Constraining fossil fuel CO_2 emissions by the joint assimilation of atmospheric CO_2 and $^{14}CO_2$

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TM Meeting, Ispra, 27th June, 2016

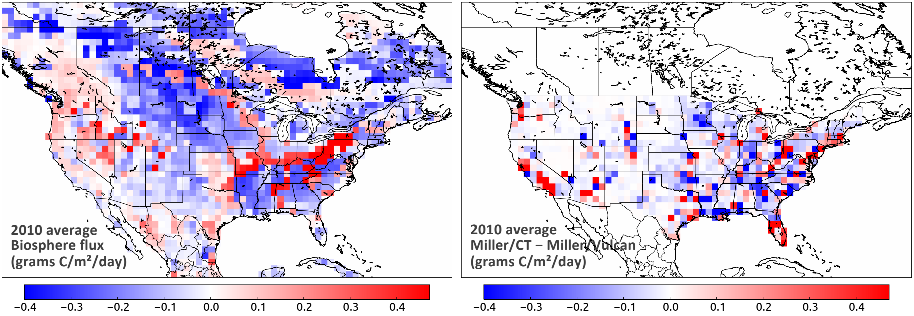
Why focus on fossil fuel emissions?

- Intended Nationally Determined Commitments (INDCs) at COP21
- E.g., the US INDC aims to reduce CO_2 equivalent GHG emissions by 25-28% by 2025, compared to 2005 levels
- Do we have the tools to verify such reductions? Inventories are hard to update and may not be "good enough". E.g., $\sim$ 8% difference between CDIAC and EDGARv4.2 FT2010 for the US in 2010.

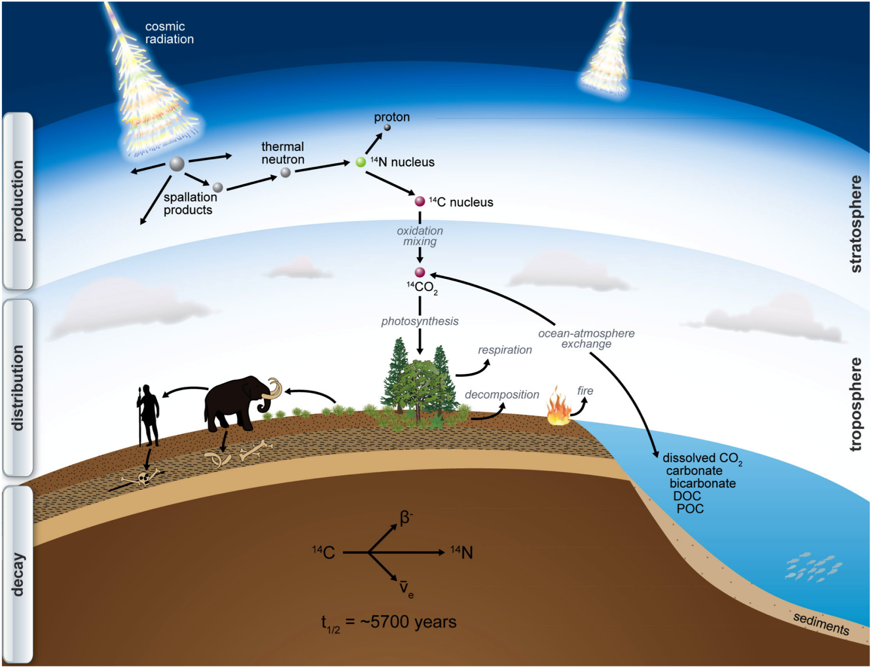
Why focus on fossil fuel emissions?

- National totals for Annex I and II countries known to within 5%, for developing countries less so. Regional monthly inventory estimates, even for developed countries, are also less accurate.
- In a pure CO_2 inversion, direct impact on NEE due to biased fossil fuel.

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



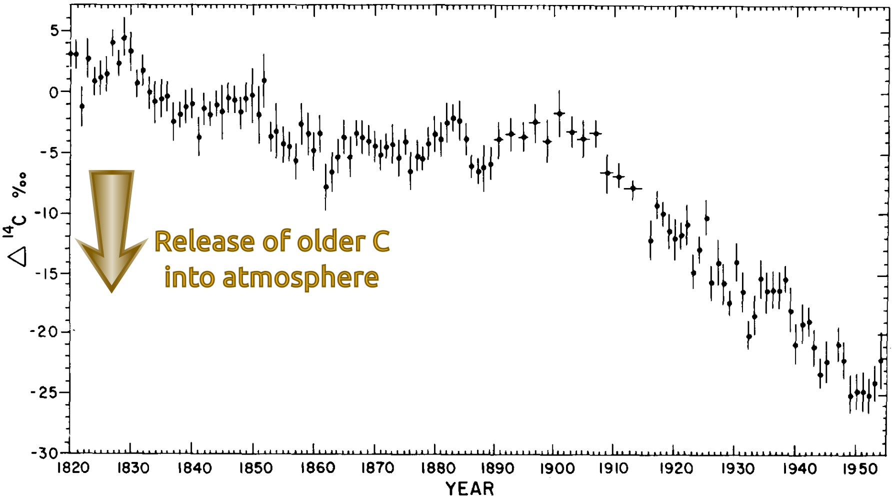
Isotope geochemistry of $^{14}CO_2$



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

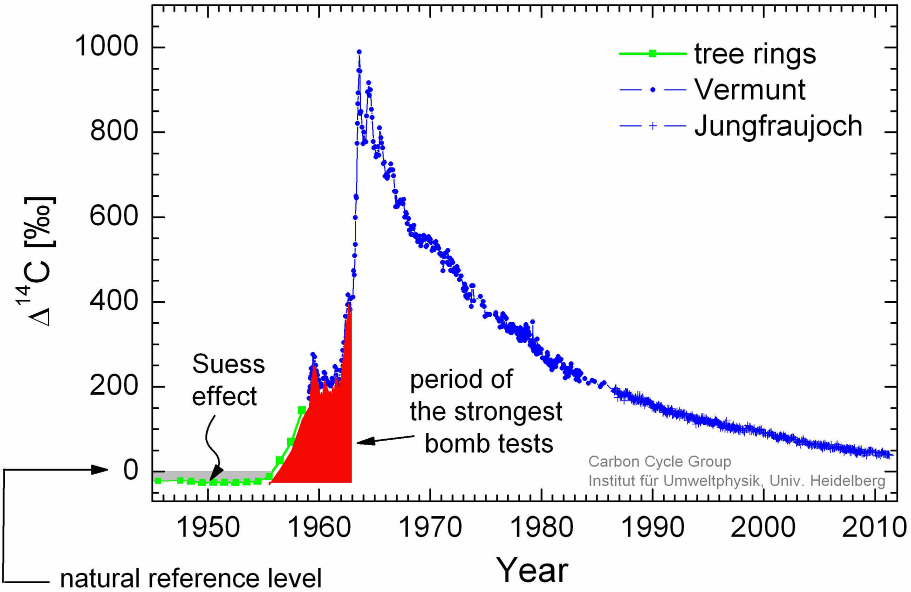
- $(^{14}CO_2/CO_2)_{\text{reference}} = 1.176 \times 10^{-12}$
- Basis for radiocarbon dating; older the sample, lower the $\delta^{14}C$
- Emitting fossil fuel CO_2 “ages” the atmosphere

Isotope geochemistry of $^{14}CO_2$



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

Long term trend of $^{14}CO_2$ in the Northern Hemisphere



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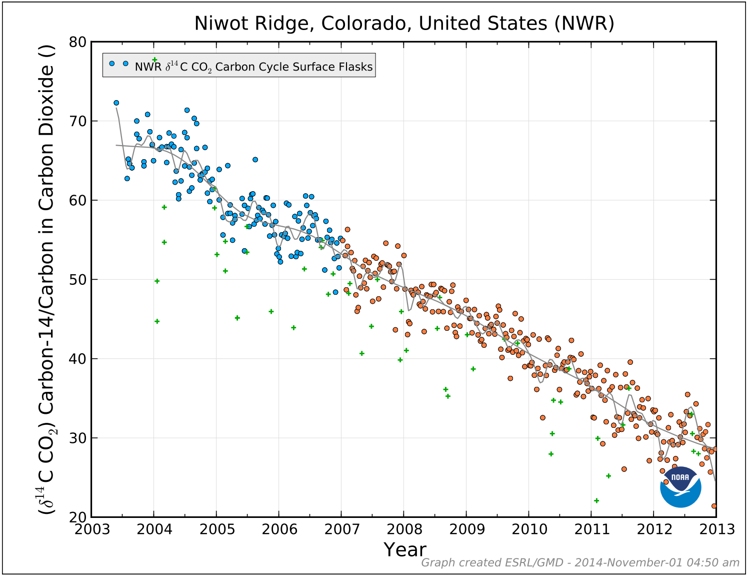

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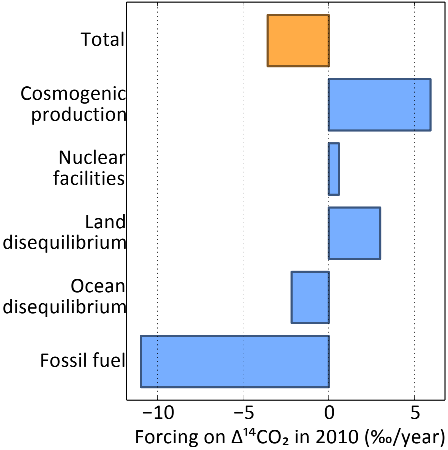
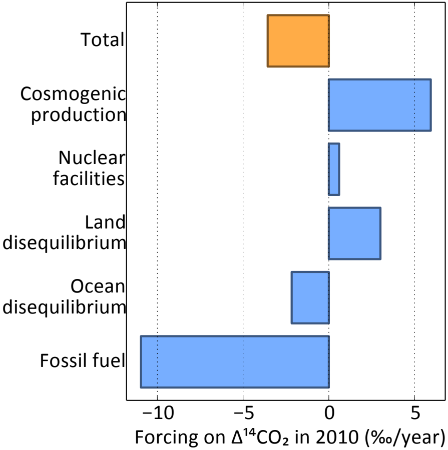
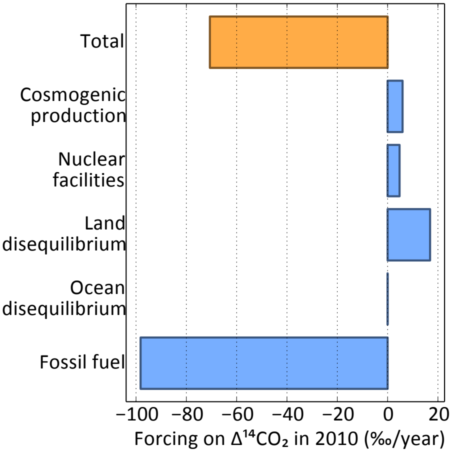


Global budget

Isotope geochemistry of $^{14}CO_2$



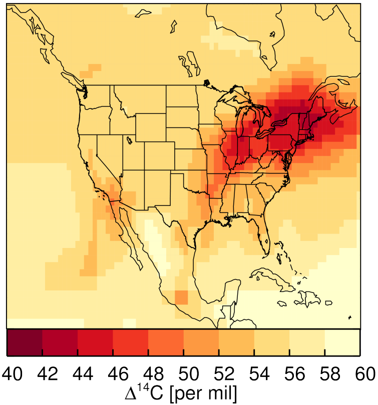
Global budget

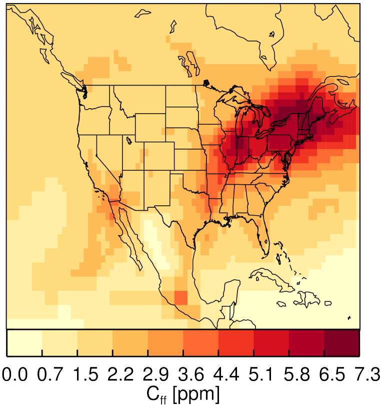


Continental US budget

Over North America, gradients of $\Delta^{14}CO_2$ almost entirely due to CO_2(ff)

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





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

fossil fuel only

Mass balance

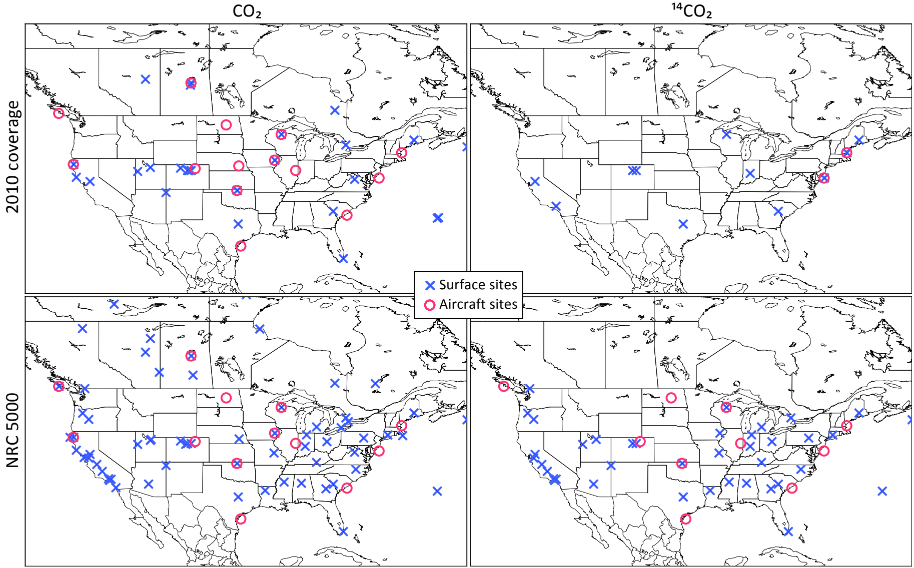
$$\frac{dC}{dt} = F_{\mathrm{oce}} + F_{\mathrm{bio}} + F_{\mathrm{fos}}$$

$$\begin{aligned}
\frac{d}{dt}\left(C \cdot \Delta_{\mathrm{atm}}\right) &= \Delta_{\mathrm{fos}} F_{\mathrm{fos}} + \Delta_{\mathrm{atm}} \left(F_{\mathrm{oce}} + F_{\mathrm{bio}}\right) \\
&\quad + (\Delta_{\mathrm{oce}} - \Delta_{\mathrm{atm}}) F_{\mathrm{oce}\rightarrow\mathrm{atm}} \\
&\quad + (\Delta_{\mathrm{bio}} - \Delta_{\mathrm{atm}}) F_{\mathrm{bio}\rightarrow\mathrm{atm}} \\
&\quad + \alpha \left(F_{\mathrm{nuc}} + F_{\mathrm{cosmo}}\right) \\
&= \Delta_{\mathrm{fos}} F_{\mathrm{fos}} + \Delta_{\mathrm{atm}} \left(F_{\mathrm{oce}} + F_{\mathrm{bio}}\right) \\
&\quad + F_{\mathrm{ocedis}} + F_{\mathrm{biodis}} \\
&\quad + \alpha \left(F_{\mathrm{nuc}} + F_{\mathrm{cosmo}}\right)
\end{aligned}$$

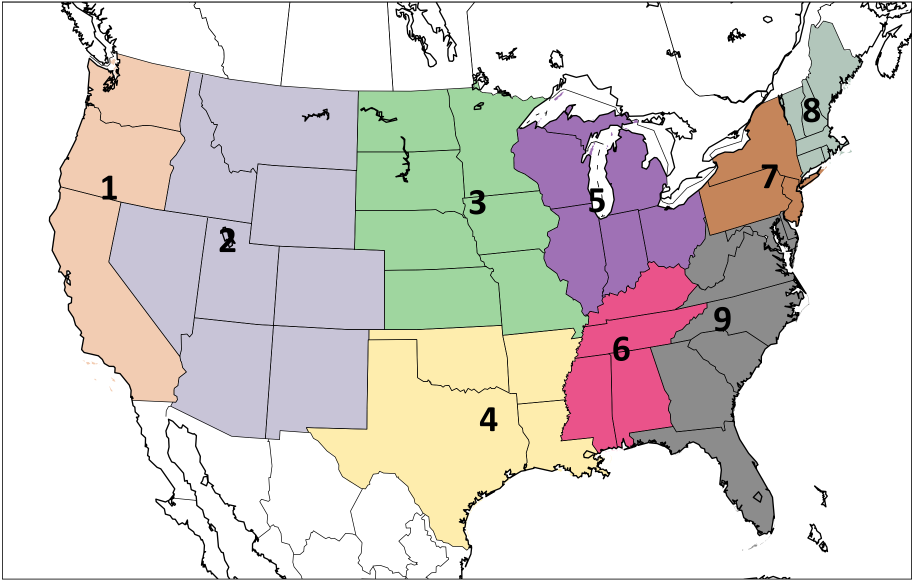
tracers transported

fluxes estimated

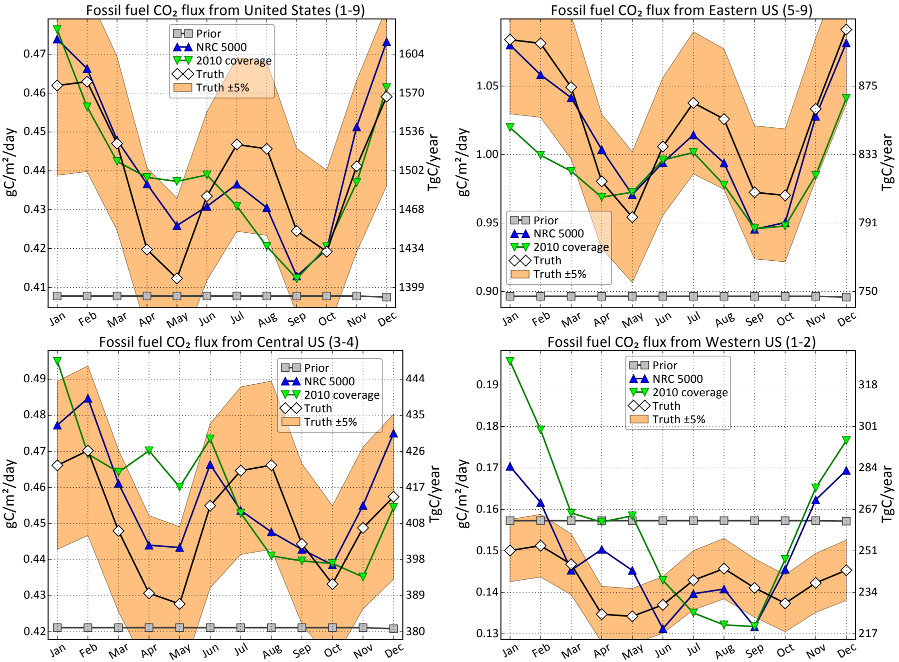
OSSE observation network



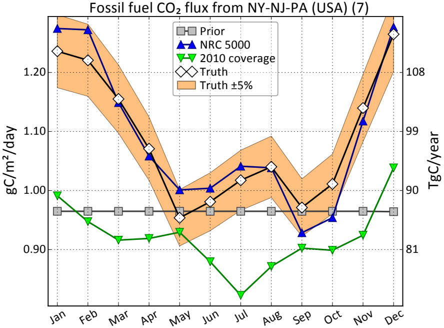
Regions for reporting fossil fuel fluxes

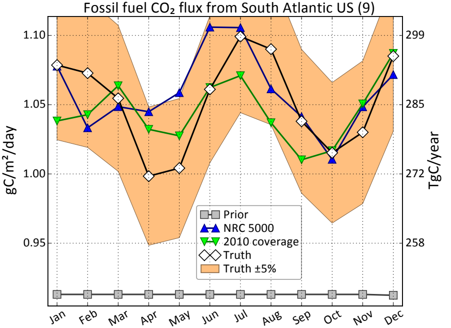


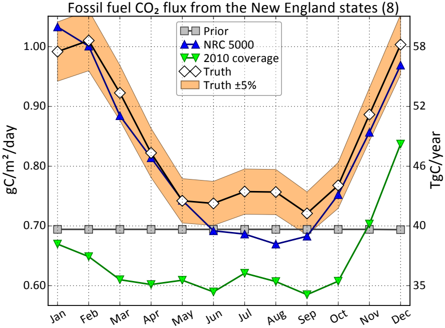
OSSE posterior flux

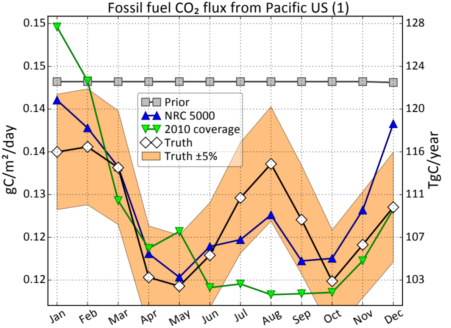


OSSE posterior flux









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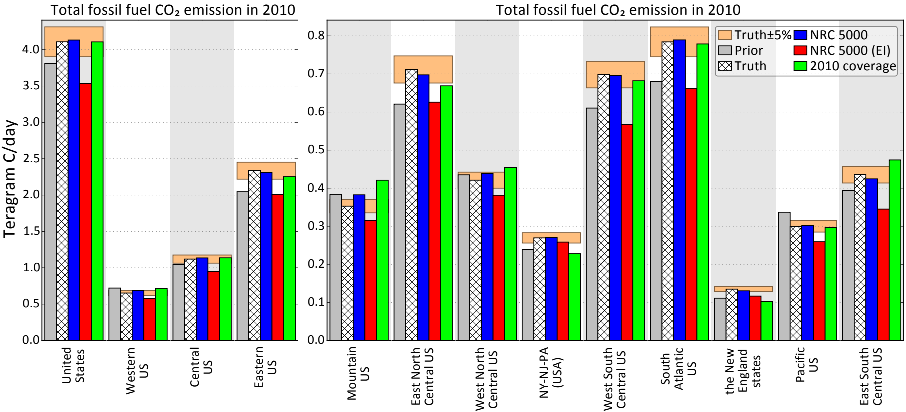
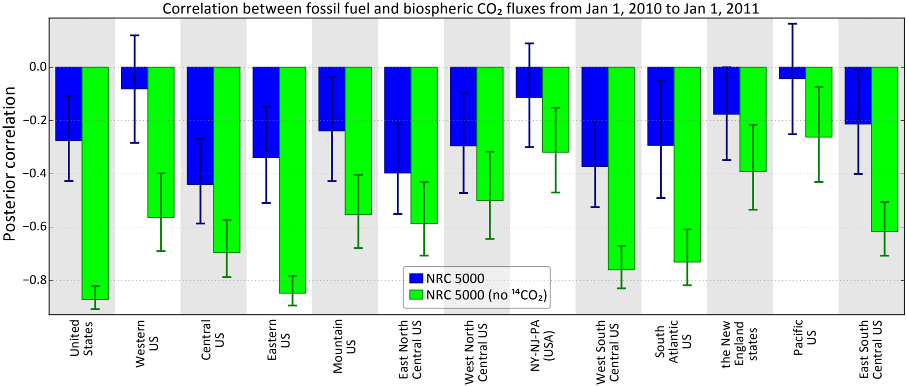


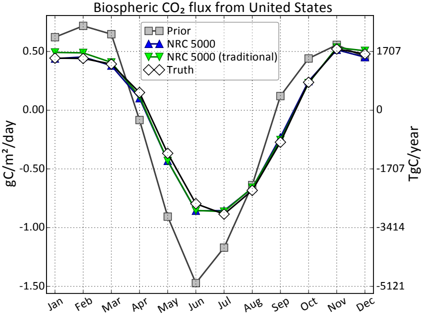
Correlation between biospheric and fossil fuel flux

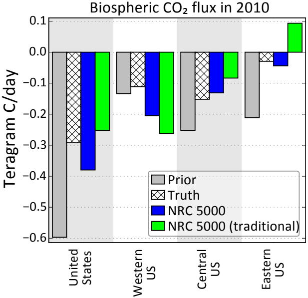
$$r = \left\langle \left(CO_2^{bio} - \left\langle CO_2^{bio} \right\rangle \right) \left(CO_2^{fos} - \left\langle CO_2^{fos} \right\rangle \right) \right\rangle$$

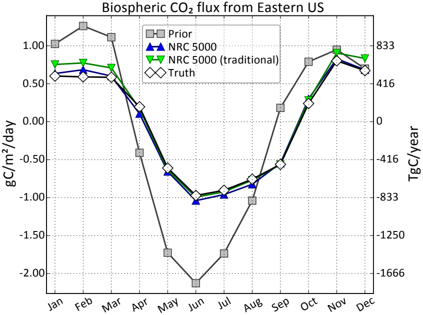
Average evaluated over 100 independent inversions with perturbed prior emissions and measurements ($\sim$ 1.2m core hours)

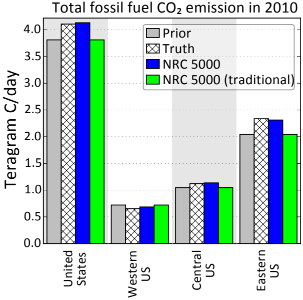


NEE bias due to wrong fossil fuel

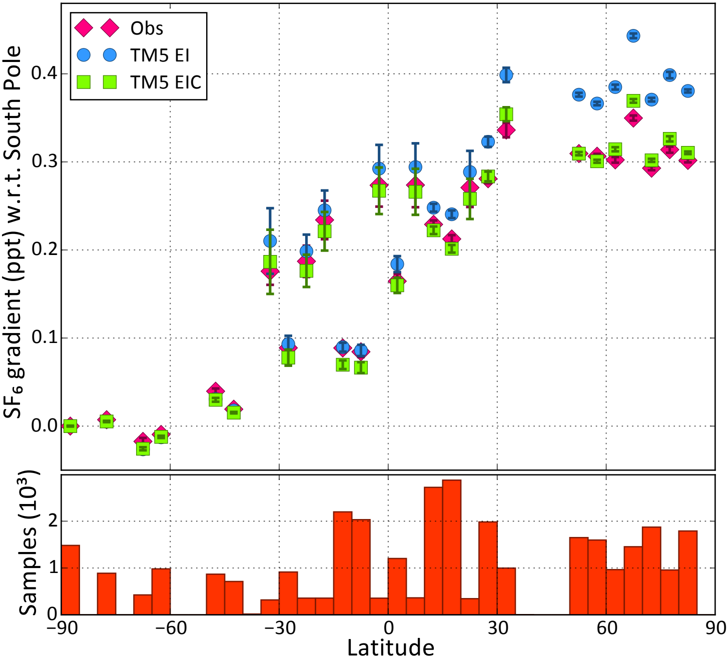








Bias due to incorrect transport (TM5 EI “sub” vs EIC “conv”)



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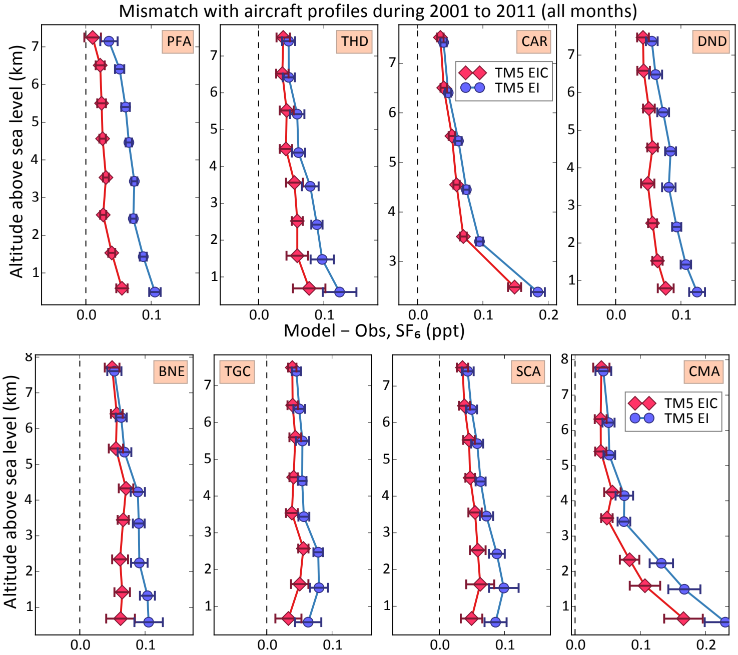

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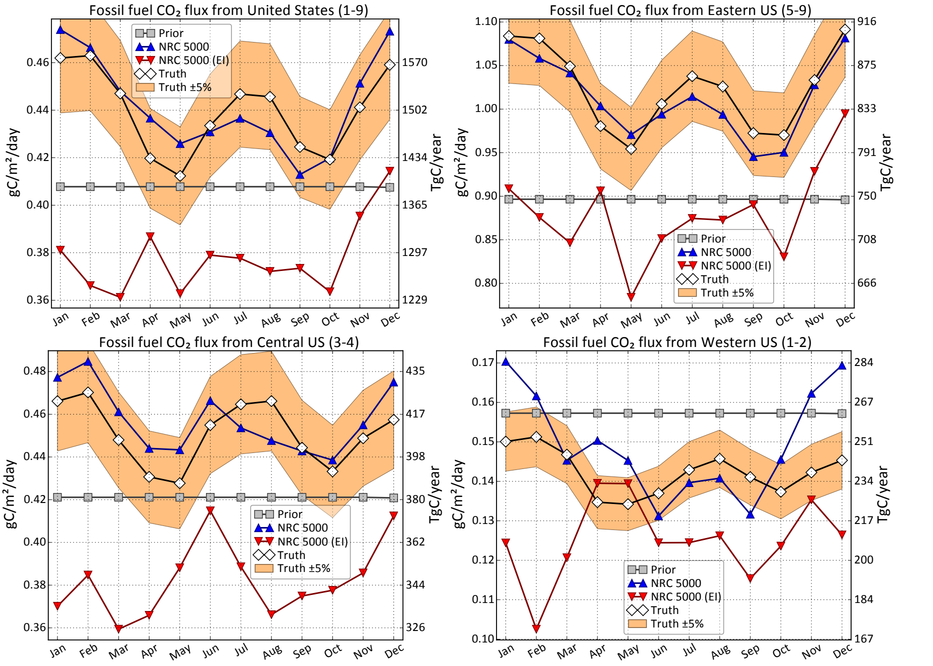

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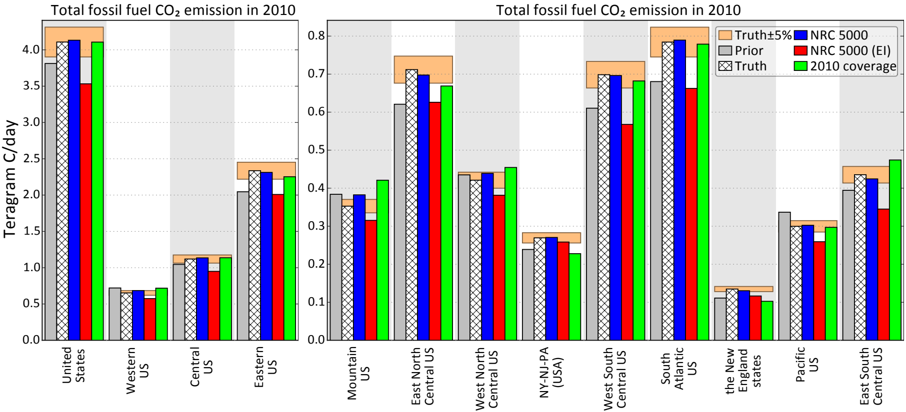


Take home messages

- Independent estimate of fossil fuel CO_2 needed for both commitments such as INDCs and for reducing biases in NEE
- $^{14}CO_2$ measurements, even though hard to perform, can provide constraints on fossil fuel CO_2
- With current network, we can estimate annual total to within a few percent. With augmented but realistic network, we can estimate monthly regional totals for highly emissive regions.
- Transport biases can severely affect this capability (much like any inversion), but trends could still be robust, to be checked in a multi-year inversion

- Define "fraction modern" as

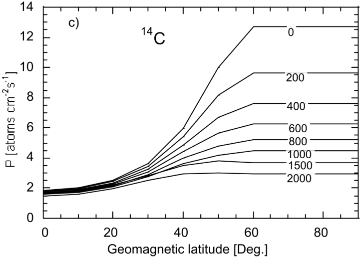
$$fm = \frac{(^{14}C/C)_{\text{sample}}}{(^{14}C/C)_{\text{standard}}}$$

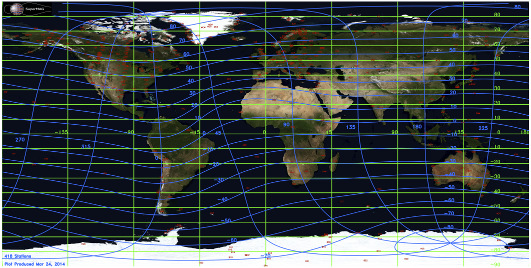
- Then δ and Δ are, respectively,

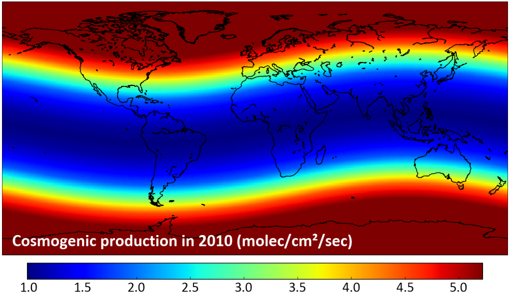
$$\delta^{14}C = (fm - 1) \times 1000\ ‰$$
$$\Delta^{14}C = \left(fm \times \left(\frac{975\ ‰}{\delta^{13}C + 1000\ ‰} \right)^2 - 1 \right) \times 1000\ ‰$$

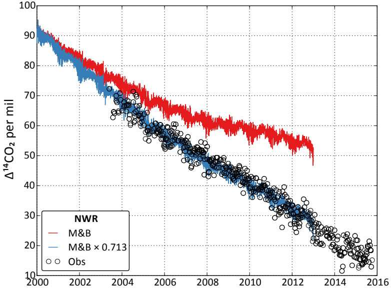
- There is *almost* no mass-dependent fractionation between reservoirs if ^{14}C signatures are expressed in Δ rather than δ

Appendix: Construction of cosmogenic ^{14}C flux









Appendix: Zonal gradient of $\Delta^{14}CO_2$ over N America