US Fossil Fuel CO_2 Estimates from Atmospheric $\Delta^{14}CO_2$ Measurements

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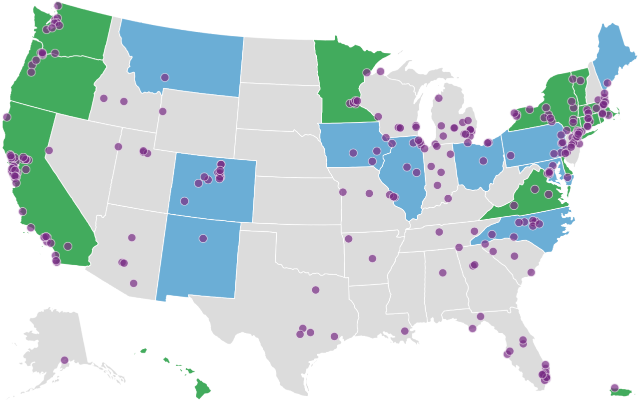
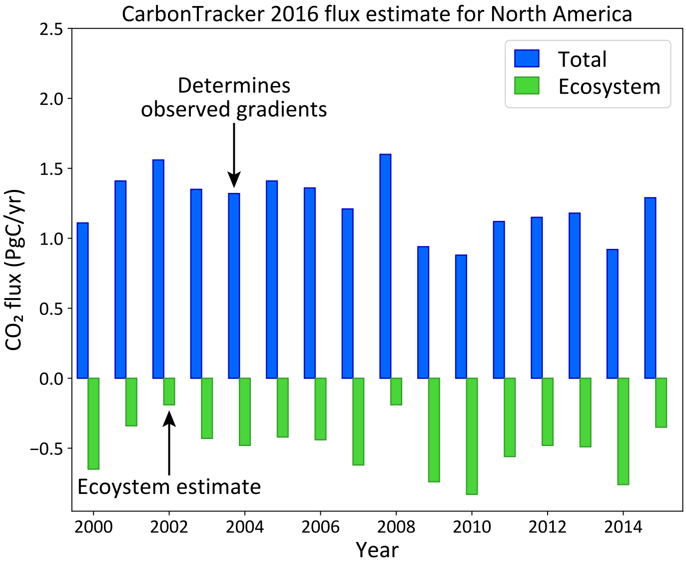
Why track US fossil fuel emissions (1)?



ALASKA, HAWAII, AND PUERTO RICO ARE NOT REPRESENTED TO SCALE.

Coalitions like the US Climate Alliance and the Regional Greenhouse Gas Initiative (RGGI) remain committed to emission reductions of the Paris Accord (or more). Regional emissions estimates needed to support these efforts. We have an independent, atmosphere-based method to track emissions.

Why track US fossil fuel emissions (2)?



- We are interested in the climate response of land ecosystem (NEE) and ocean fluxes
- CarbonTracker-like CO_2 flux estimation systems solve for NEE from observed atmospheric gradients

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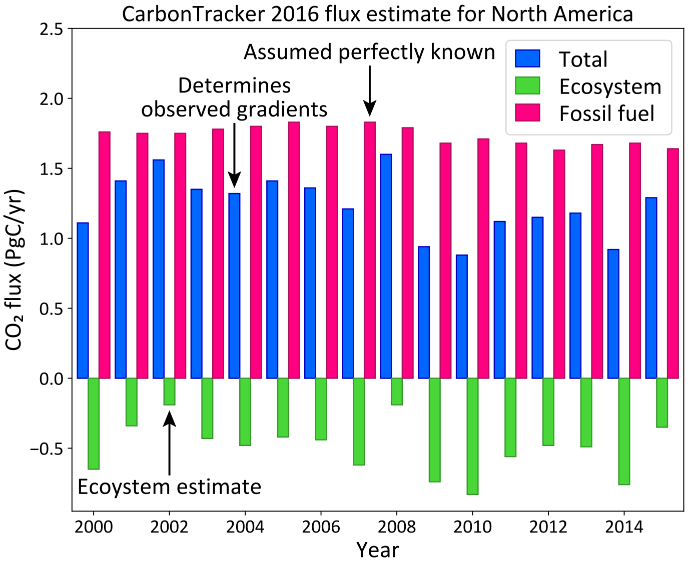
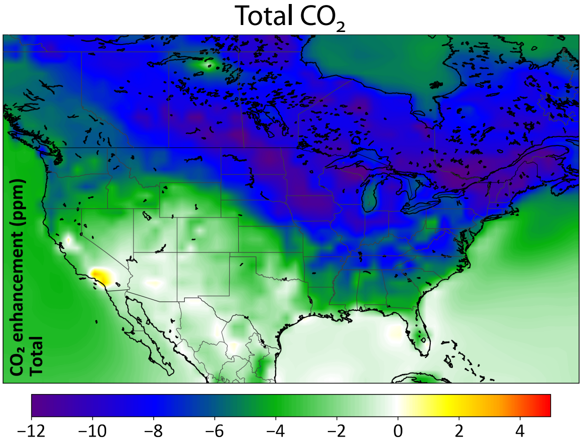
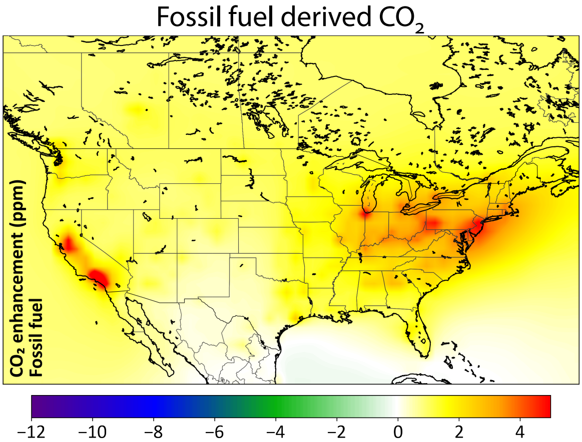


- We are interested in the climate response of land ecosystem (NEE) and ocean fluxes
- CarbonTracker-like CO_2 flux estimation systems solve for NEE from observed atmospheric gradients
- Fossil fuel emissions assumed to be perfectly known
- Errors in FF (especially seasonal) can impact diagnosed NEE anomalies and climate response

Can we track emissions using CO_2 measurements only?

Summer-time mid-afternoon near-surface gradients





Near-surface gradients of CO_2 are completely different from that of fossil fuel derived CO_2

It is not possible to estimate the latter by measuring the former

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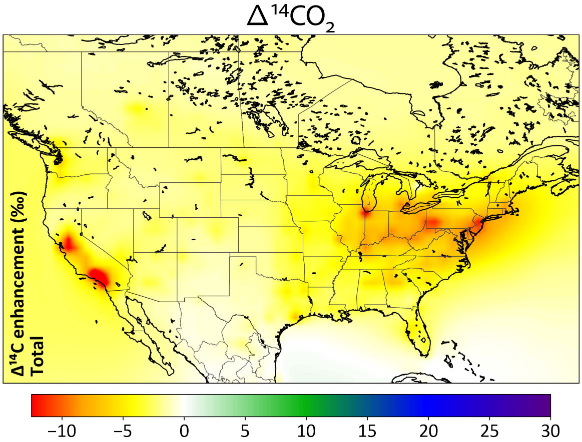
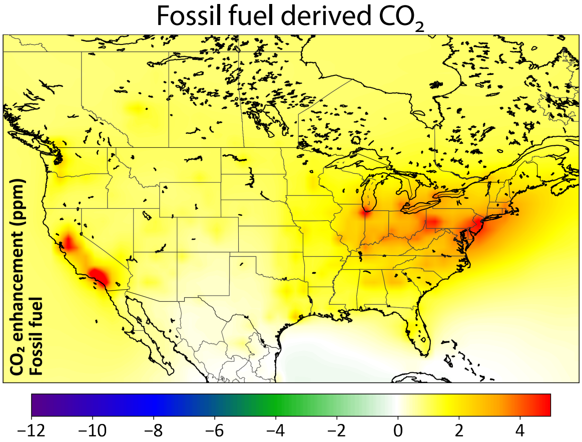




1 ppm fossil fuel CO_2 = −2.5 ‰ in $\Delta^{14}CO_2$ (roughly)

Correlation is tight enough to estimate FF CO_2 from $\Delta^{14}CO_2$ gradients

Mass balance

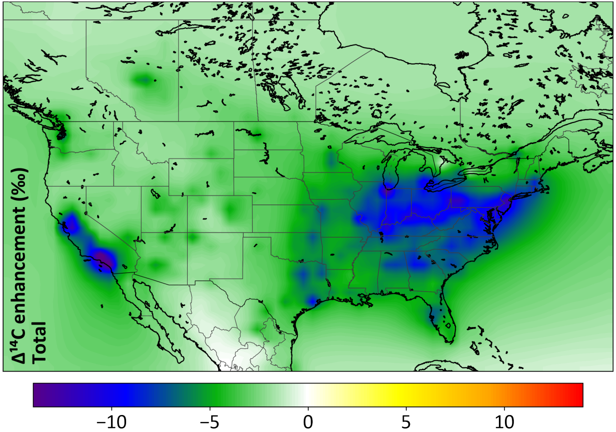
$$\frac{dC}{dt} = F_{\text{oce}} + F_{\text{bio}} + F_{\text{fos}}$$

$$\begin{aligned} C\frac{d}{dt}\Delta_{\text{atm}} &= (\Delta_{\text{fos}} - \Delta_{\text{atm}})\, F_{\text{fos}} \\ &\quad + \Delta_{\text{oce}} F_{\text{oce}\to\text{atm}} + \Delta_{\text{bio}} F_{\text{bio}\to\text{atm}} \\ &\quad + \alpha\,(F_{\text{nuc}} + F_{\text{cosmo}}) \end{aligned}$$

measurements assimilated

fluxes estimated

Fossil fuel flux is the main driver of $\Delta^{14}CO_2$ gradients over North America



$\Delta^{14}CO_2$ gradients are determined by fossil fuel, cosmogenic production, nuclear production, and oceanic and terrestrial disequilibria

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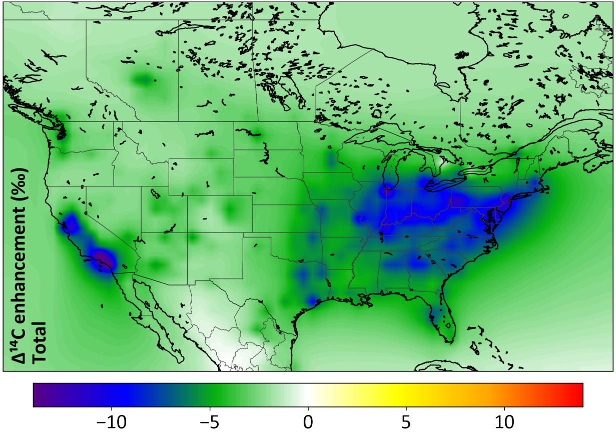

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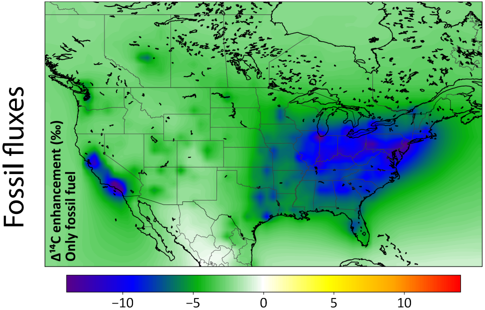
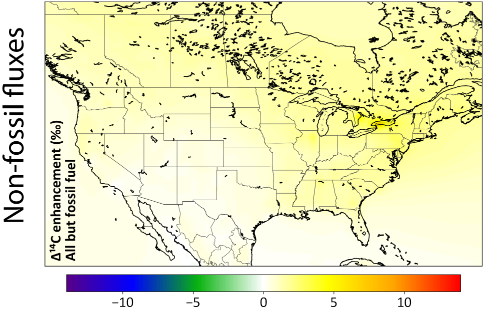
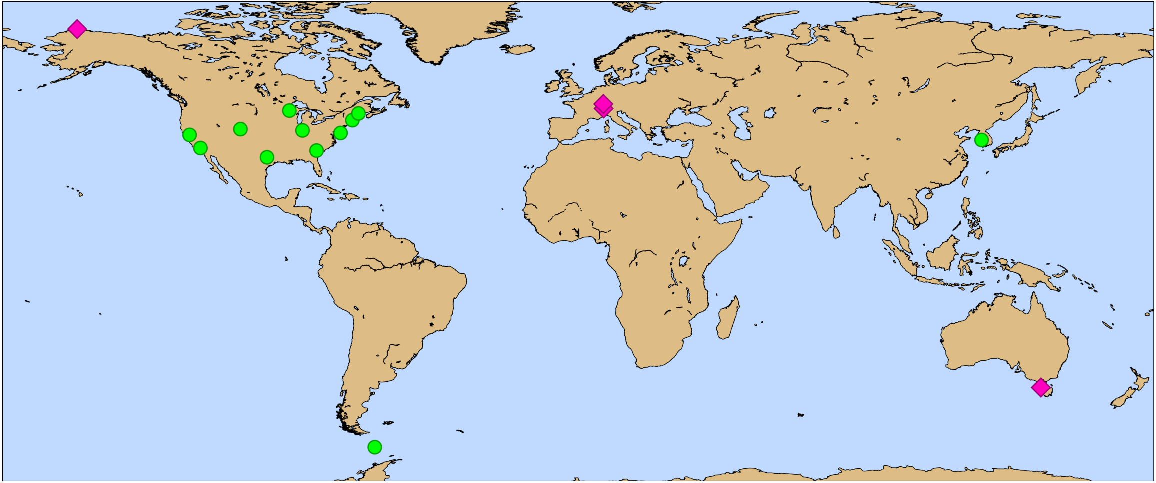




Inversion of real $^{14}CO_2$ measurements for 2010: Sites



NOAA GMD/CU INSTAAR (895)

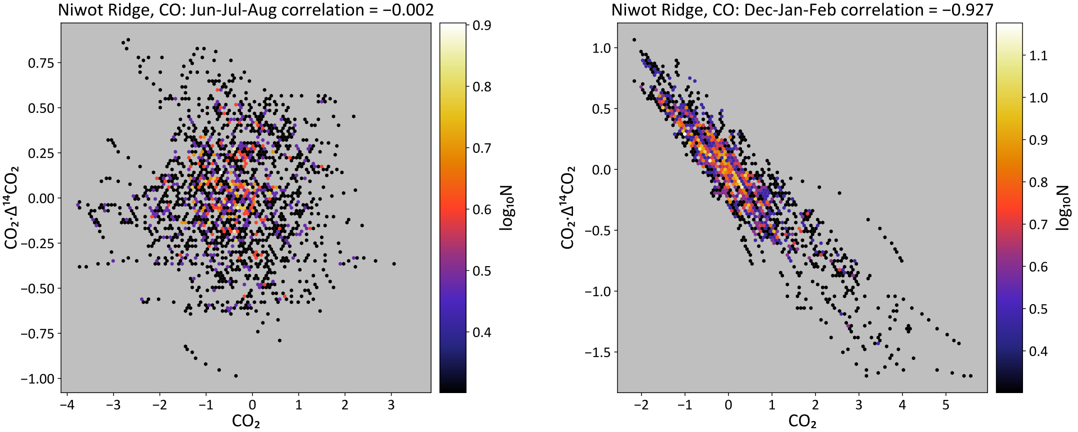
External (89)

How are uncertainties evaluated?

- Random uncertainty (posterior covariance) evaluated by performing 110 inversions with perturbed fluxes and measurements (Monte Carlo)

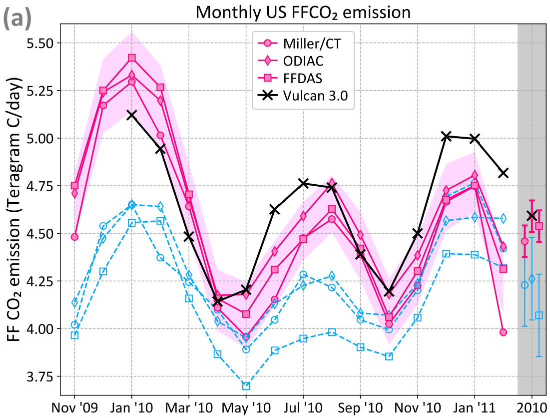
- Systematic errors from doing inversions with different configurations (prior FF, prior NEE, disequilibrium, ^{14}C production, etc.)

Correlation between CO_2 and $\Delta^{14}CO_2$ measurements



In the summer, CO_2 variations are primarily due to the biosphere. However, in the winter a significant component of the CO_2 variation could be FF CO_2. We evaluated this by looking at residuals of CO_2 and $CO_2 \cdot \Delta^{14}CO_2$ from smooth curves over three years.

Results: Monthly US FF CO_2



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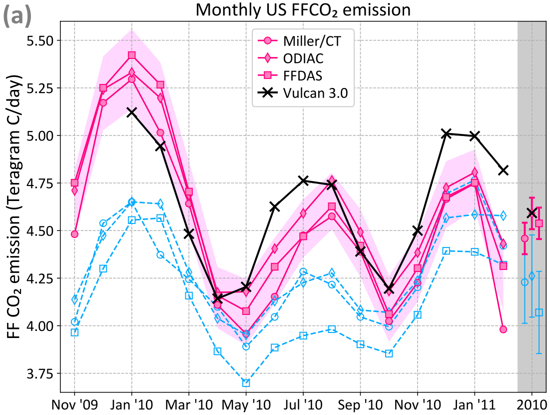
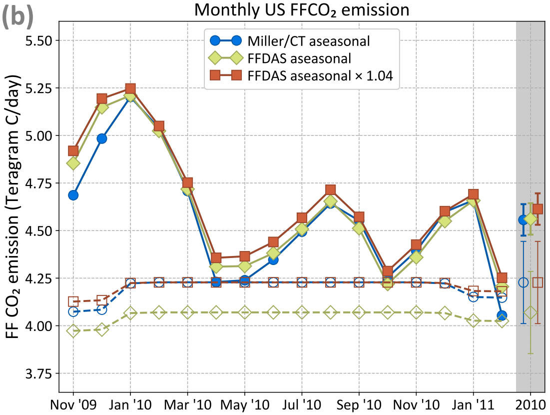




Systematic errors/sensitivity tests

Region	2010 Total FF CO_2 ($TgC\ yr^{-1}$)		Analytical uncertainty				Spread due to prior FF		Spread due to prior NEE				Spread from other sensitivity runs	
			Prior		Posterior				2010 coverage		NRC5000			
	Inversion	Vulcan	$TgC\ yr^{-1}$	%	$TgC\ yr^{-1}$	%	$TgC\ yr^{-1}$	%	$TgC\ yr^{-1}$	%	$TgC\ yr^{-1}$	%	$TgC\ yr^{-1}$	%
United States	1653	1676	78.8	5.2	30.2	1.8	56.4	3.4	86.2	5.2	26.3	1.6	29.4	1.8
Eastern US	889	953	56.2	6.3	26.2	3.0	15.7	1.8	34.3	3.9	18.7	2.1	15.0	1.7
Western US	302	310	32.8	12.4	12.4	4.1	35.8	11.9	49.9	16.6	7.6	2.5	5.2	1.7
Central US	463	413	36.1	9.6	19.6	4.2	8.8	1.9	1.9	0.4	0.0	0.0	9.2	2.0

- Of all the sensitivity tests run, FF CO_2 seems to be the most sensitive to prior NEE
- This is not a theoretical limit, but due to small number of $\Delta^{14}CO_2$ obs, disappears if that number is increased

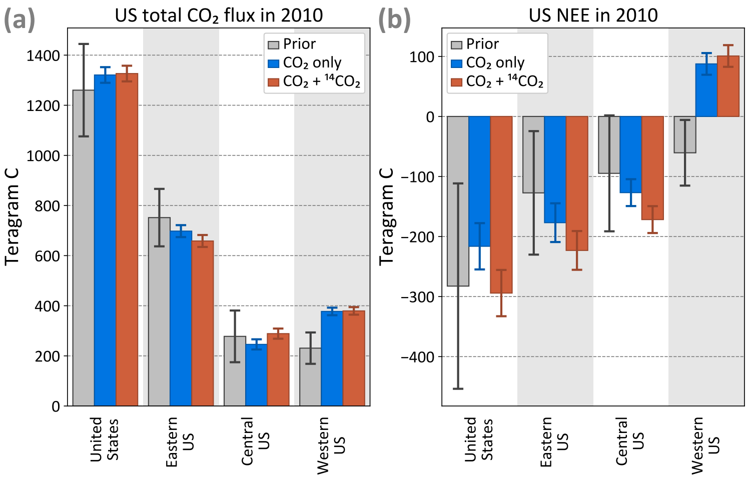
Comparison to inventories is not so straight-forward

- Inherent problem with aggregating gridded inversion estimates, since 1×1 grid is fairly coarse to properly account for coastal urban areas and country boundaries
- Inventories typically serve UNFCC reporting requirements, which ignore bunker fuels, and include some non-fossil CO_2 emissions
- US gasoline contains $\sim$10% ethanol, which is included in the total automotive sector of some inventories
- Vulcan includes some airline emissions (below 1 km), other inventories vary
- Some inventories report both gridded and national emissions, but what country masks they use (if any) is unclear

After some adjustments...

Source	FF CO_2 (TgC yr^{-1})	
	Reported	Adjusted
CDIAC	1471	1513
EDGAR 4.2 FT2010	1497	1522
EDGAR 4.3	1505	1545
US EPA	1555^{+62}_{-31}	1581^{+62}_{-31}
Vulcan 3.0	1638	1676
	Prior	Posterior
Inverse estimate (mean)	1528	1653 ± 30
Inverse estimate (CT/Miller prior)	1543	1627 ± 30
Inverse estimate (seasonal FFDAS prior)	1485	1656 ± 30
Inverse estimate (ODIAC prior)	1555	1675 ± 30

NEE estimates can have significant errors due to wrong FF



- Difference in NEE due to adjusting FF CO_2 is ~75 TgC/yr
- For comparison, US average NEE from CarbonTracker NAM is ~300 TgC/yr, and inter-annual variations are ~100 TgC/yr
- More importantly, difference is $> 2\sigma$ of posterior error

Take home points

- $\Delta^{14}C$ of CO_2 is a very sensitive and accurate tracer for recently derived FF CO_2
- $\Delta^{14}CO_2$-derived FF CO_2 for the US in 2010 is higher than most inventories used for carbon accounting, including the US EPA. However, it is quite close to the US-specific high resolution Vulcan inventory.
- Random errors on the annual national total are $\sim$2% with existing coverage, errors on monthly totals are $< 5\%$
- Fixed FF CO_2 in CO_2 inversions can significantly bias NEE, can be solved by also assimilating $\Delta^{14}CO_2$
- Possibility for a post-doc to work on this at NOAA Boulder. If you're a post-doc or may soon become one, and are proficient in TM5, contact me for more details.

Correlations between different regions

Region 1	Region 2	Prior	Posterior
Eastern US	Central US	0.08	-0.27
	Western US	0.07	-0.02
	Central + Western US	0.10	-0.25
Central US	Eastern US	0.08	-0.27
	Western US	0.04	-0.04
	Eastern + Western US	0.09	-0.26
Western US	Eastern US	0.07	-0.02
	Central US	0.04	-0.04
	Eastern + Central US	0.08	-0.05

Mass balance equation for TM5 4DVAR

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

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

tracers transported

fluxes estimated