# The potential for $^{14}CO_2$ measurements to estimate North American fossil fuel $CO_2$ emissions

Sourish Basu, John Miller, Scott Lehman




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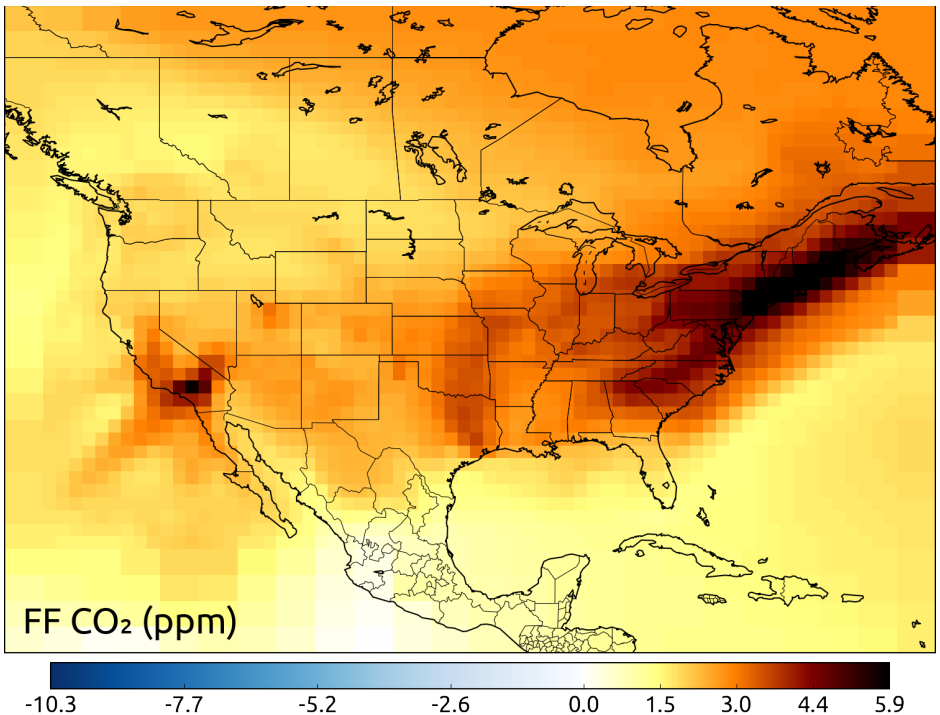
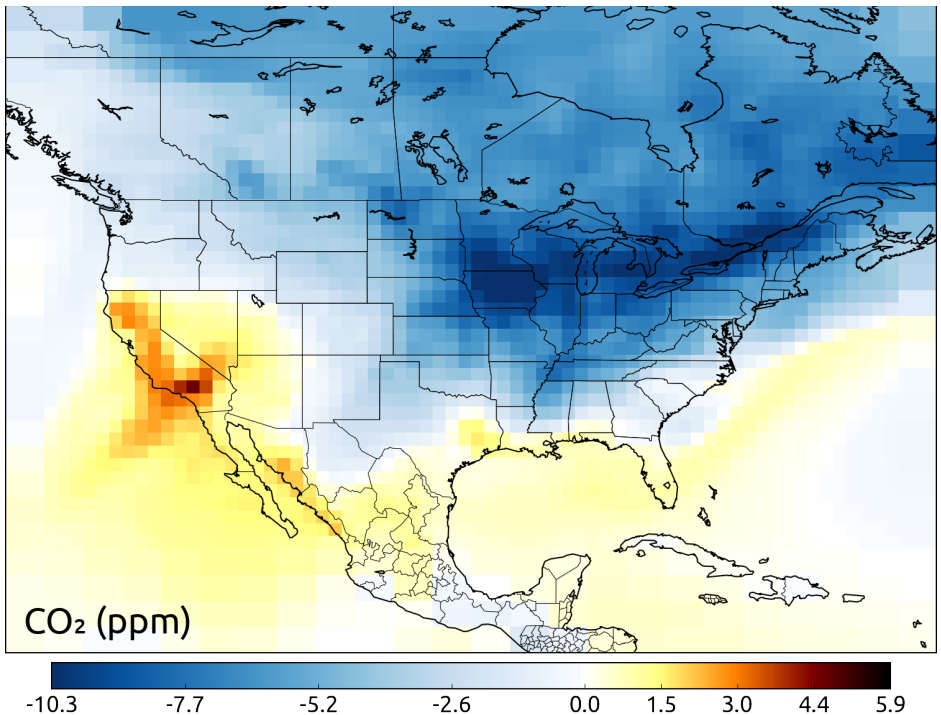
Boulder, 19 May 2015

Measurements of total $CO_2$ are generally ineffective at estimating fossil fuel $CO_2$ emissions

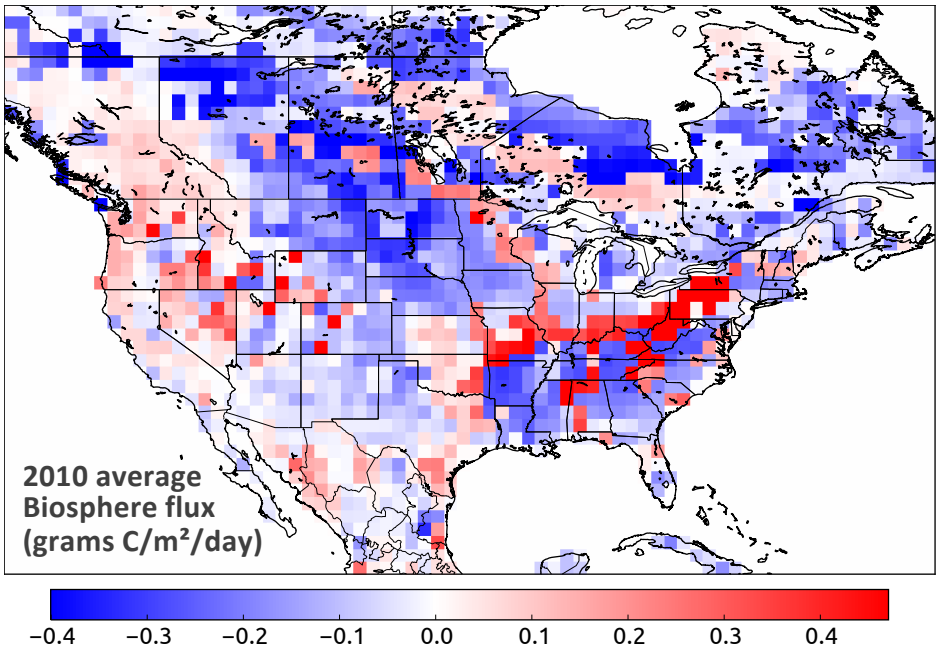


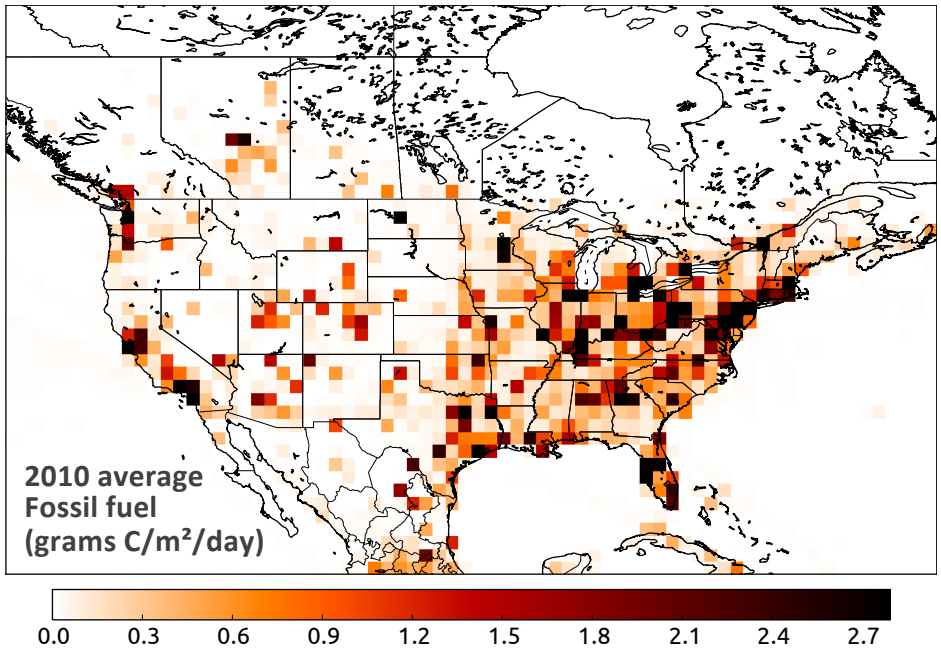

Fossil fuel $CO_2$




Total $CO_2$

$$\frac{dC}{dt} = F_{oce} + F_{bio} + F_{fos}$$




- Almost all atmospheric $CO_2$ inversions assume $CO_2$(ff) "perfectly" known, solve for natural fluxes
- Global annual FF known to within 10%, not true at small scales
- Usually not up to date, EDGAR 6 yr old, Vulcan 14 yr old

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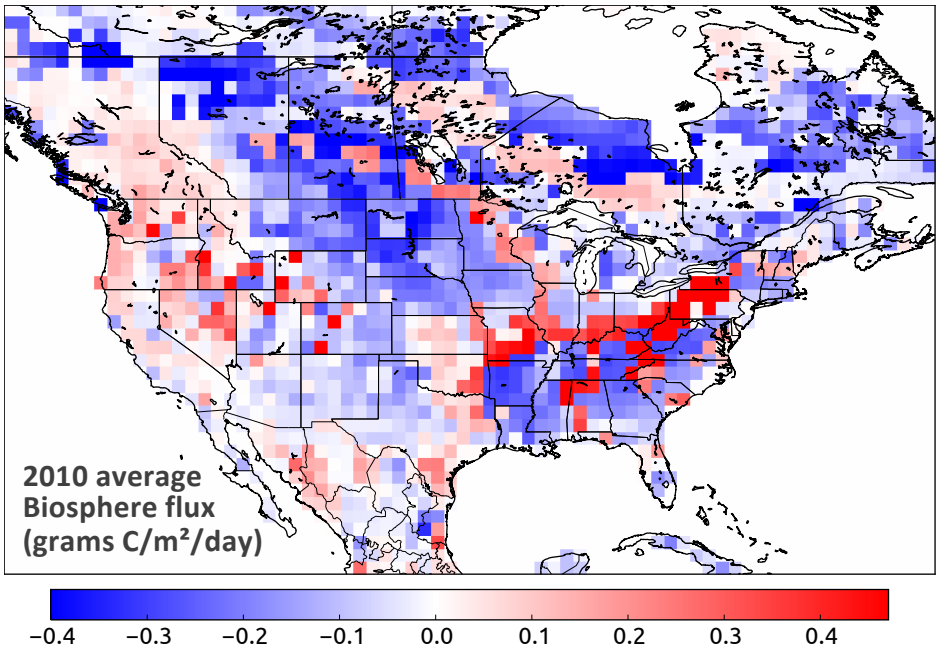


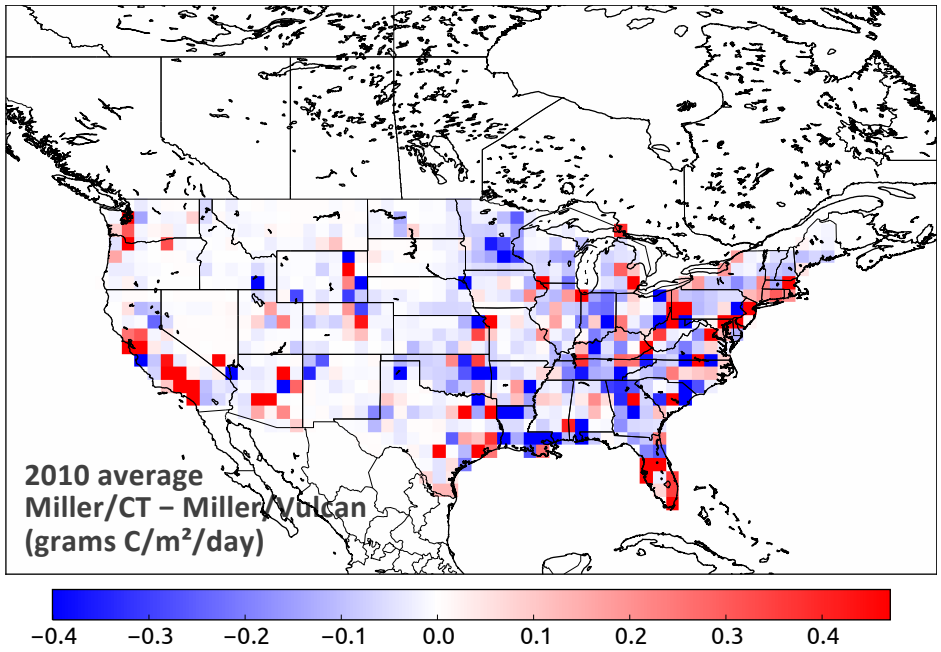


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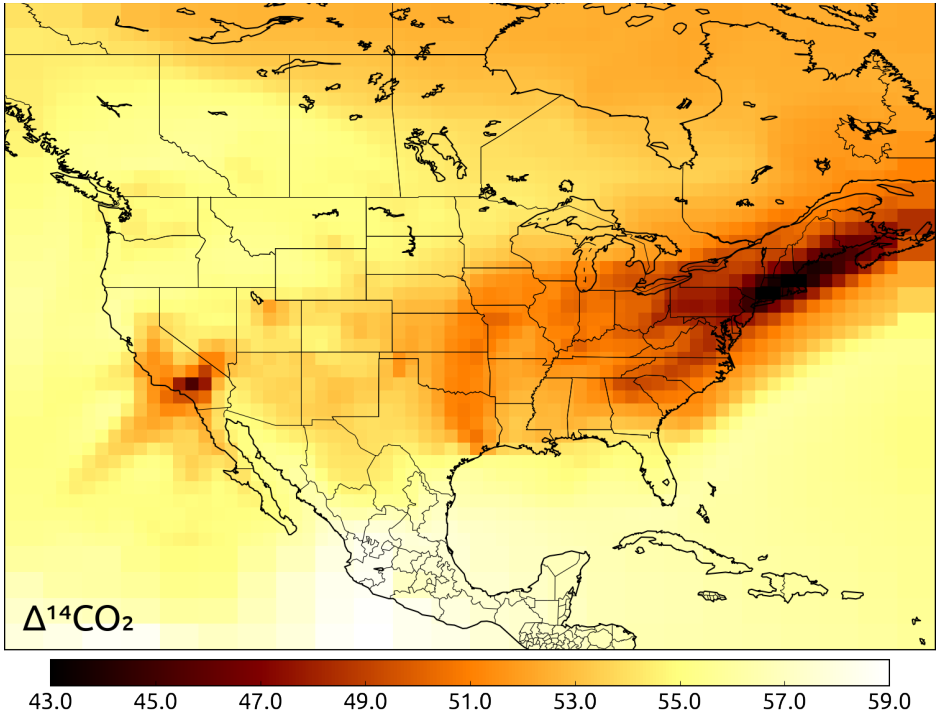
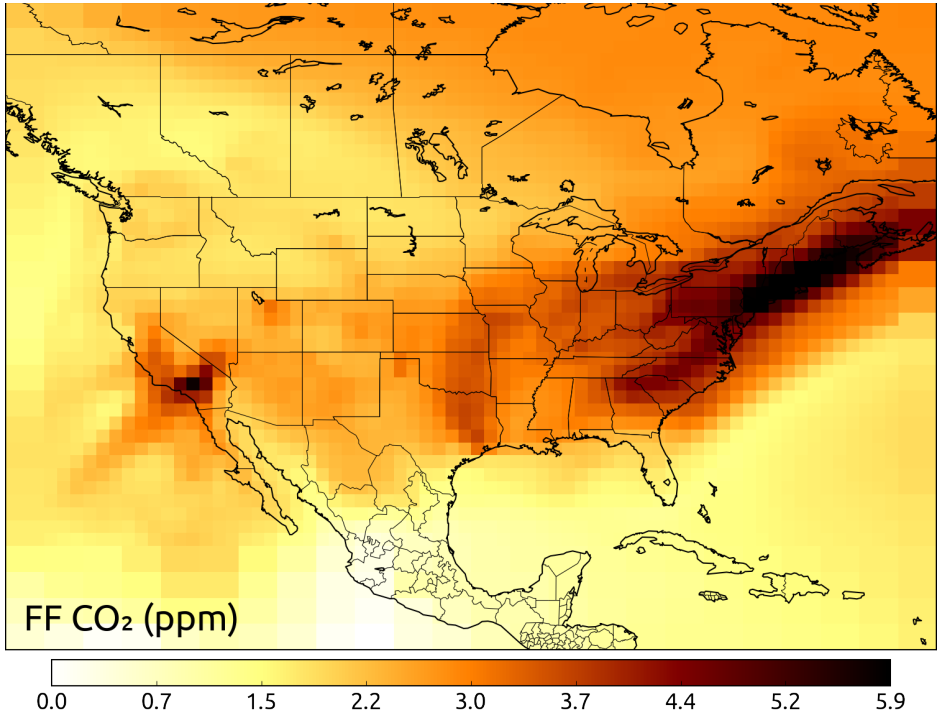
# Over ConUS, $\Delta^{14}CO_2$ signal dominated by fossil fuel

$$\Delta^{14}C_{ff} = -1000\ ‰ \text{ (i.e., zero } {}^{14}CO_2)$$
$$\text{Scaling in 2006} = -2.7\ ‰\ \Delta^{14}C \text{ for 1 ppm } CO_2(ff)$$



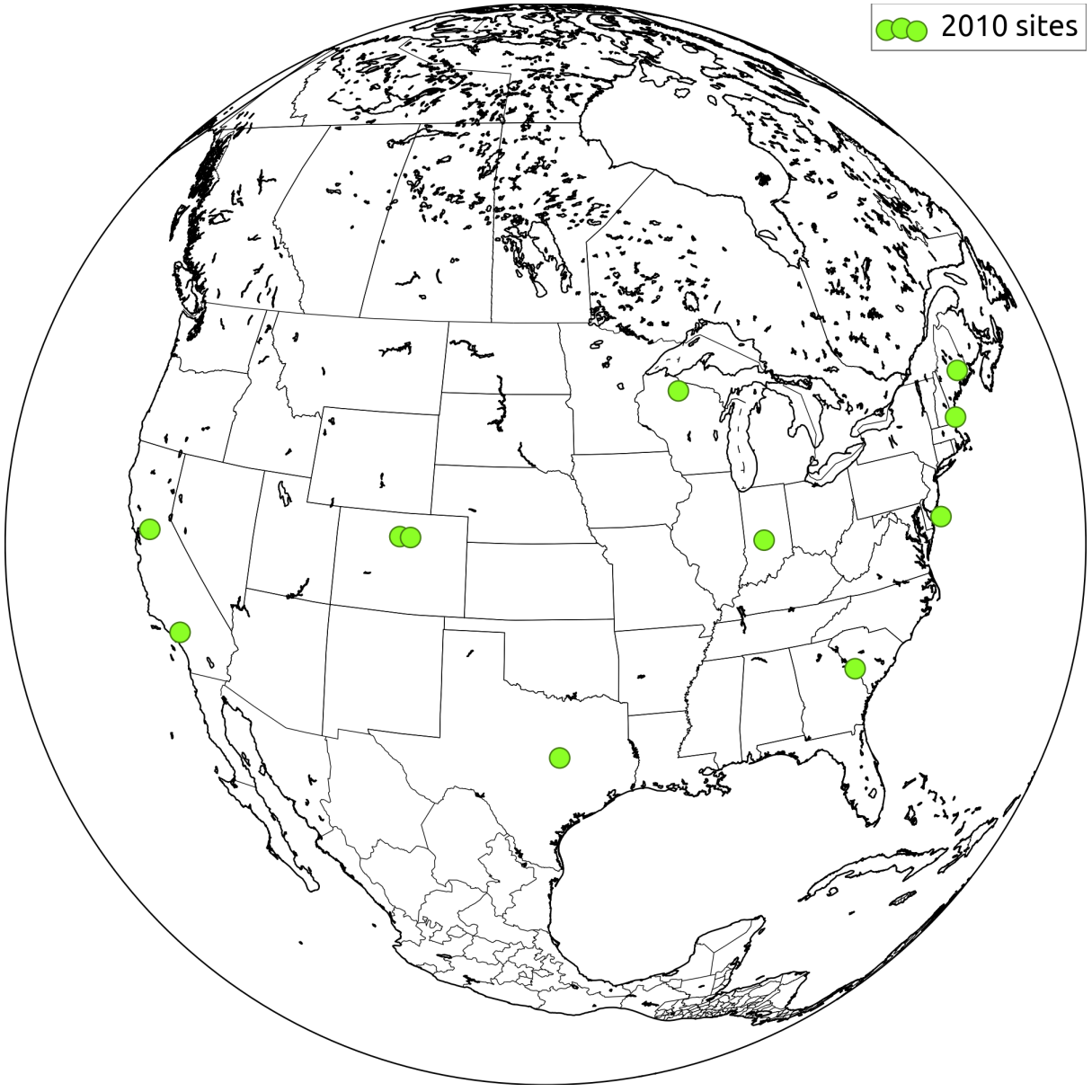

fossil fuel, ocean and land disequilibrium, nuclear and cosmogenic production

fossil fuel only

## OSSE to gauge potential of $^{14}CO_2$ measurements

How accurately can a $CO_2 + {}^{14}CO_2$ inversion estimate fossil fuel fluxes

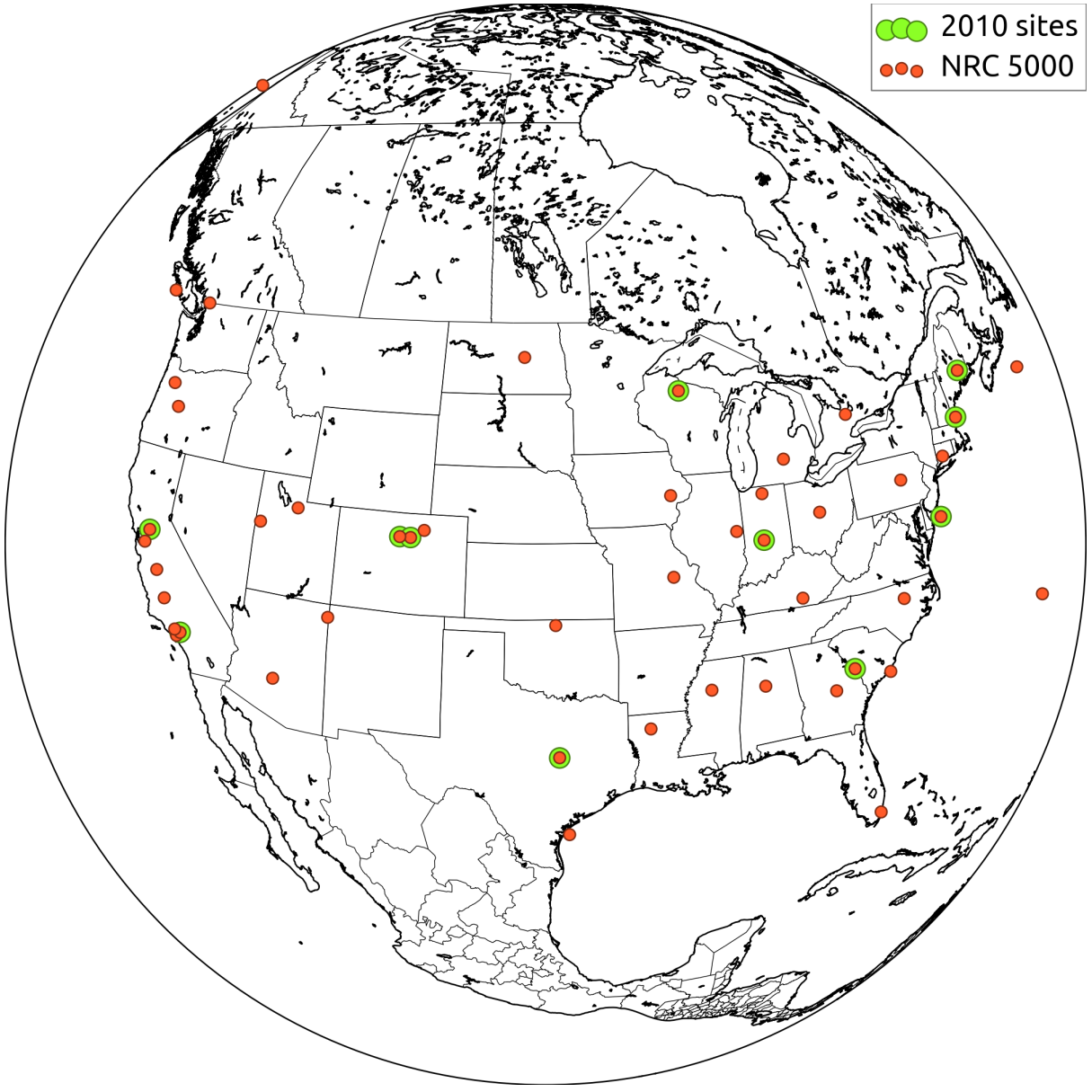
- with $^{14}CO_2$ measurements at the level of 2010 coverage?



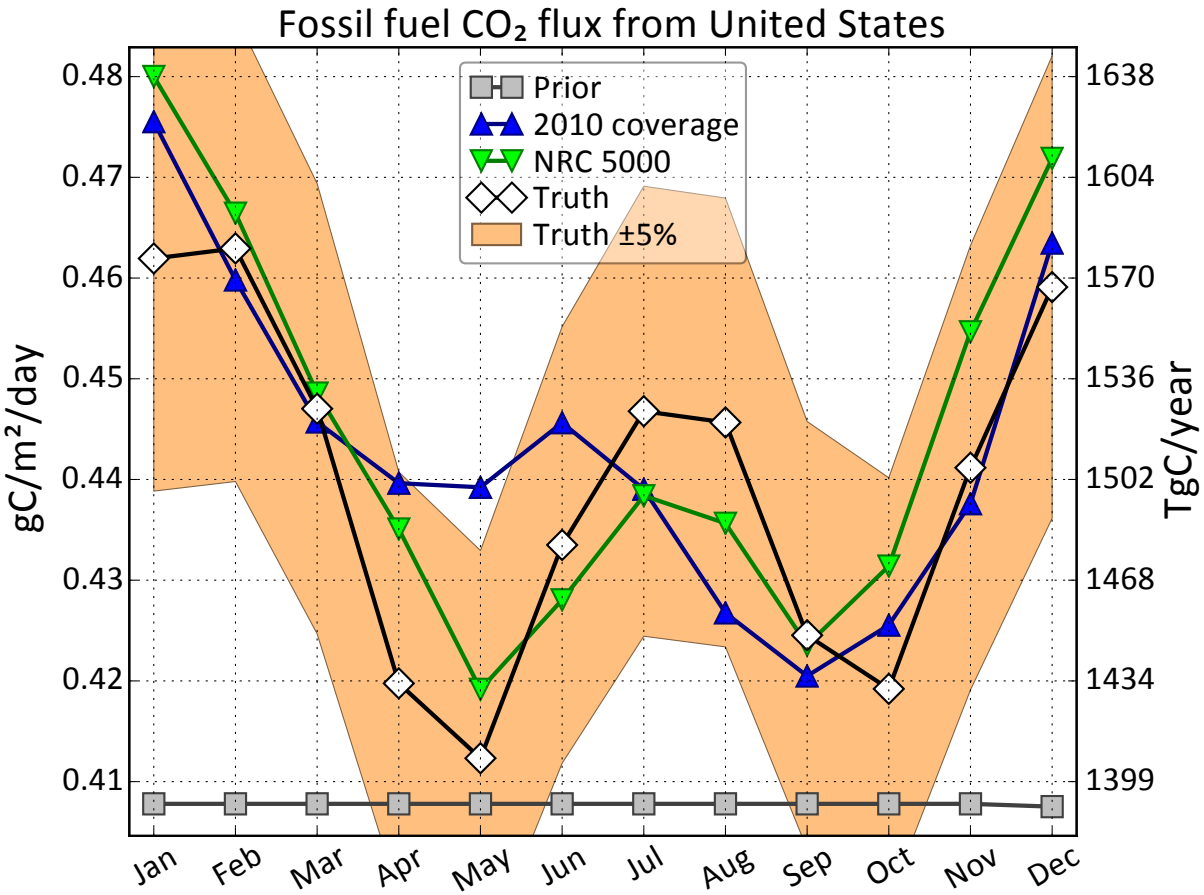
## OSSE to gauge potential of $^{14}CO_2$ measurements

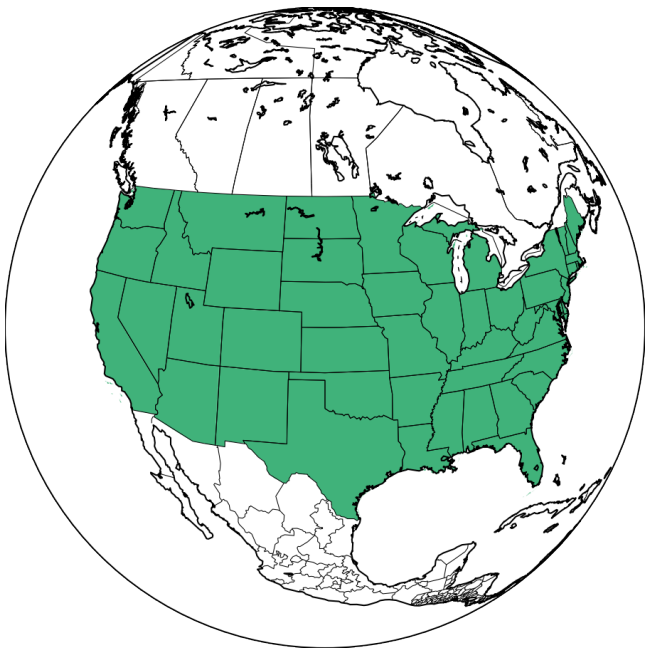
How accurately can a $CO_2 + {}^{14}CO_2$ inversion estimate fossil fuel fluxes

- with $^{14}CO_2$ measurements at the level of 2010 coverage?
- with $\sim$ 5000 $^{14}CO_2$ measurements/year?



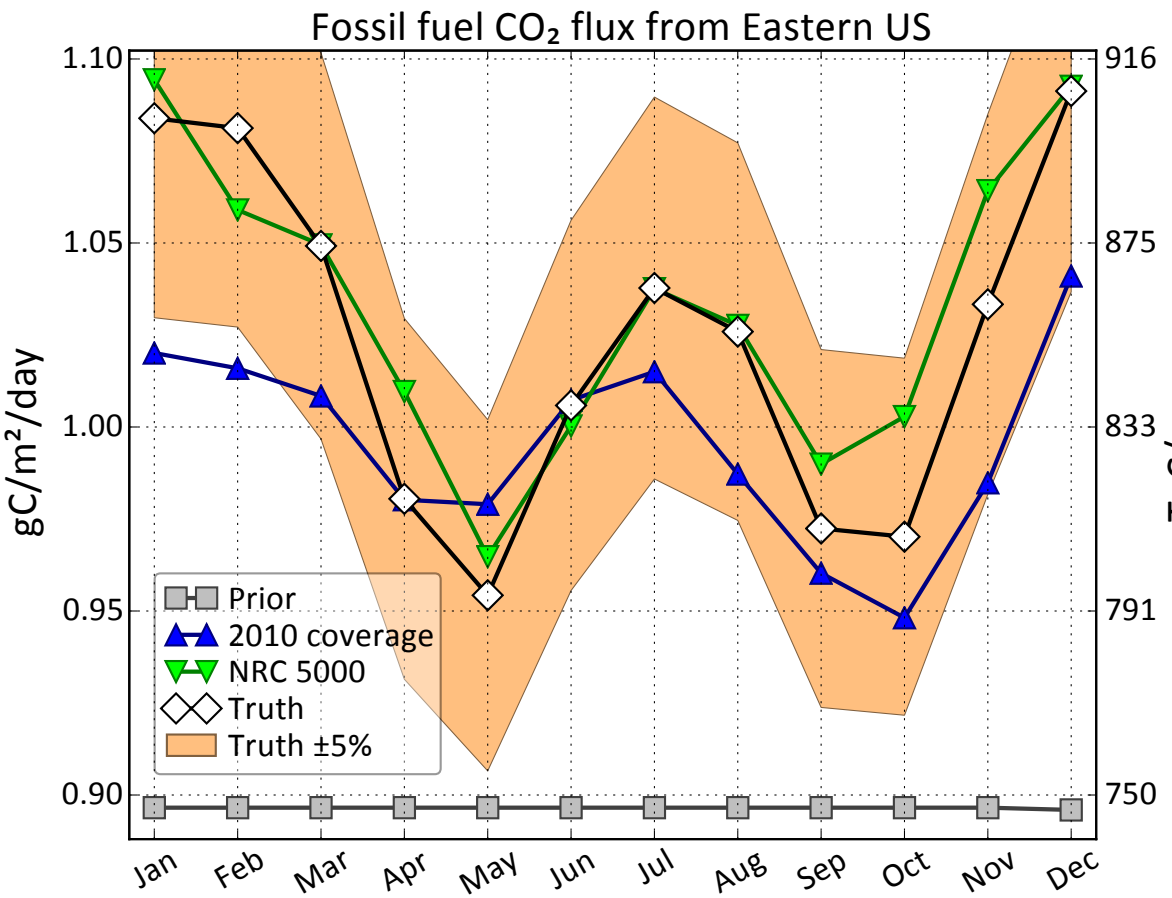
# OSSE results 1: fluxes



Monthly fluxes ± 5% recovered for the continental US ...

# OSSE results 1: fluxes




... for large subregions ...

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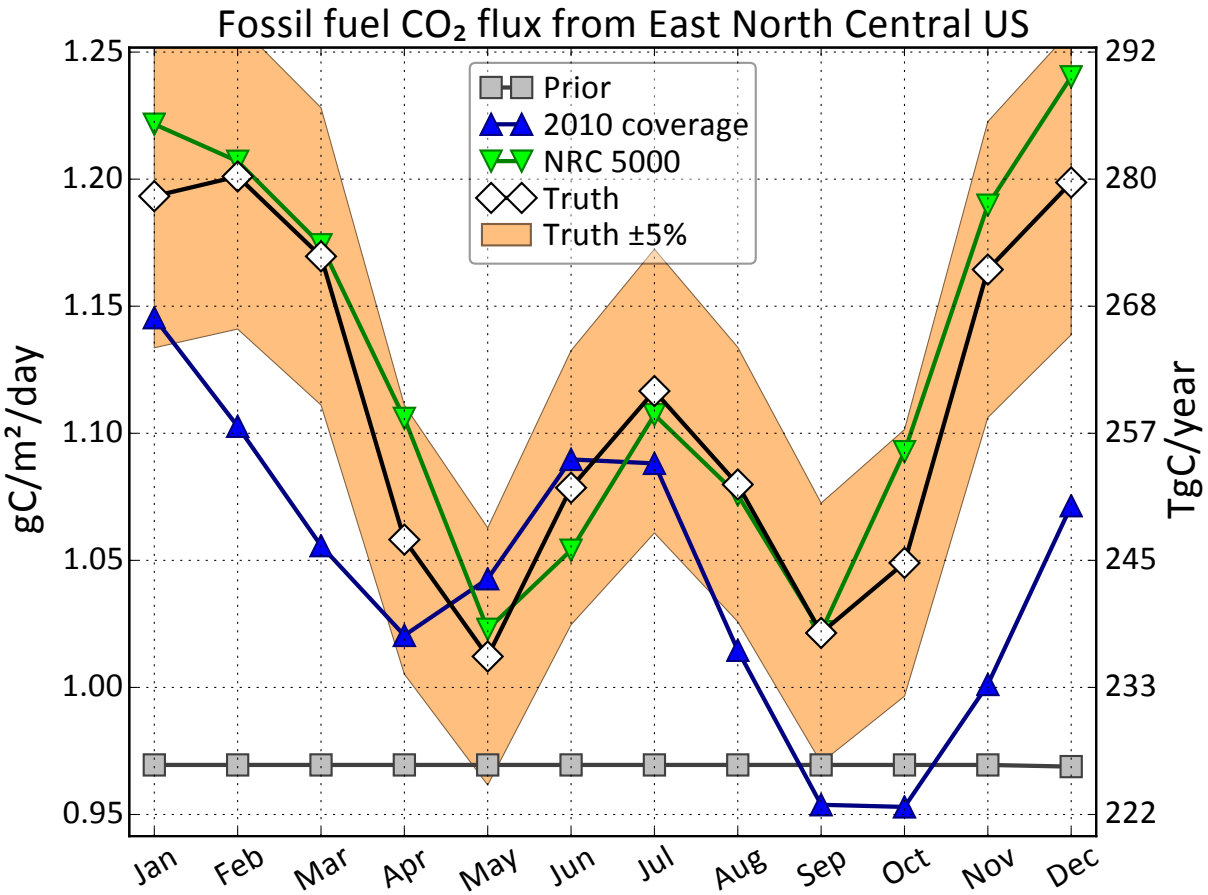


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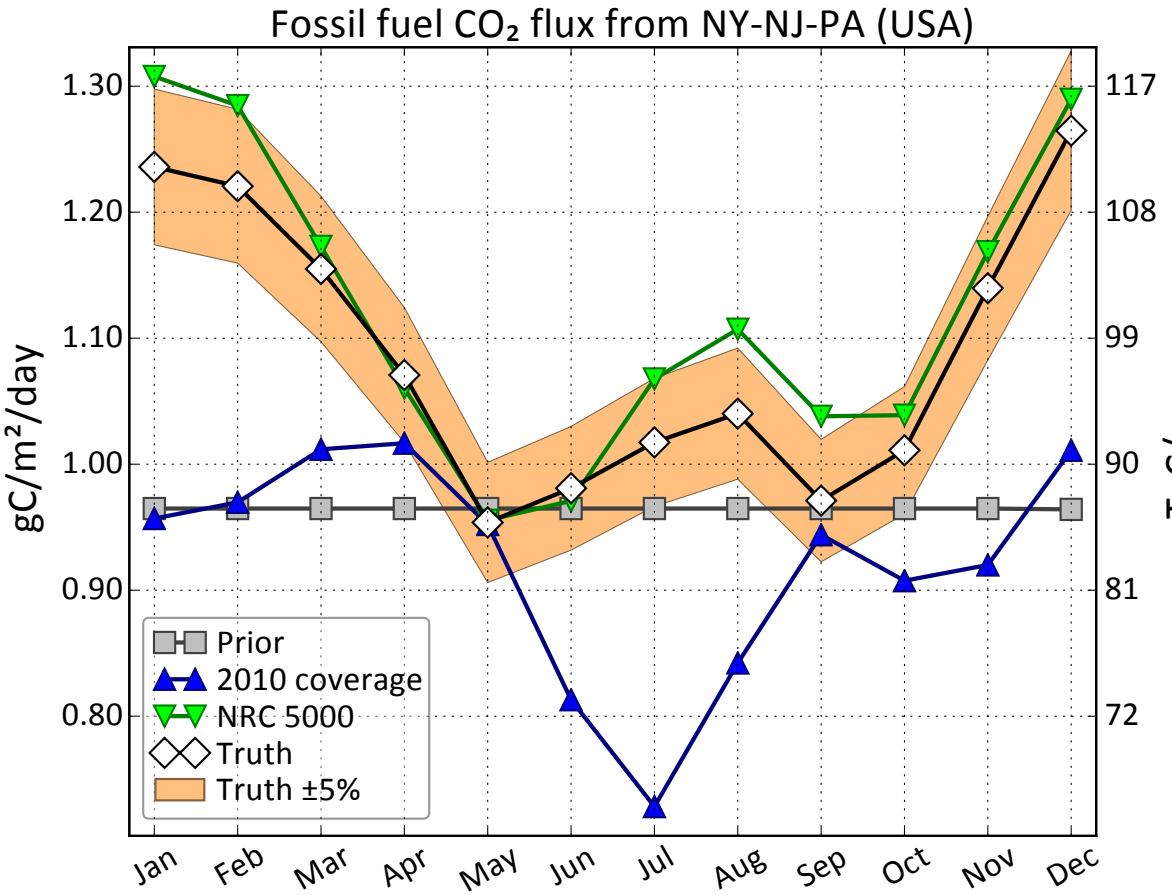


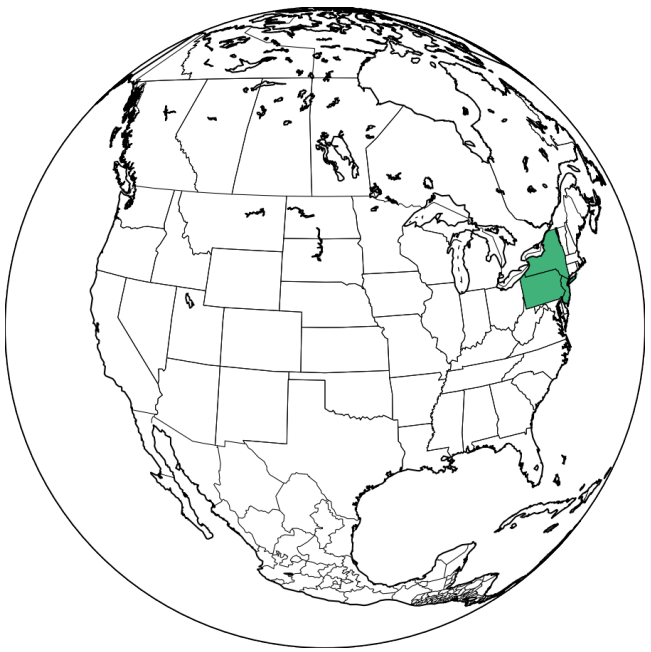

... and even for fairly small regions.

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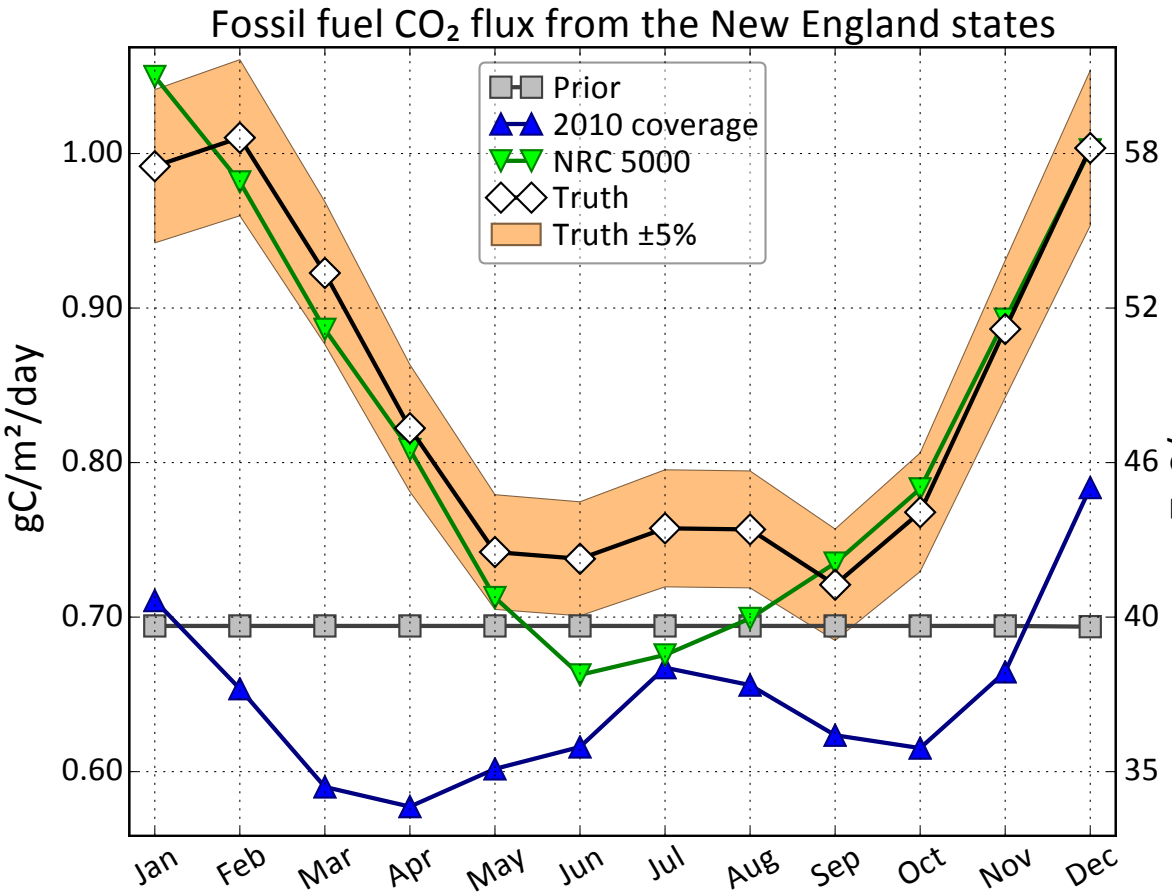


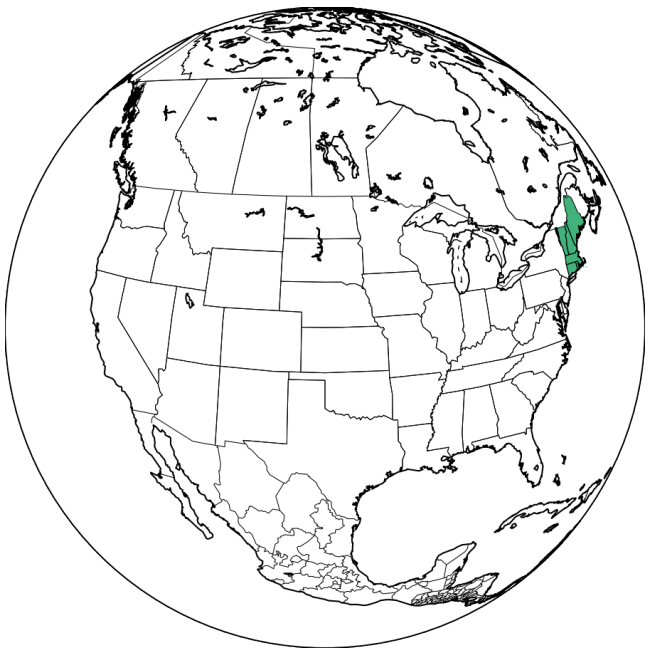

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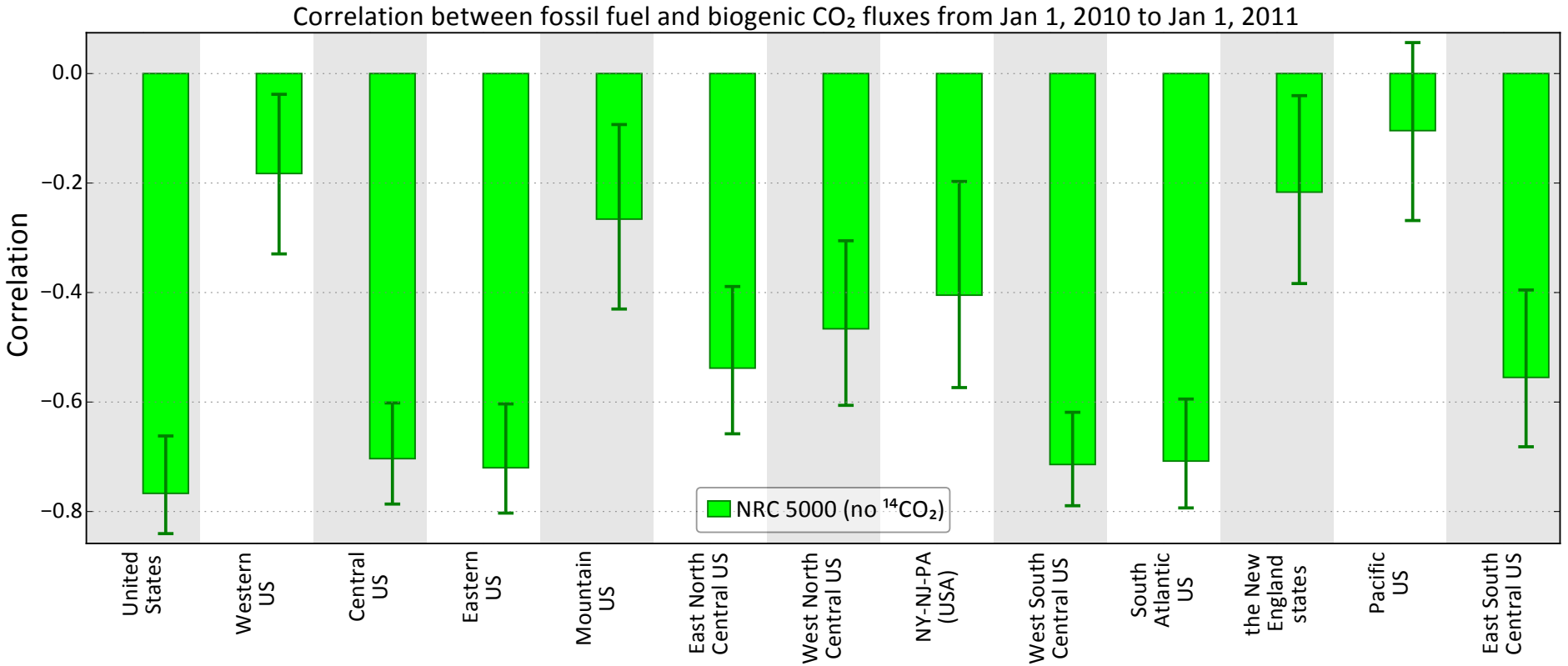
# OSSE results 2: correlations




$$\frac{dC}{dt} = F_{\text{natural}} + F_{\text{fos}}$$

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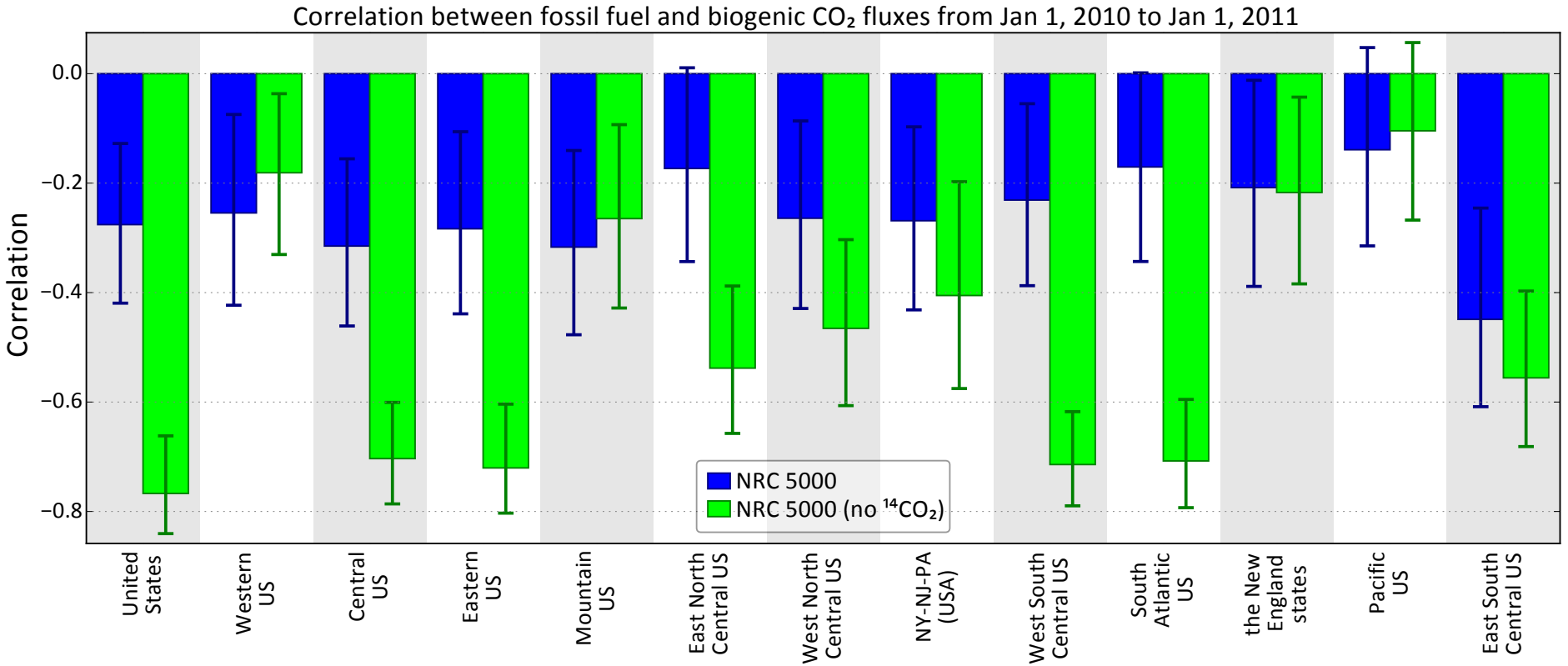


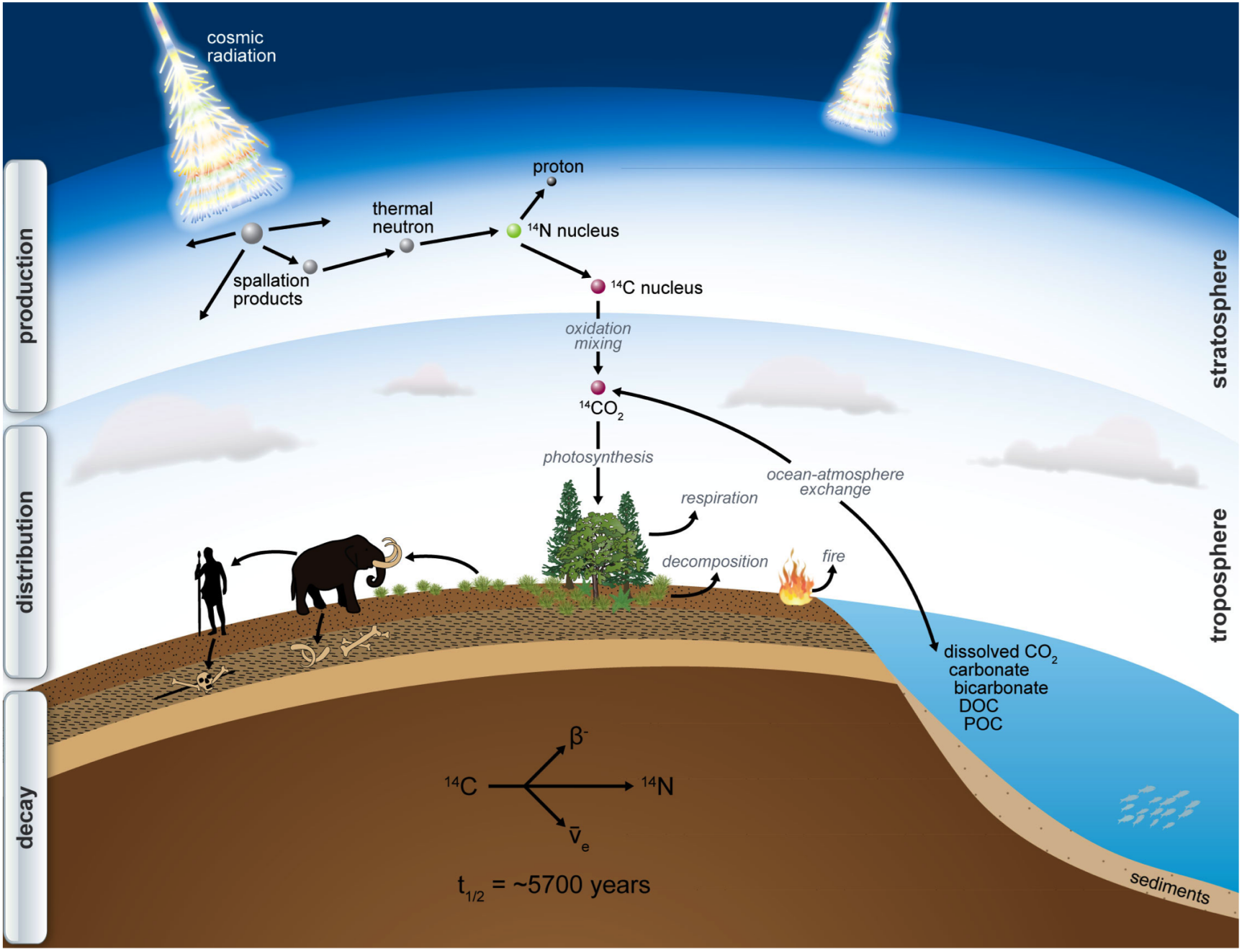

$$\frac{dC}{dt} = F_{\text{natural}} + F_{\text{fos}}$$

$$C\frac{d}{dt}\Delta_{\text{atm}} = (\Delta_{\text{fos}} - \Delta_{\text{atm}})F_{\text{fos}} + \cdots$$

# Take home messages

- $^{14}CO_2$ measurements provide a top-down constraint on fossil fuel $CO_2$ emission estimates
- All $CO_2$ inversions assume a "known" fossil fuel flux, which can be relaxed using measurements of $^{14}CO_2$
- With 5000 $^{14}CO_2$ obs/year, we could recover the monthly national total FF $CO_2$ to 5%, and also monthly regional FF $CO_2$ from high-emitting regions
- Even with 2010 coverage, we could recover the monthly national total FF $CO_2$ to 5% for most months

# Isotope geochemistry of $^{14}CO_2$



# Isotope geochemistry of $^{14}CO_2$

$$\delta^{14}CO_2 = \left[\frac{(^{14}CO_2/CO_2)_{\text{sample}}}{(^{14}CO_2/CO_2)_{\text{reference}}} - 1\right] \times 1000‰$$
$$= \left[\frac{\text{relative abundance in sample}}{\text{“typical” relative abundance}} - 1\right] \times 1000‰$$

- $(^{14}CO_2/CO_2)_{\text{reference}} = 1.176 \times 10^{-12}$
- Basis for radiocarbon dating; older the sample, lower the $\delta^{14}C$
- Emitting fossil fuel $CO_2$ “ages” the atmosphere

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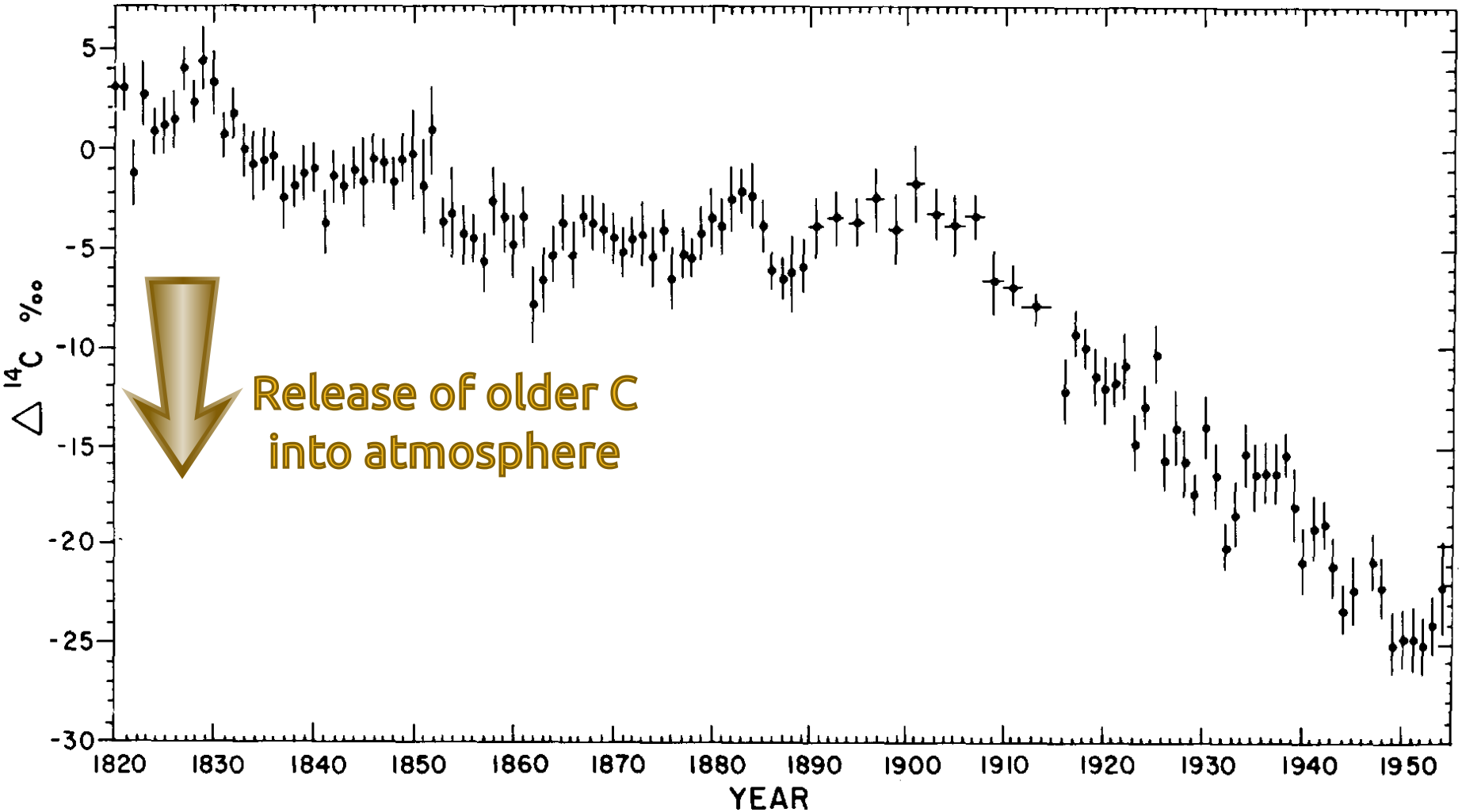
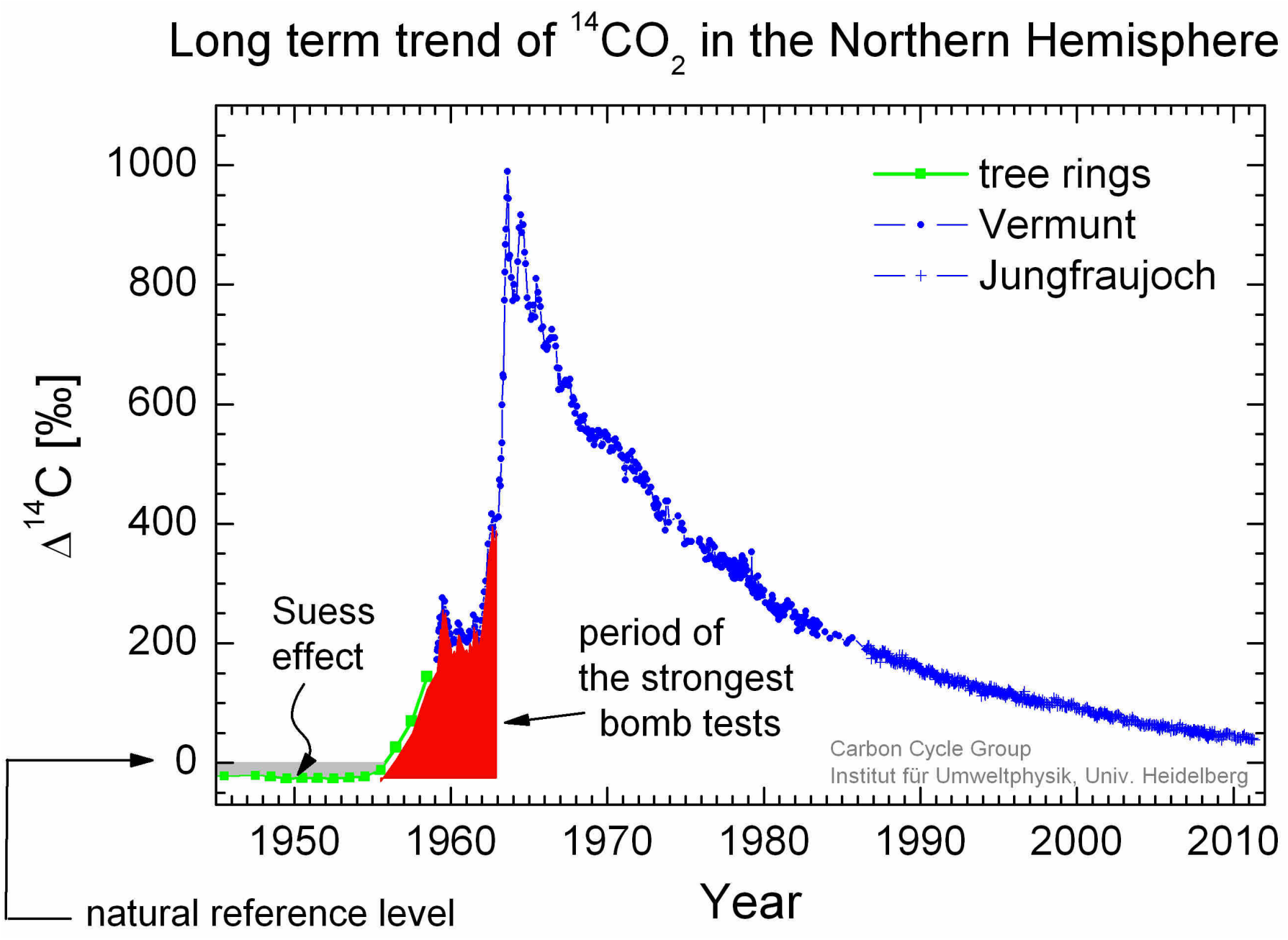



Tree ring $\Delta^{14}C$ by Stuiver & Quay, 1981


Long term trend of $^{14}CO_2$ in the Northern Hemisphere
tree rings
Vermunt
Jungfraujoch
$\Delta^{14}C$ [‰]
1000
800
600
400
200
0
Suess effect
period of the strongest bomb tests
natural reference level
1950
1960
1970
1980
1990
2000
2010
Year
Carbon Cycle Group
Institut für Umweltphysik, Univ. Heidelberg

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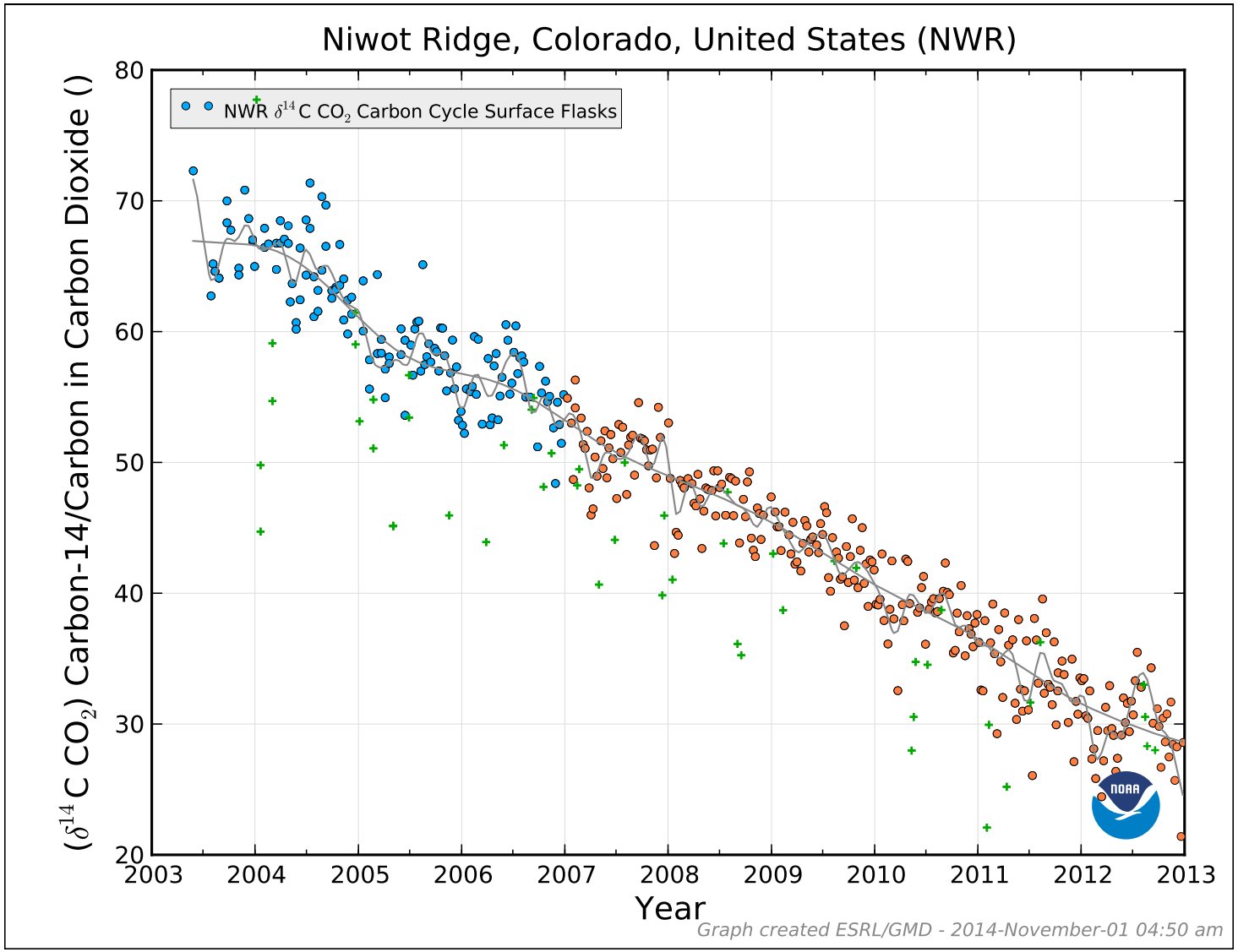

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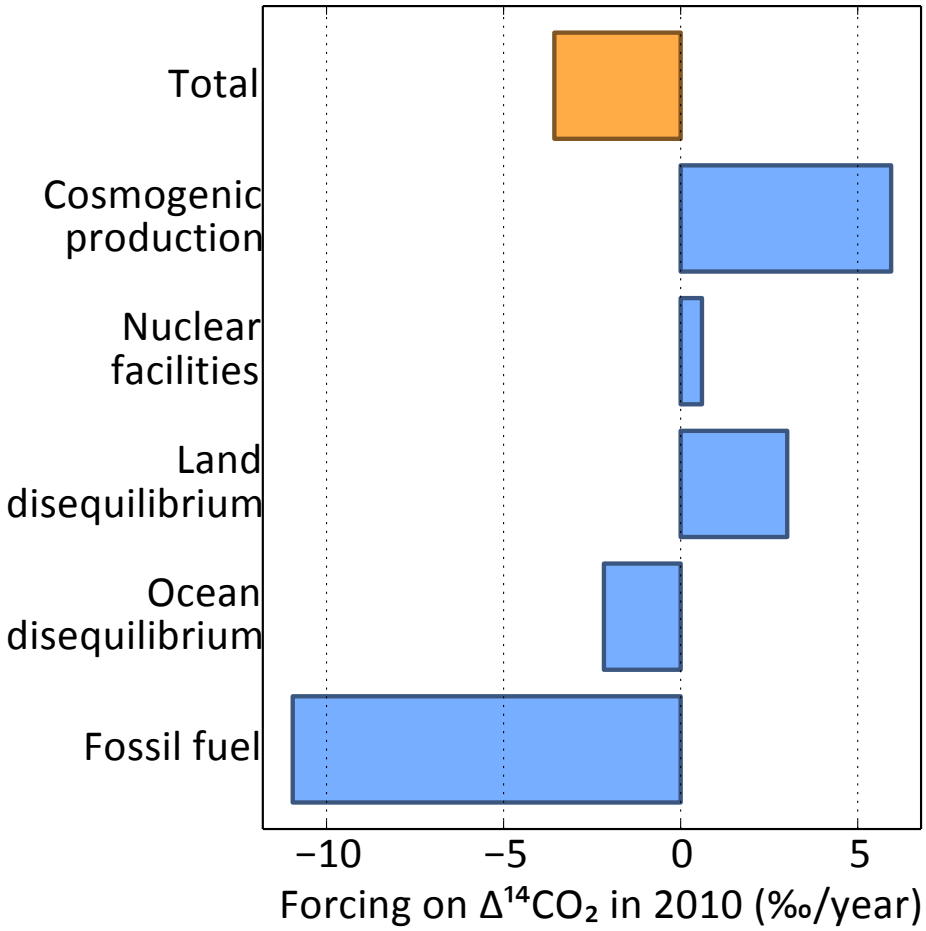


Global budget

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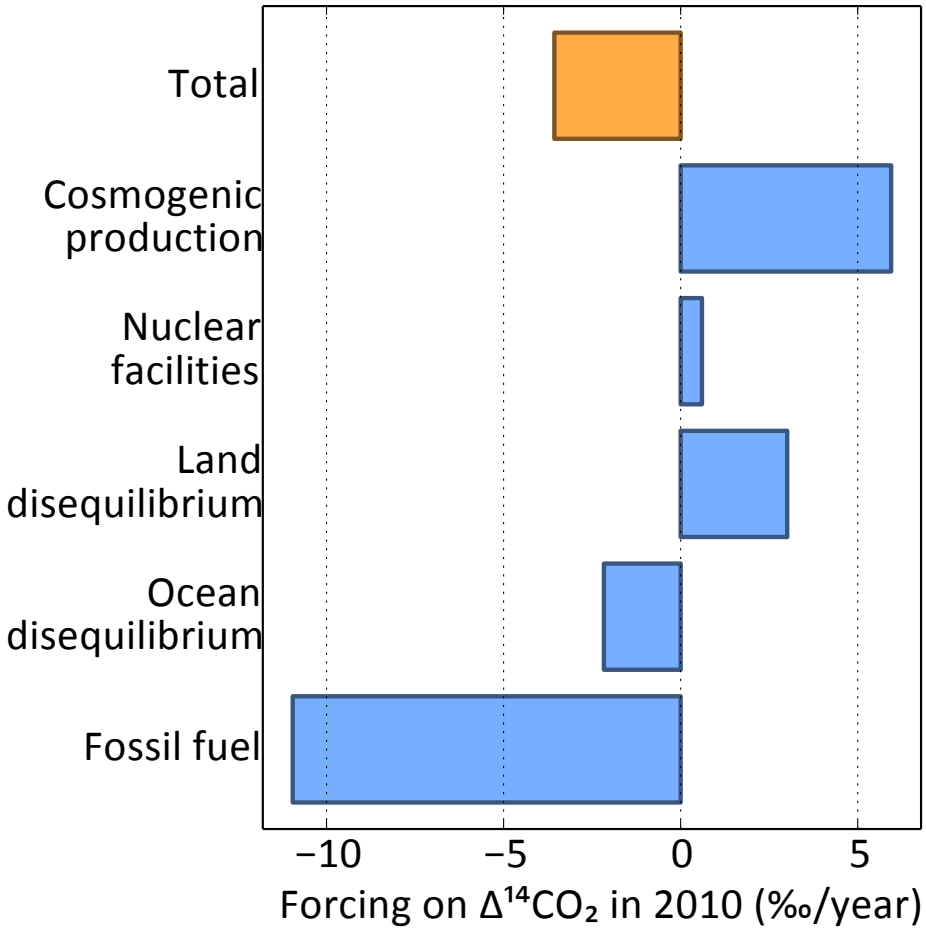


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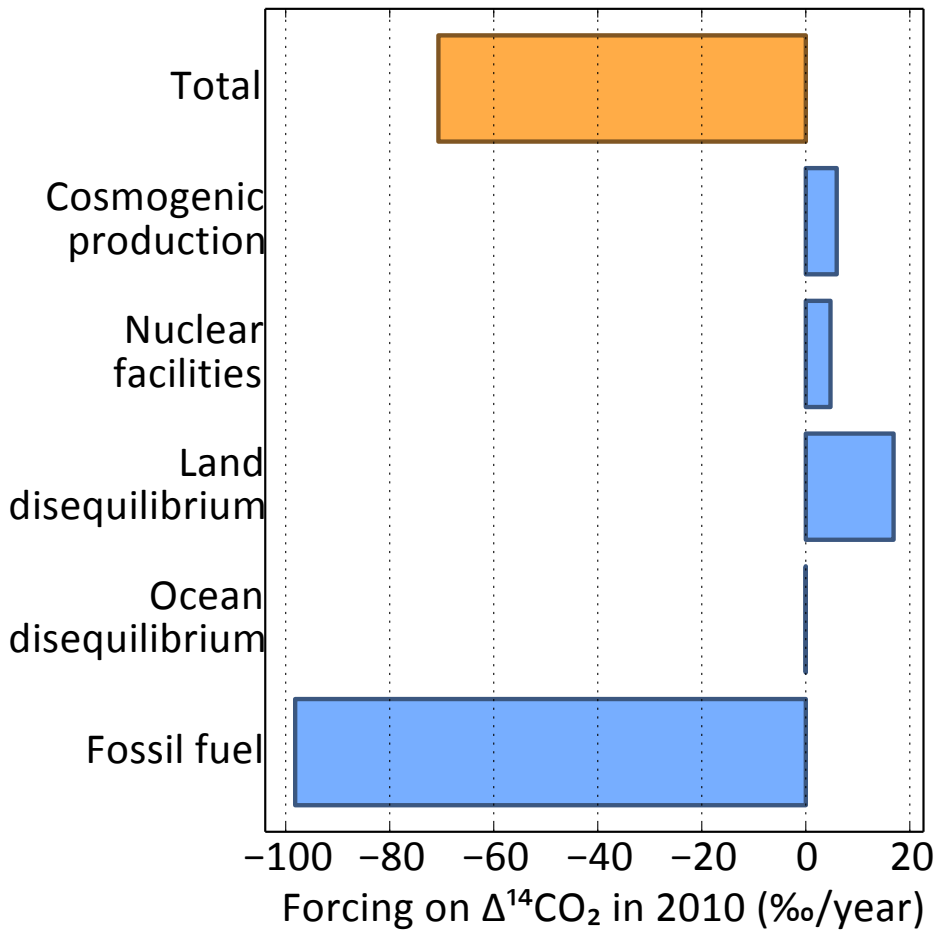


Continental US budget

# Over North America, fossil fuel dominates

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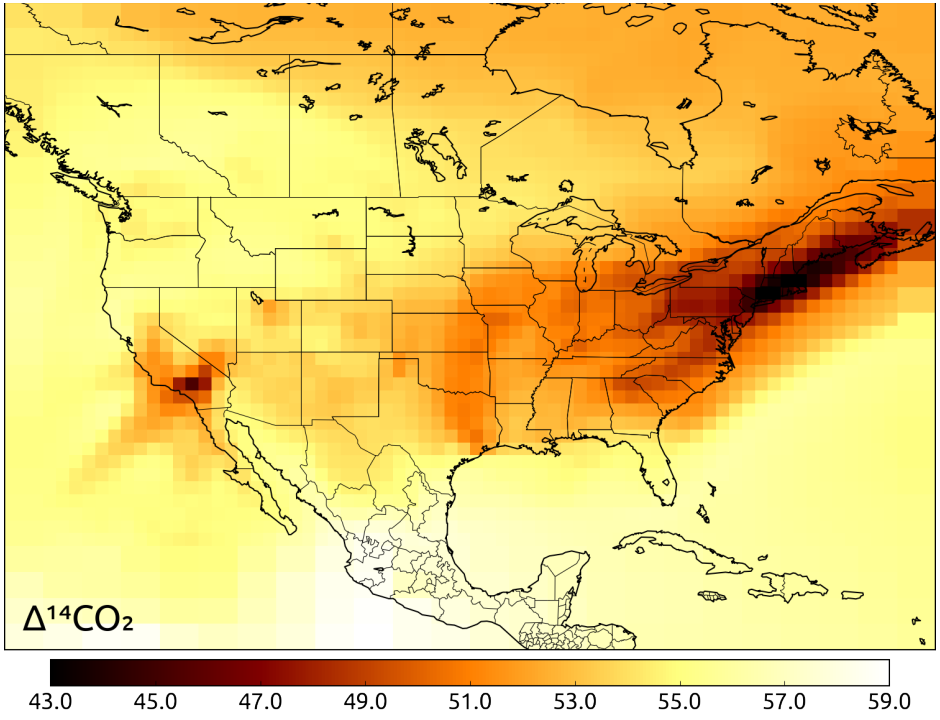
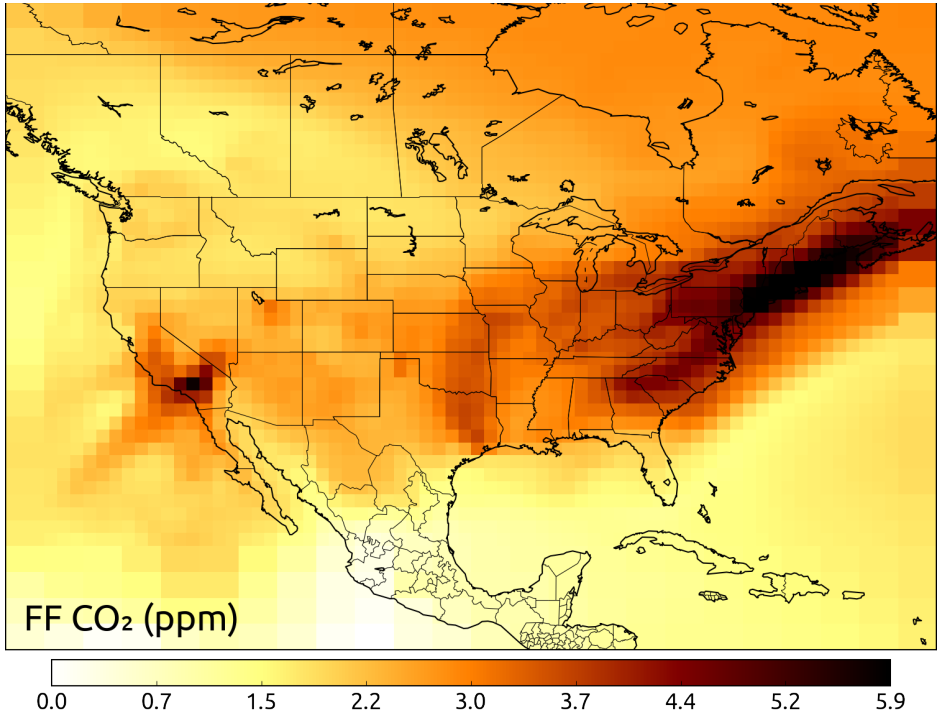
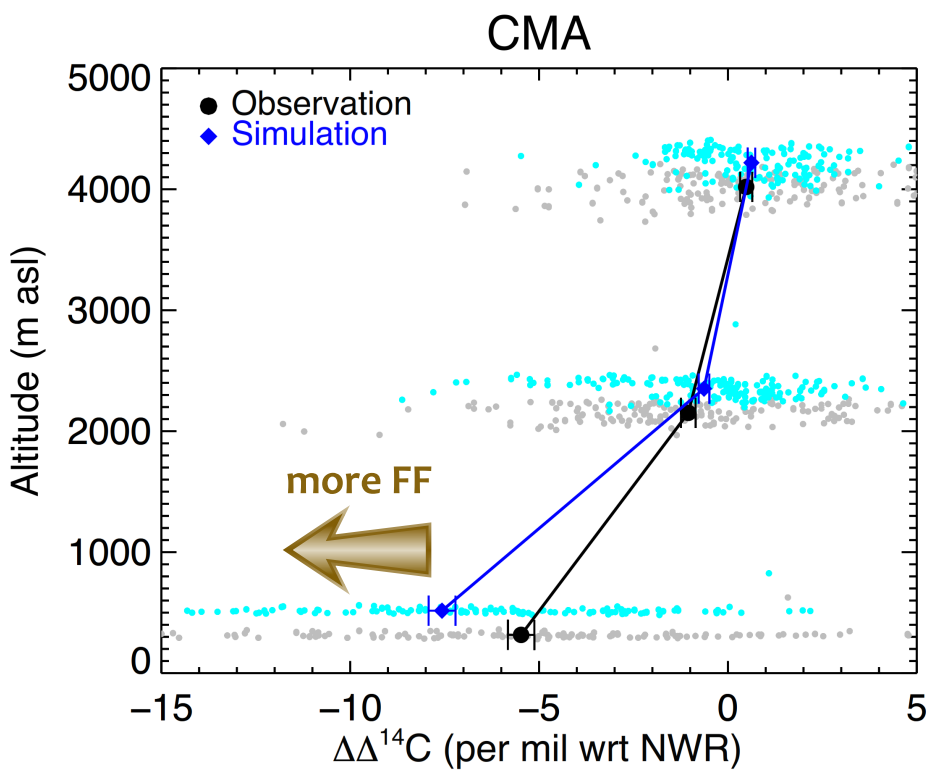
Scaling in 2006 = −2.7 ‰ $\Delta^{14}C$ for 1 ppm $CO_2$(ff)

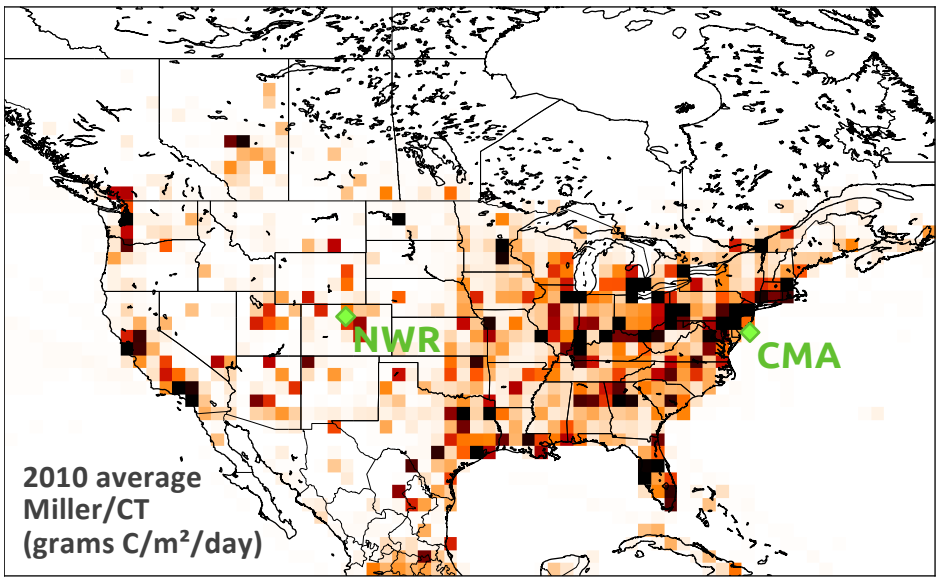


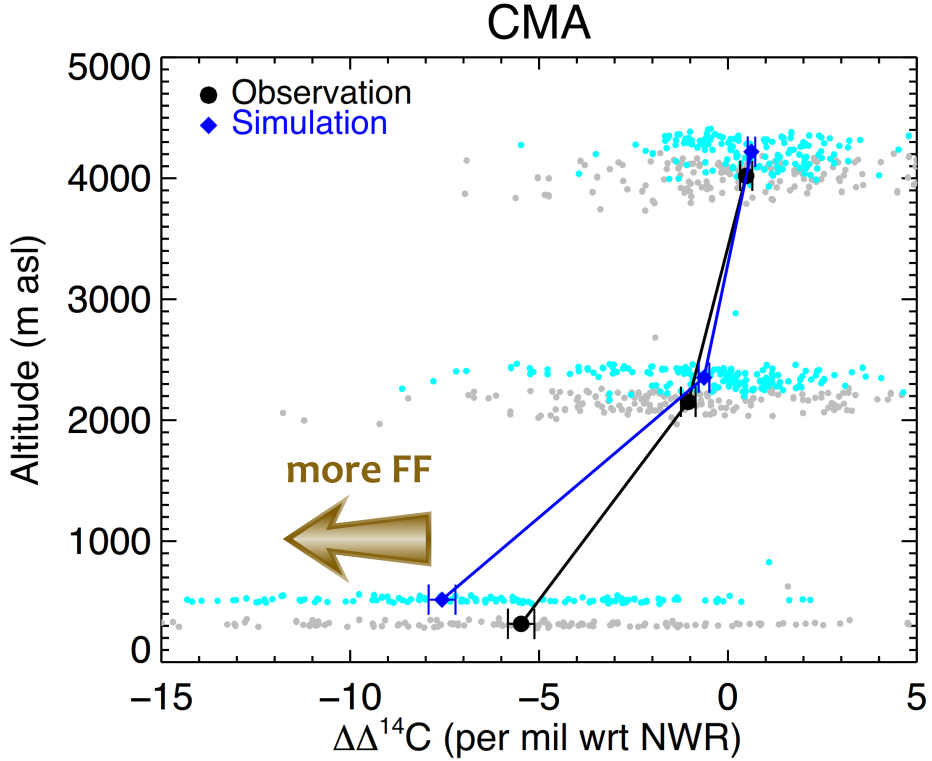




fossil fuel, ocean and land disequilibrium, nuclear and cosmogenic production

fossil fuel only


CMA
Observation
Simulation
more FF
Altitude (m asl)
5000
4000
3000
2000
1000
0
−15
−10
−5
0
5
ΔΔ14C (per mil wrt NWR)


NWR
CMA
2010 average
Miller/CT
(grams C/m²/day)
0.0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7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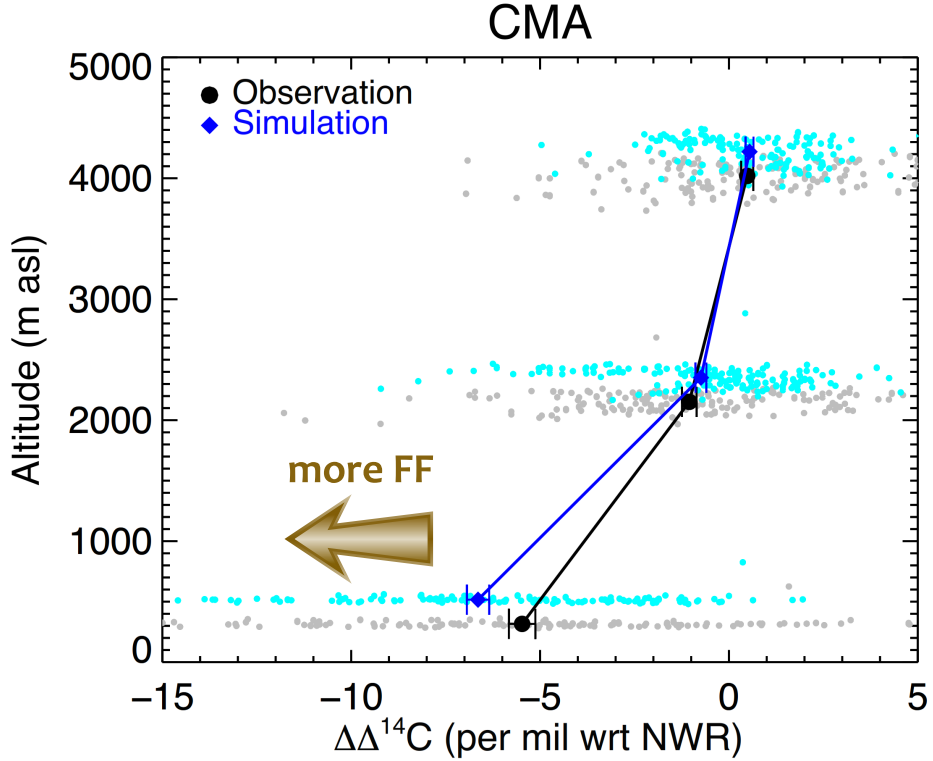
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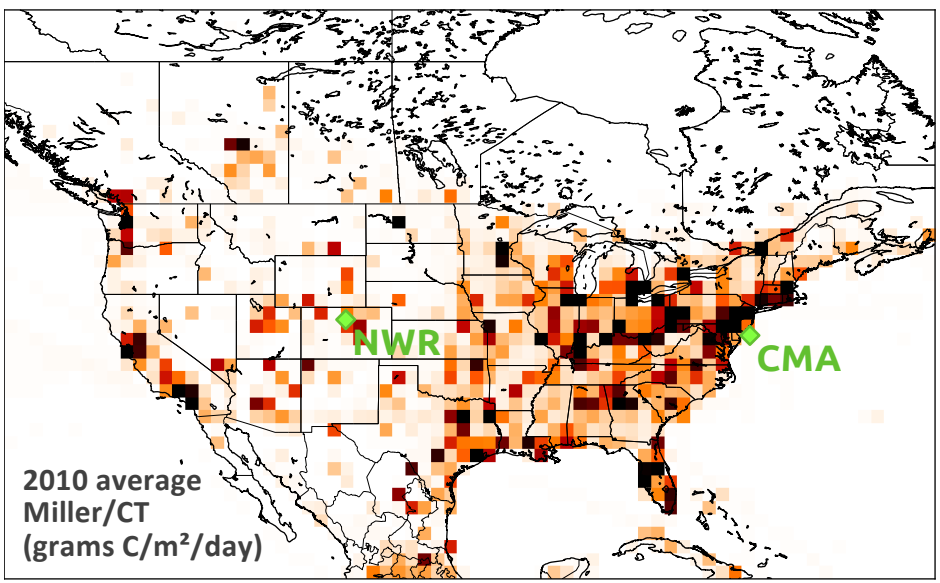
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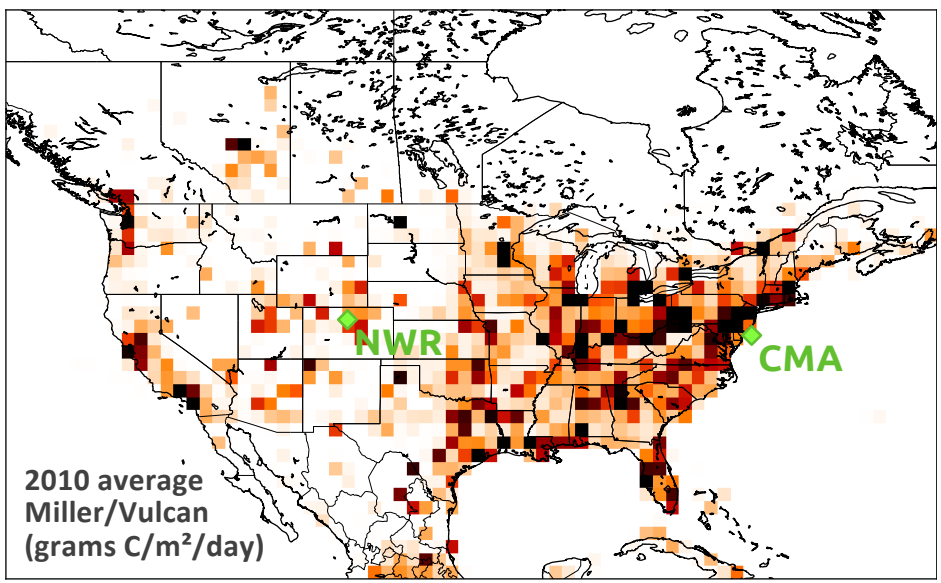

NWR
CMA
2010 average
Miller/Vulcan
(grams C/m²/day)
0.0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4

# Mass balance

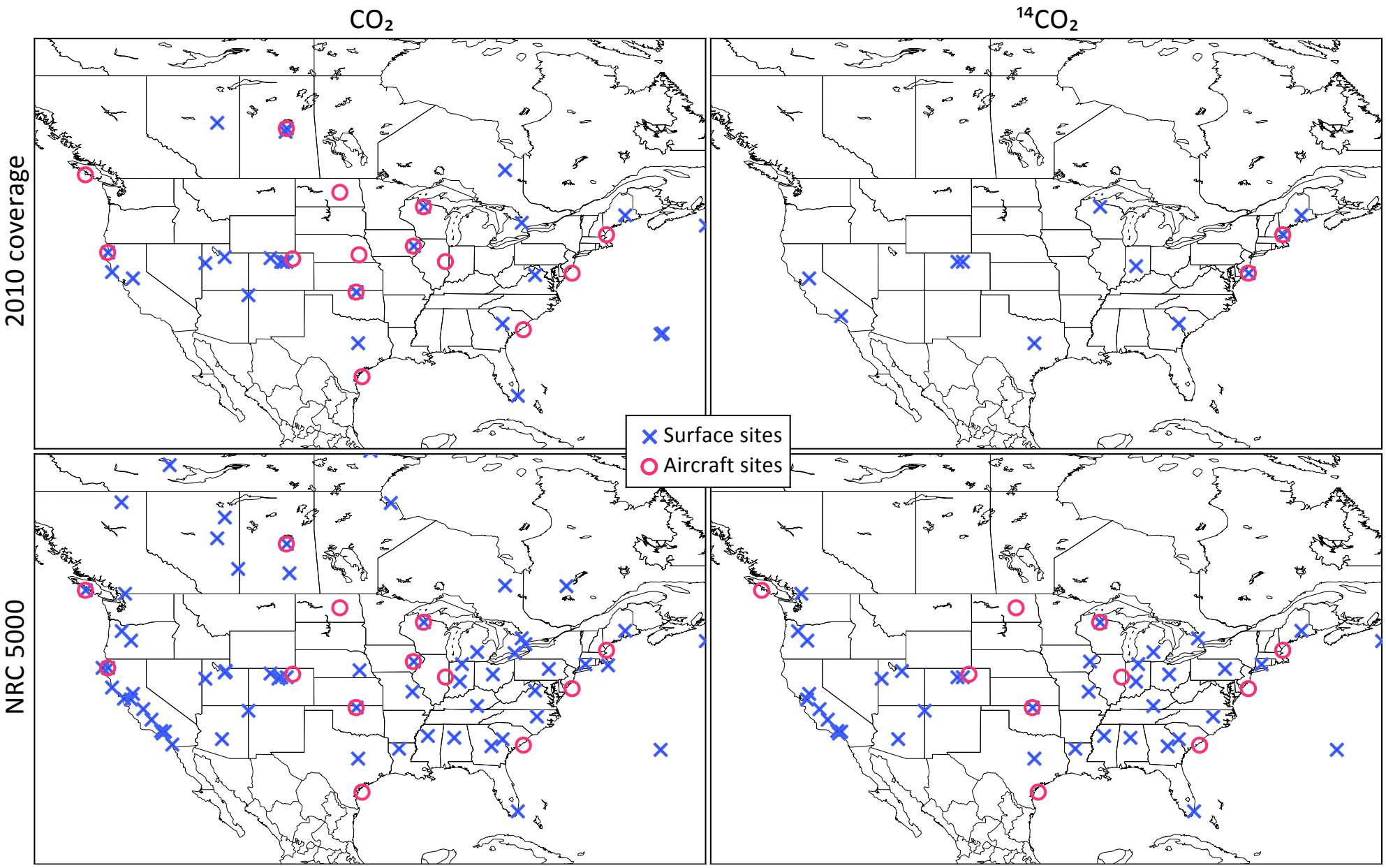
$$\frac{dC}{dt} = F_{oce} + F_{bio} + F_{fos}$$

$$\frac{d}{dt}\left(C \cdot \Delta_{atm}\right) = \Delta_{fos} F_{fos} + \Delta_{atm}\left(F_{oce} + F_{bio}\right) + \Delta_{oce} F_{oce \rightarrow atm} + \Delta_{bio} F_{bio \rightarrow atm} + \alpha\left(F_{nuc} + F_{cosmo}\right)$$

tracers transported

fluxes estimated

# Sampling sites in 2010 and NRC 5000



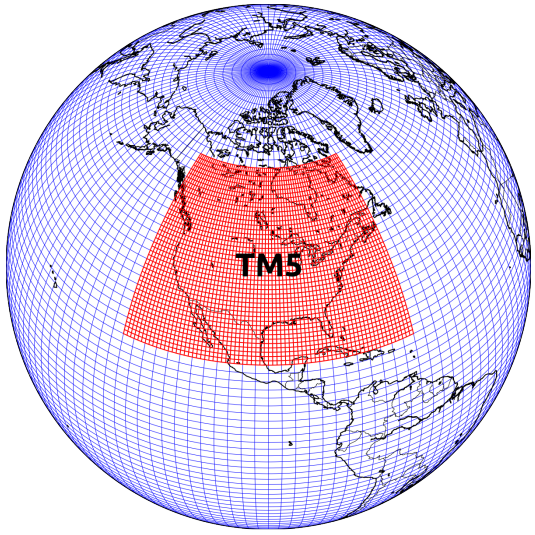
# Inversion framework

Optimization algorithm

$x_{n+1}$

Tracer emissions

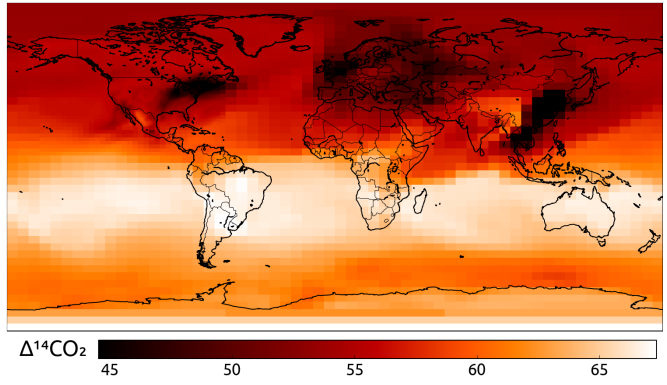
$x_n$




Transport model

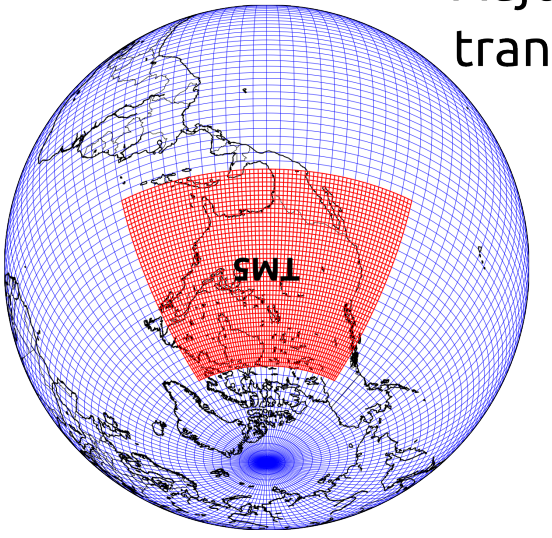
$Hx_n$

Model ⇔ Measurements




$Hx_n - d$

Adjoint transport model




$H^T(Hx_n - d)$