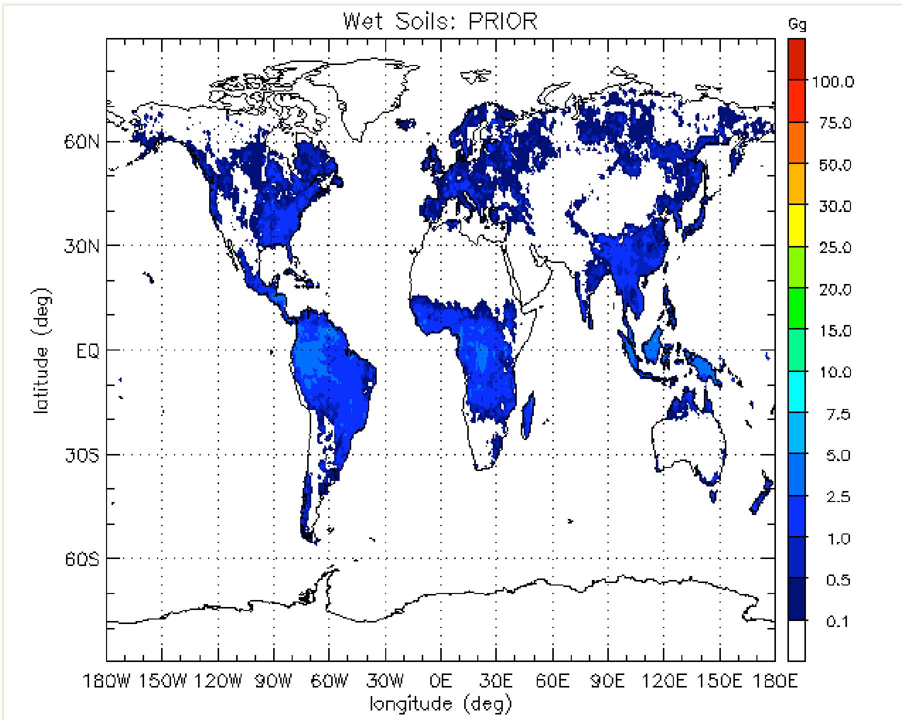


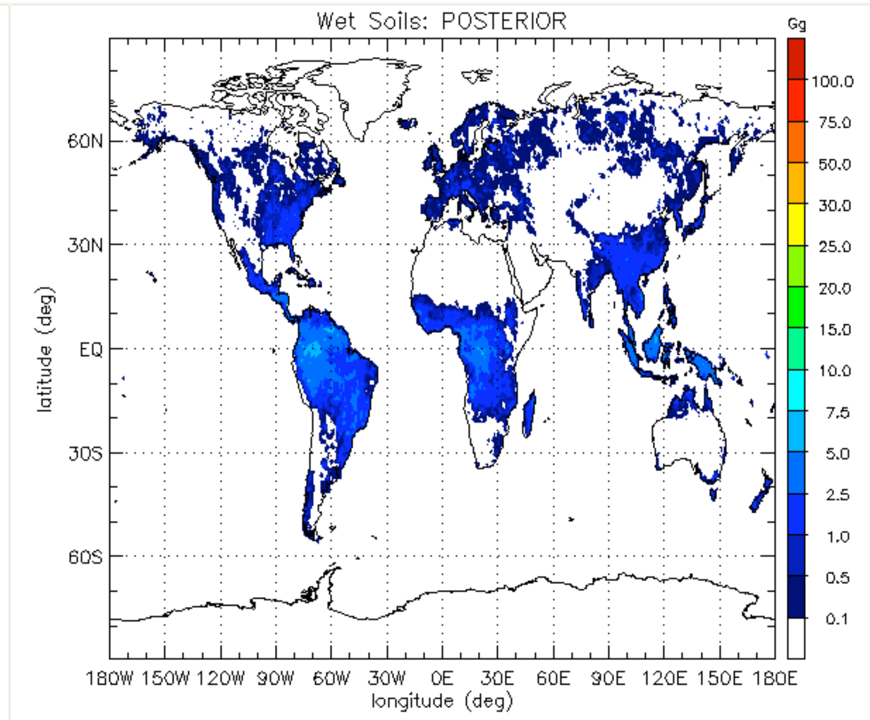
117 Tg / y

135 Tg / y

Tropical Wetlands are increased.

Adjustment of Wetland Components



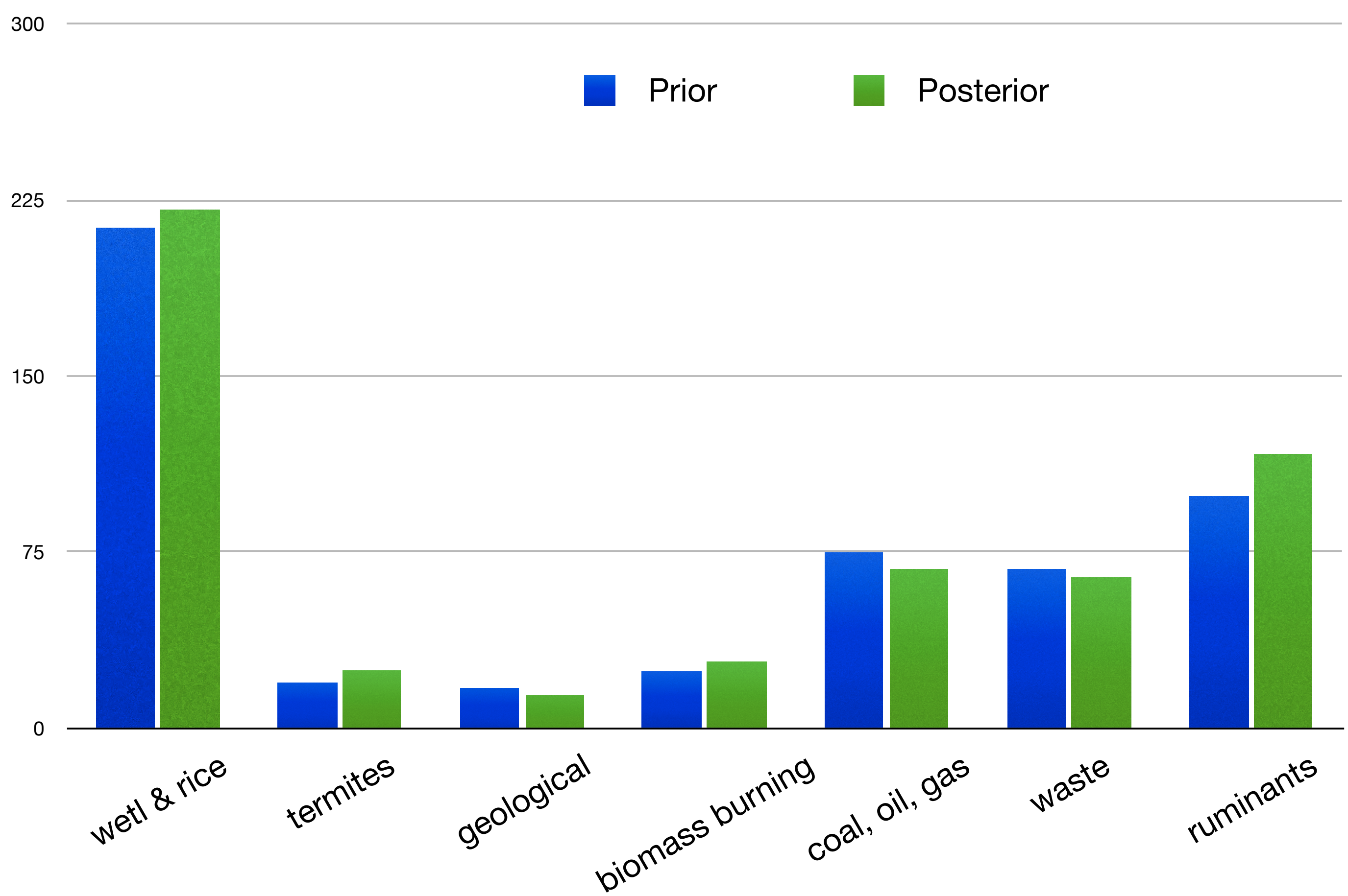


58 Tg / y

60 Tg / y

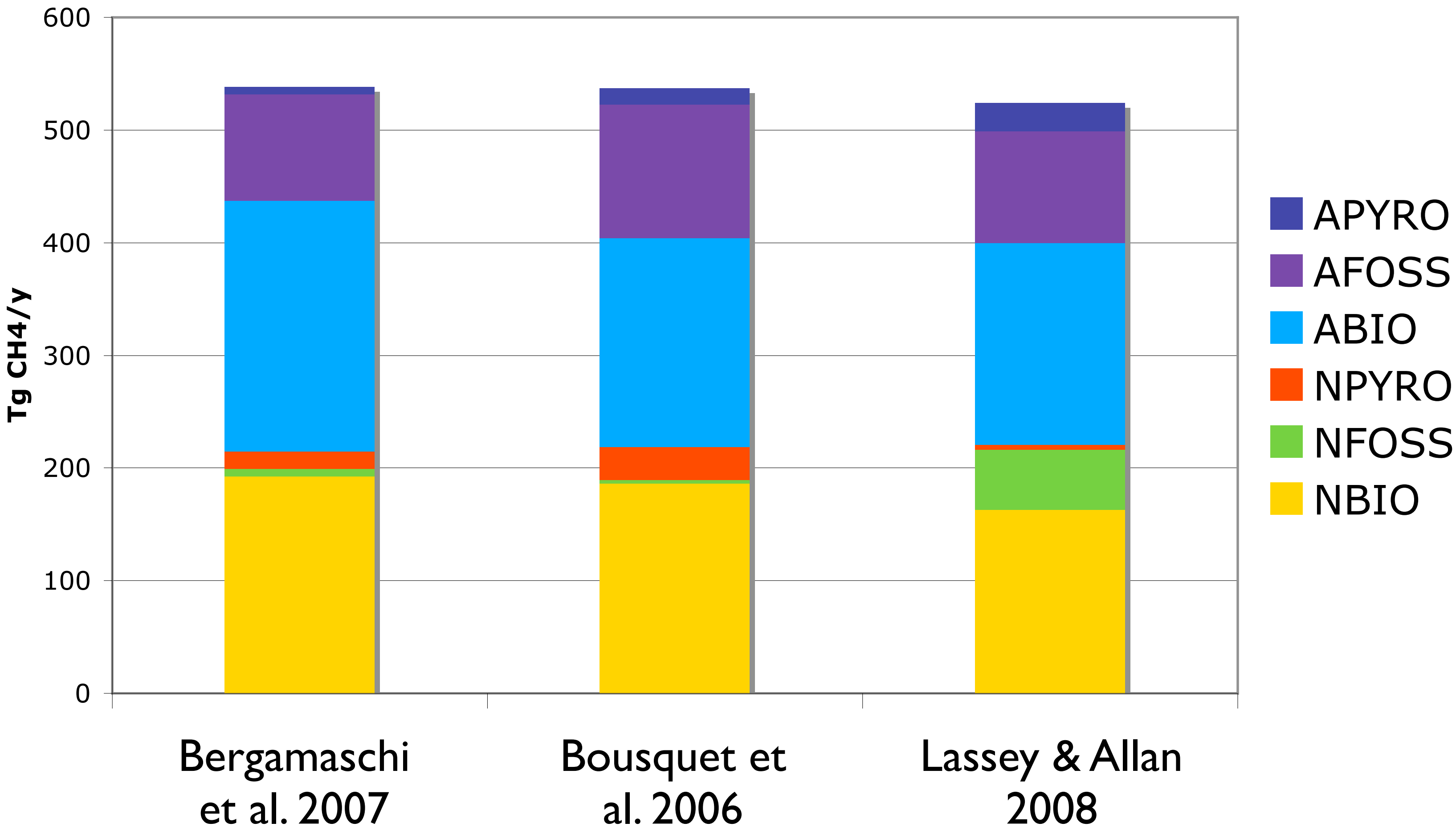
Wet soil emissions hardly change.

A Sample Inversion



We've constrained the spatial structure of emissions, but how robust are our source category estimates?

Compare 3 Emission Scenarios Taken from the Literature

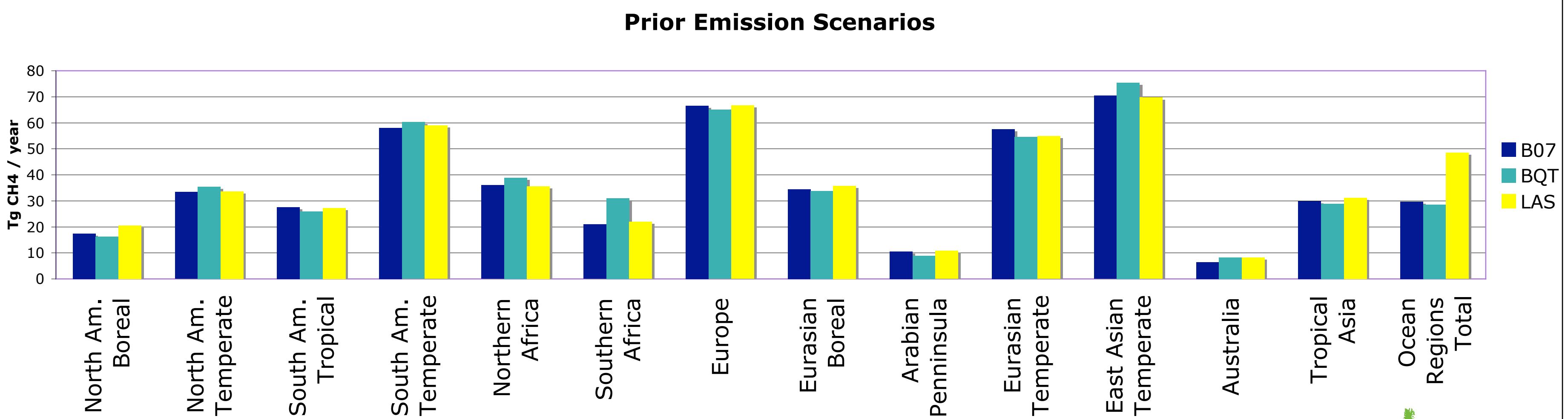


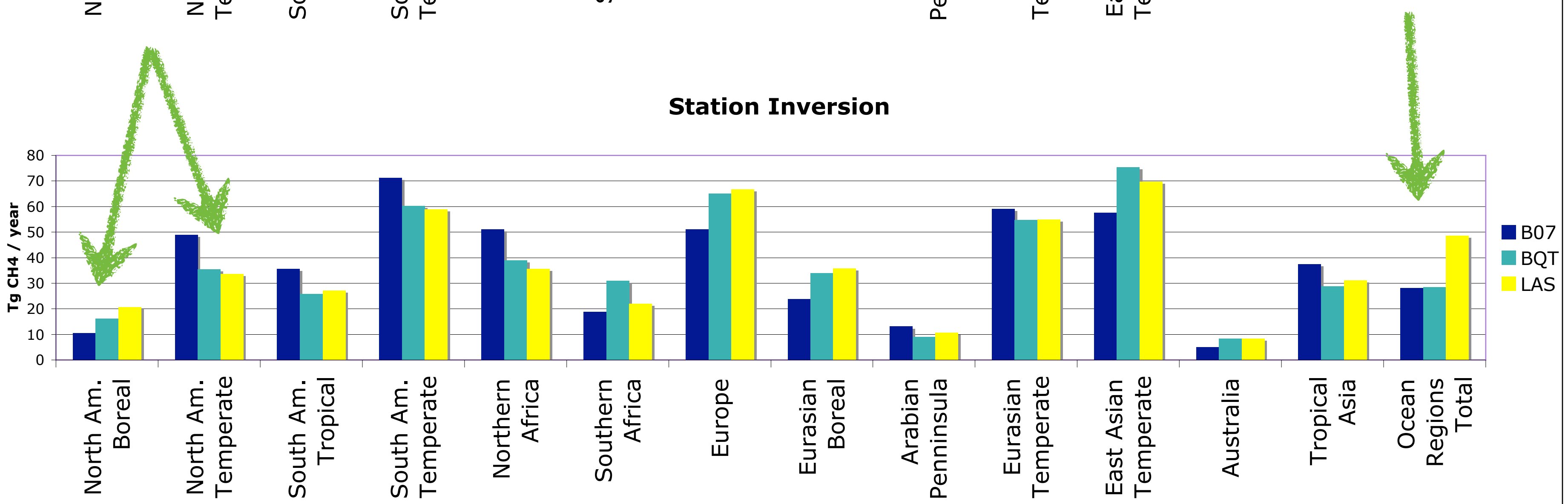
strongly biogenic

strong fire source

strong geological source

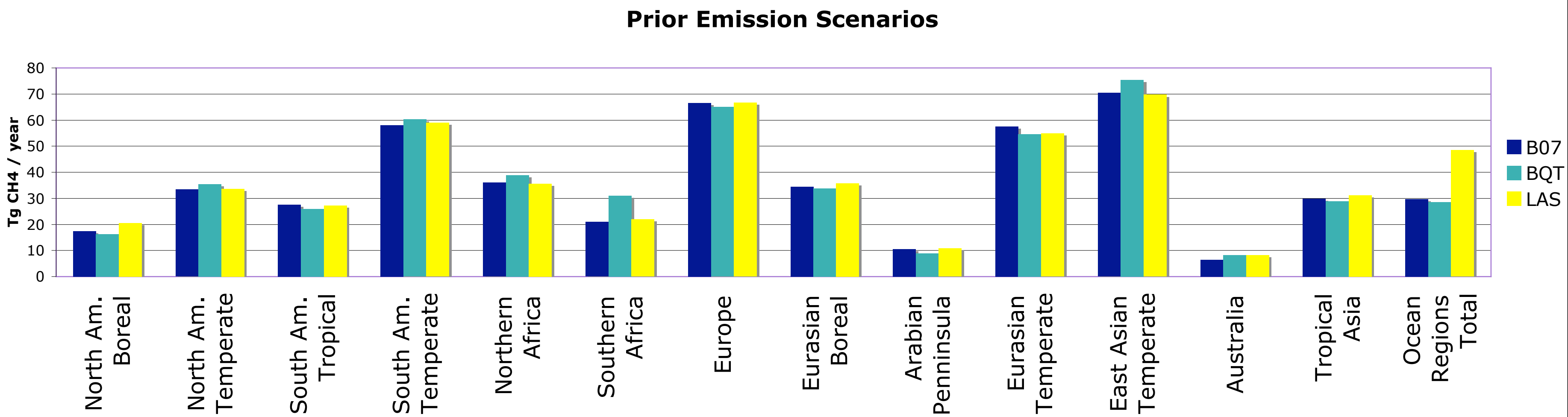
Spatial Inversion: Where are the Fluxes?

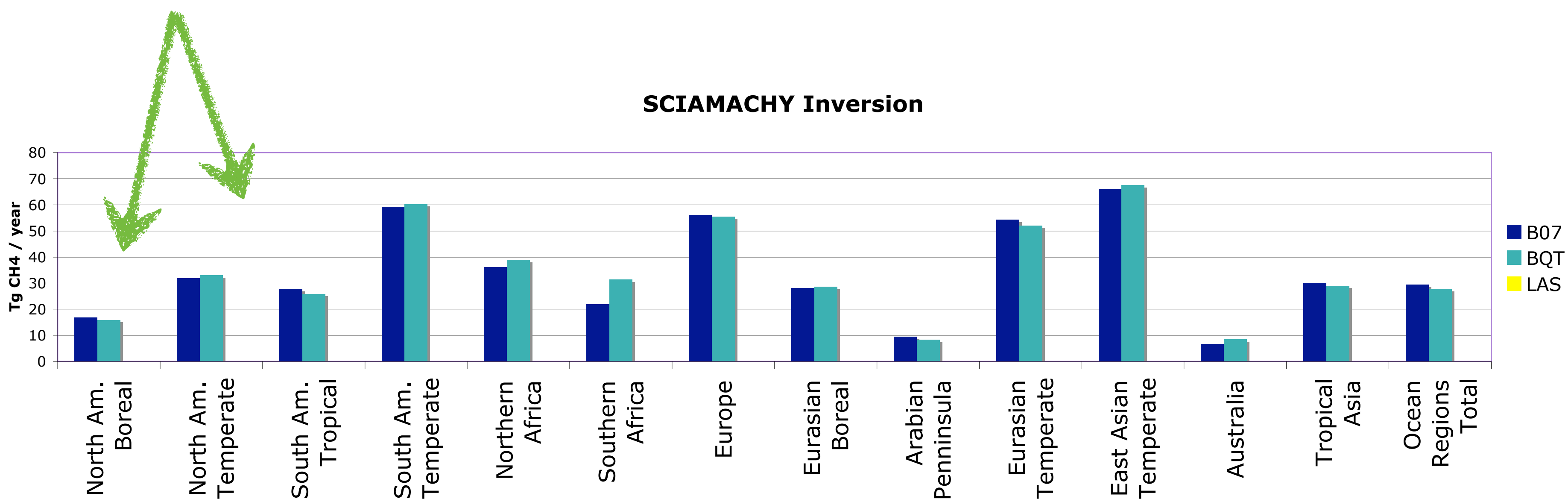




Different spatial emission distributions fit the station obs.

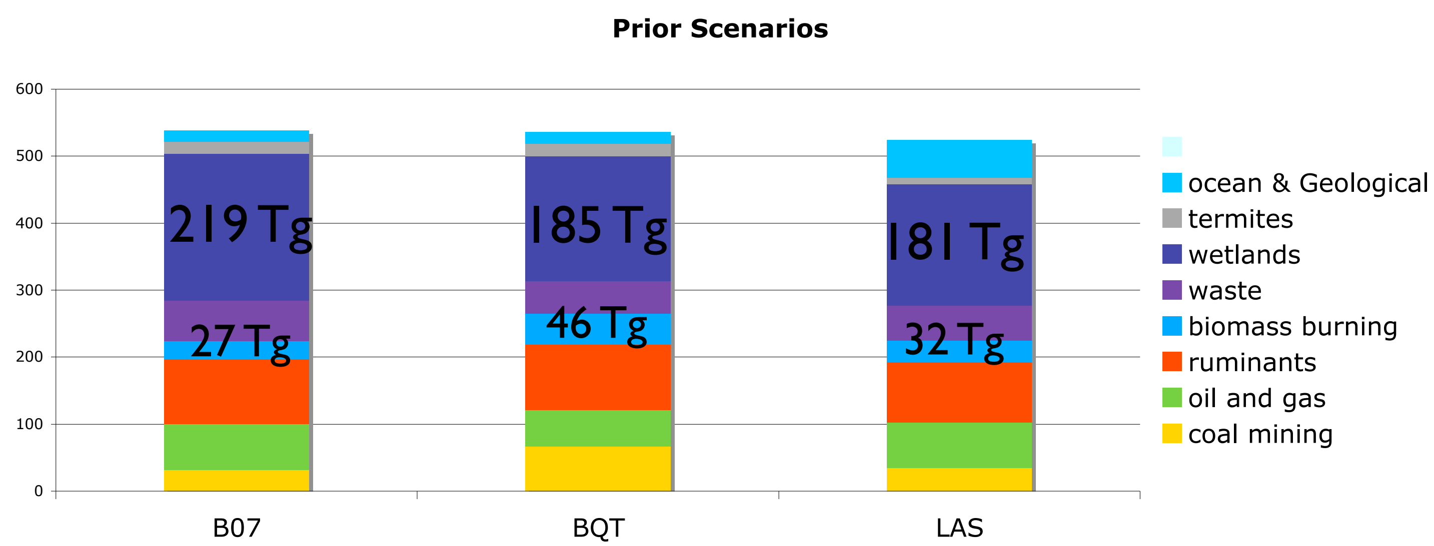
Spatial Inversion: Where are the Fluxes?

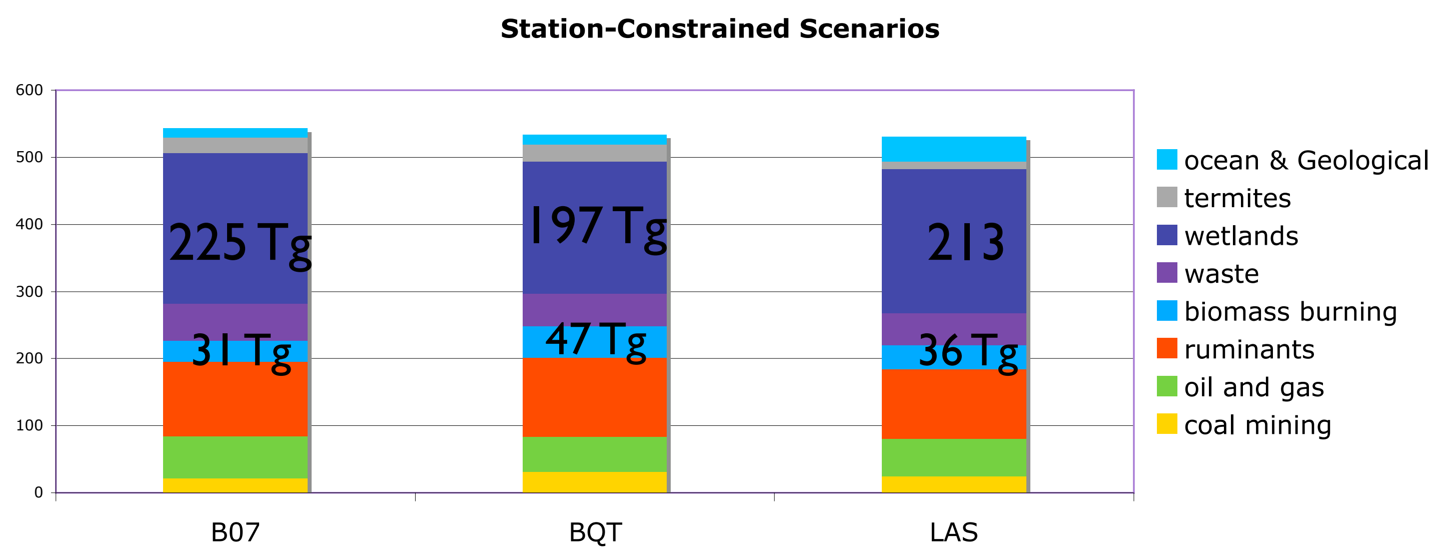




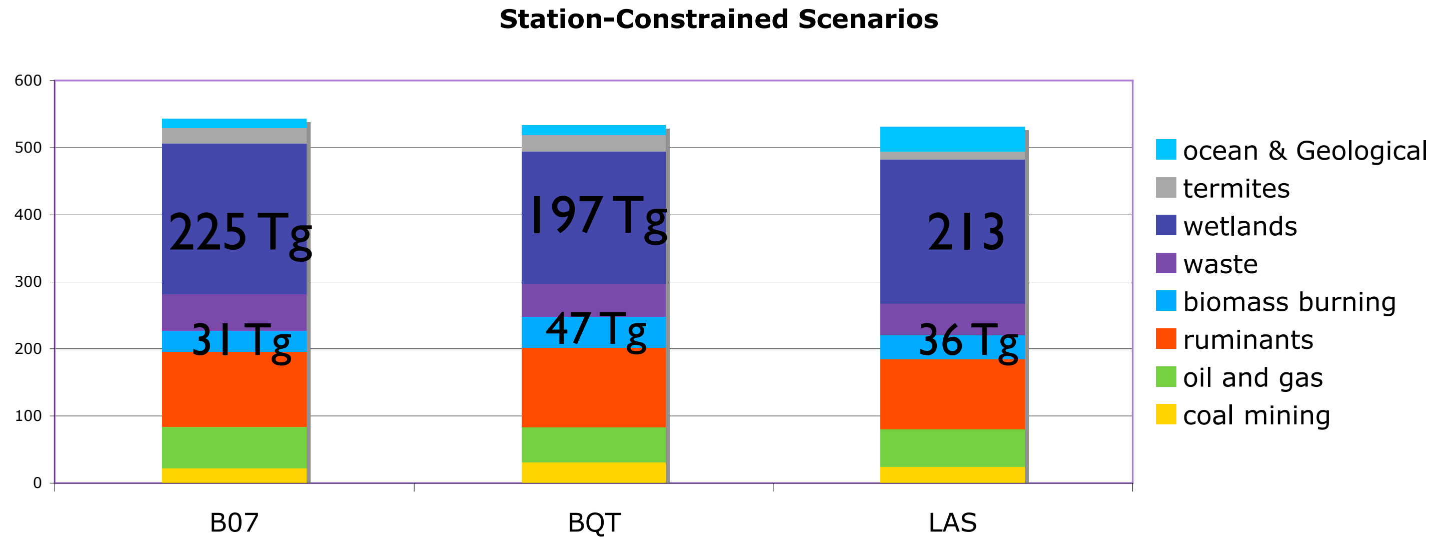
Adding satellite obs, the posterior scenarios agree more

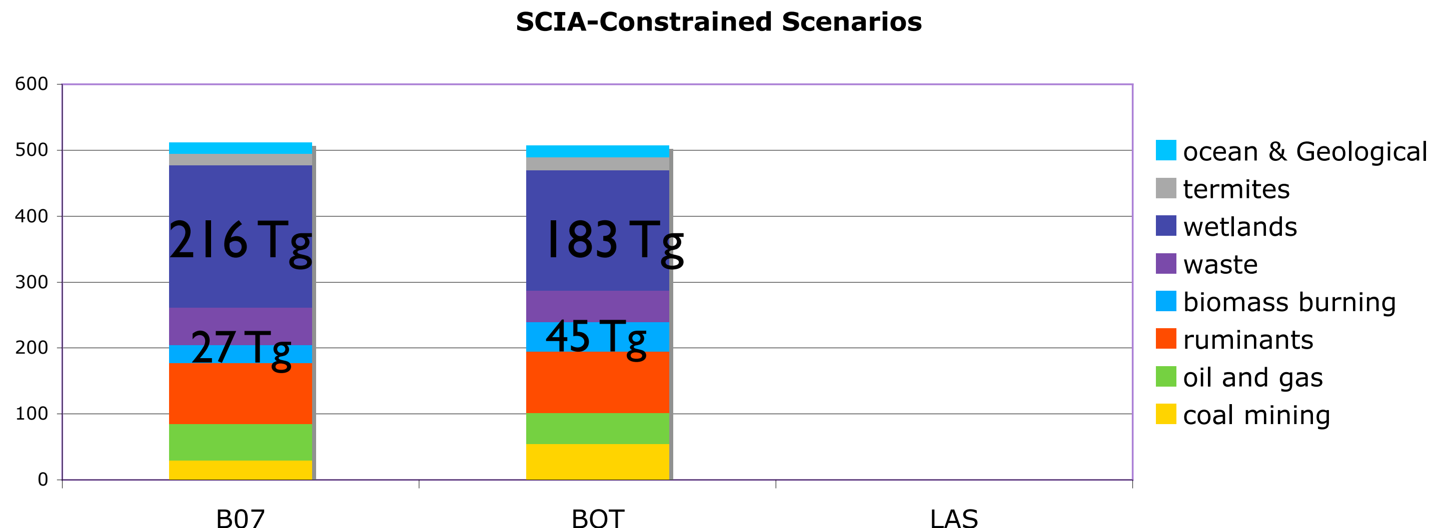
Spatial Inversion: Which Source Types?





Spatial Inversion: Which Source Types?





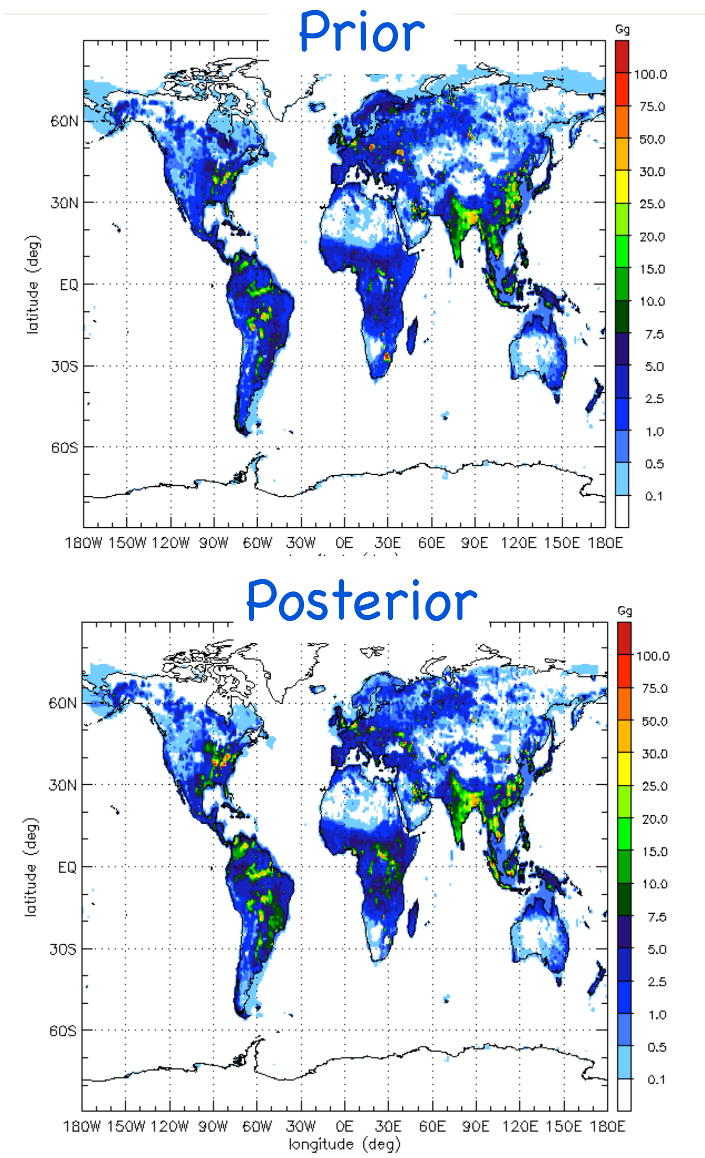
Despite spatial similarity, scenarios remain distinct

Summary

What We Have Found:

+ Adjustment of wetland emission regions: less in the NH, more in the tropics

+ Different scenarios fit the (2004) spatial / temporal emission field implied by obs.



so many outstanding issues...

- Statistical significance of the differences between scenarios
- Statistical independence of source types (e.g. wetlands vs. burning)
- Model error!!
- Interannual variability and trends

Where to Go Next?

+ improving prior estimates (especially wetlands, rice, geological, biomass burning)

+ more analysis: just plain looking at the results more closely (e.g. fit to unassimilated observations, "look out the window")

+ more analysis: looking at statistics and sensitivities

+ more sophisticated statistics: are we making the right statistical assumptions? (e.g. Gaussianity - P. Kasibhatla & others)

+ how closely are these results tied to our model? -- Comparing results to others (P. Bousquet, LSCE)

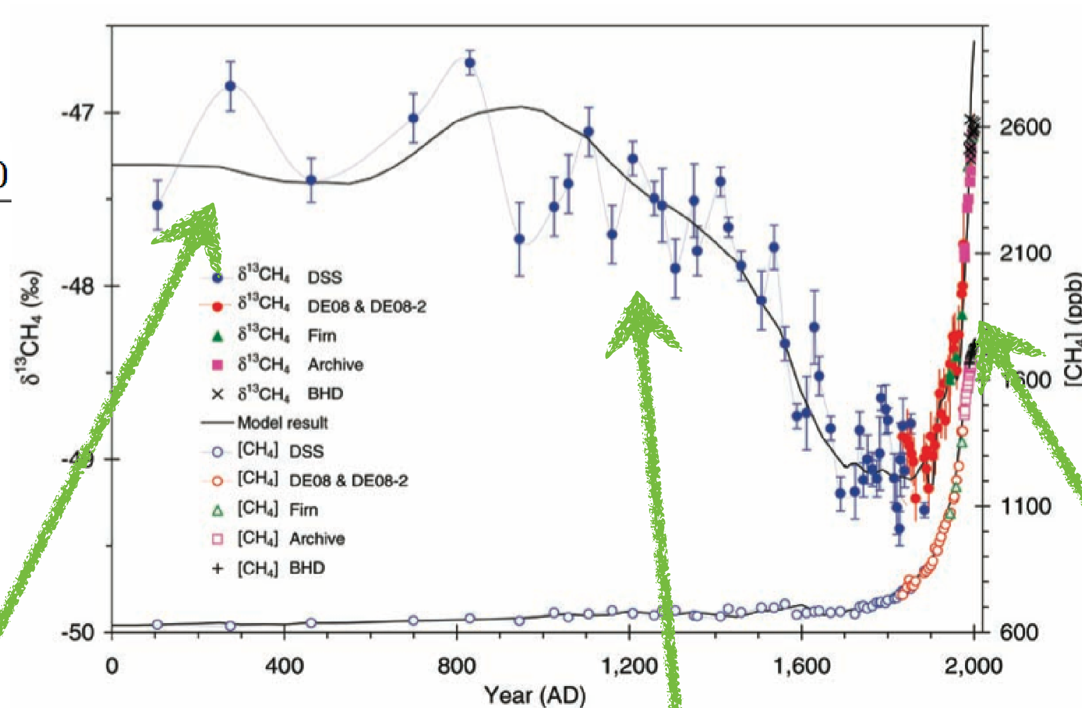
Overall we need better quantification of what we can / can't be confident of.

Extra Stuff

What can the Isotopic Record Tell Us?

$$\delta^{13}C = \frac{R - R_0}{R_0}$$

$$R = \frac{^{13}CH_4}{^{12}CH_4}$$



"Pre-agricultural" budget is a mix of the signatures of natural sources

Biogenic sources (agricultural) are strongly depleted in 13C

Fossil & thermogenic sources are enriched in 13C

Optimal Estimation of Global Source Strengths Using Isotopic Measurements

$$\mathbf{x}^a = \mathbf{x}^b + \mathbf{K}\left[\mathbf{y} - H\left(\mathbf{x}^b\right)\right]$$

Fluxes per Source

Observed global-average atmospheric isotope depletion

Box model (13C in - 13C out)