





# Assessing California's Fossil Fuel $CO_2$ Emissions Using Atmospheric Observations and Models


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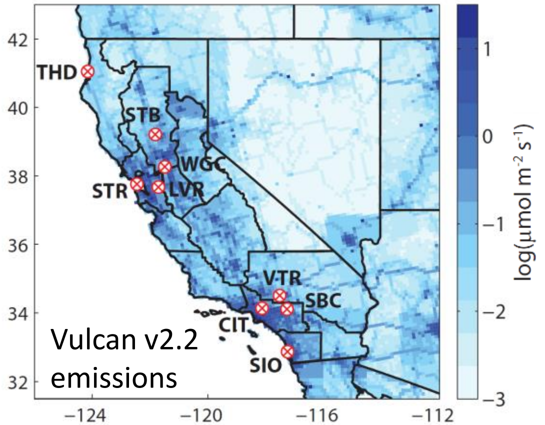


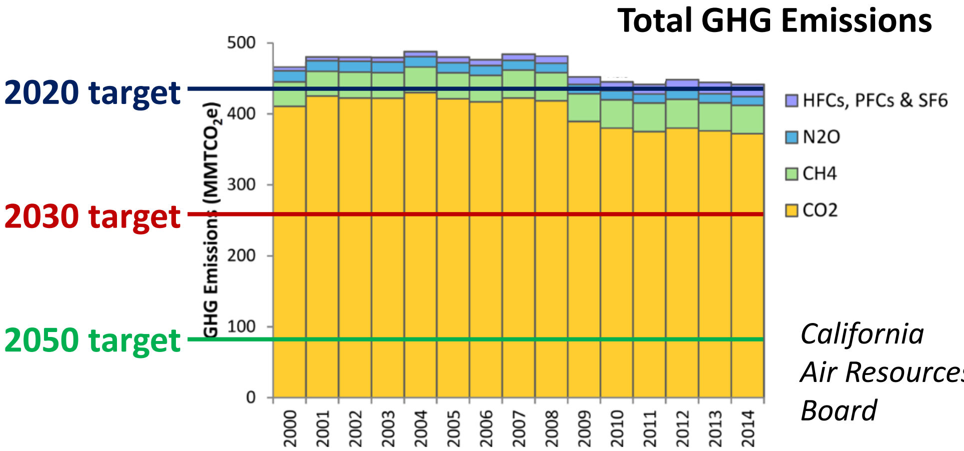
# California's ff$CO_2$ emissions

Fossil fuel $CO_2$ emissions are ~100 MtC/yr

California law requires progressive GHG emissions reductions by 2020, 2030 and 2050

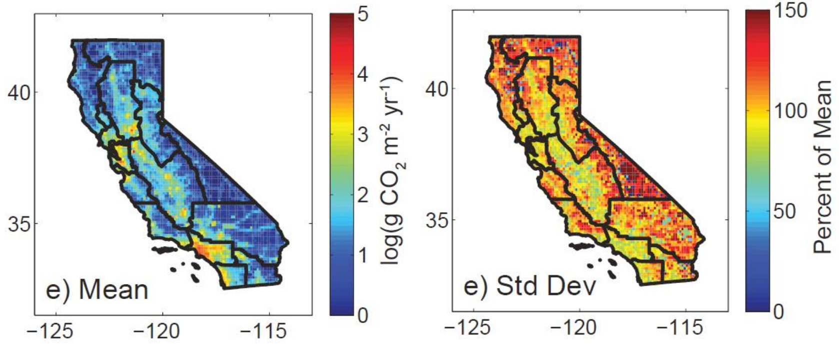
State total fossil fuel emissions varies by ±11% across four different fossil fuel emissions inventory maps (Vulcan 2002, EDGAR 2008, FFDAS 2008, ODIAC 2008)

Largest discrepancies in fossil fuel emissions in San Joaquin Valley and San Francisco Bay




*California Air Resources Board*

Fossil fuel emissions from four inventories




| | CA Total | South Coast | SF Bay | SJ Valley | Sac Valley | San Diego |
|---|---|---|---|---|---|---|
| Standard deviation | 11 % | 10 % | 23 % | 36 % | 8 % | 4 % |

*Fischer et al. 2017*

# Fossil fuels have no radiocarbon, so observations of $^{14}C/C$ ($\Delta$) in $CO_2$ can distinguish fossil fuel-derived $CO_2$


$$CO_2m = CO_2bg + ffCO_2 + bioCO_2$$

$$ffCO_2 = CO_2m\frac{\Delta_{bg} - \Delta_m}{\Delta_{bg} + 1000‰} + \beta$$

# Flasks collected at relatively high resolution in different seasons for $ffCO_2$ estimation using $\Delta^{14}CO_2$

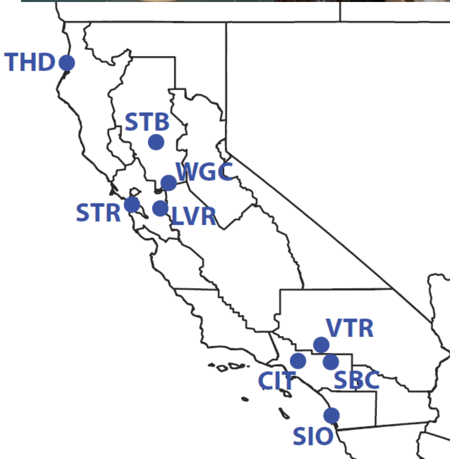


## Observations

- 3 Campaigns: May 2014, Oct-Nov 2014, Jan-Feb 2015
- Flasks sampled approx. every 3 days at 14:30 PST
- 9 tower sites (CARB, CIT, EN, LBNL, NOAA, SIO, SNL)
- Flask $CO_2$ and CO concentration and $\delta^{13}CO_2$ analysis at SIO
- $\Delta^{14}CO_2$ analysis at LLNL, uncertainty of ±2.5 to ±3.2 ‰

## $ffCO_2$ calculation

- Background $\Delta^{14}CO_2$ from highest 25% of coastal data (21.8, 22.2 and 17.8 ‰)
- Respiration correction of 0 to 1.1 ppm, using respiration fluxes from CASA and WRF-STILT modelling, estimated $\Delta^{14}C$ of 70±35 ‰ in respiration
- $ffCO_2$ uncertainty of ±1.0 to ±1.9 ppm, mainly determined by measurement uncertainty



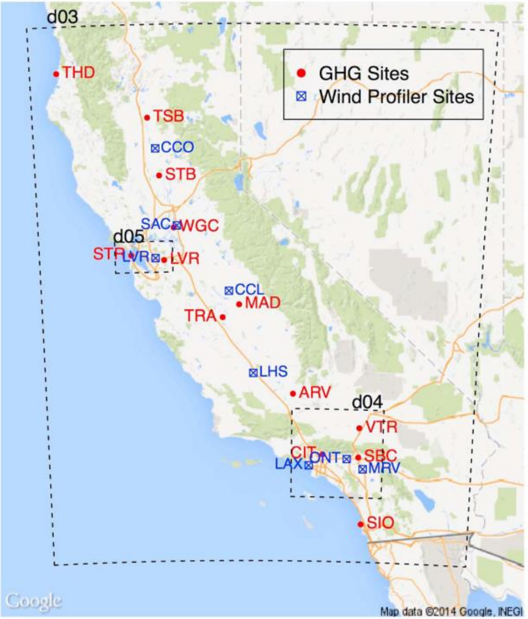
# Regional modelling and inversion system for $CO_2$ in California builds on prior work with $CH_4$ and $N_2O$

## Transport Modelling

- WRF-STILT with nested domains, 4 km resolution across California, 1 km in urban regions
- Transport evaluated with wind profiler data, CO modelling

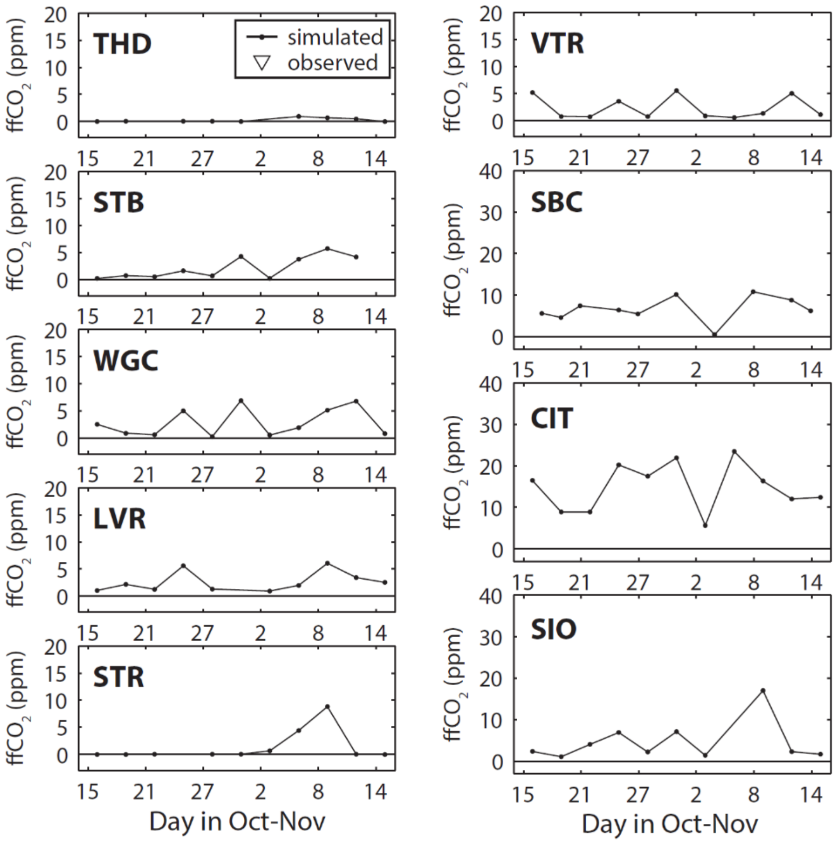
## Flux Inversion

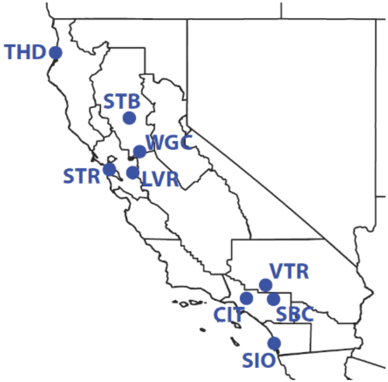
- Optimization of regional scaling factors by Bayesian inversion
- Prior $ffCO_2$ emissions from time-varying Vulcan for 2002 in US and EDGAR v4.2FT for 2008 outside US
- Prior uncertainty in each region from inventory comparison, model-data uncertainty of ±50% and measurement uncertainty of ±1.0 to ±1.9 ppm
- Tests varying prior flux, uncertainty, inversion type, outliers



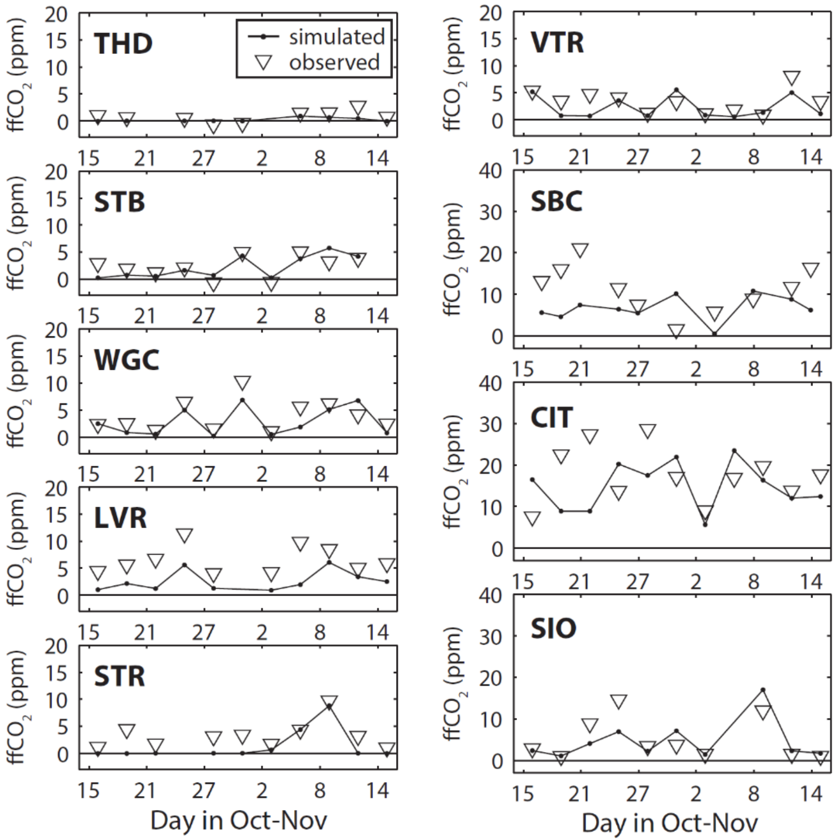

Fischer et al. 2017,
Jeong et al. 2013, 2016,
Bagley et al. 2017

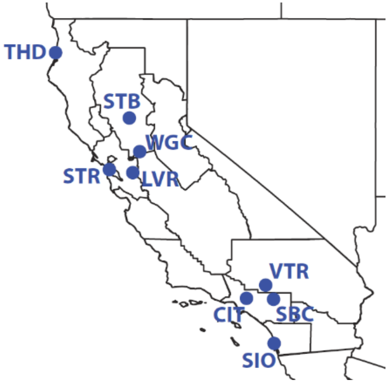
# Model simulations show highest $ffCO_2$ at Southern sites with 5-10 ppm day-to-day variability across California



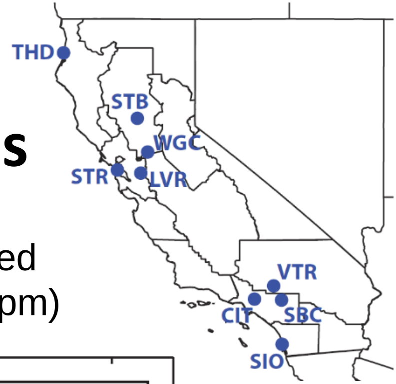



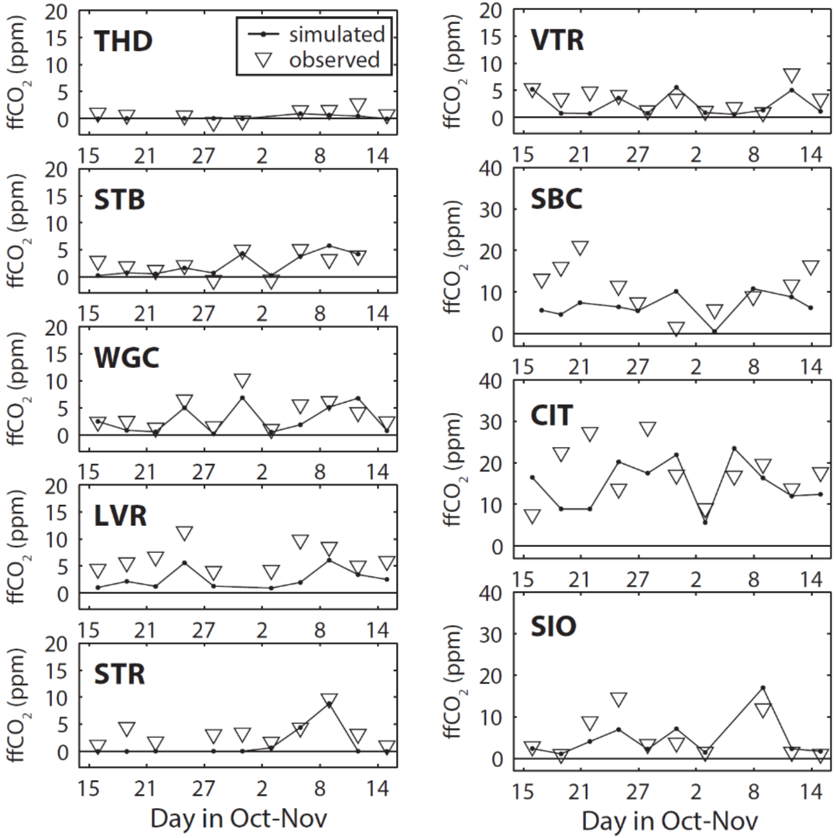
# Observed mean $ffCO_2$ and temporal variability is largely consistent with the model



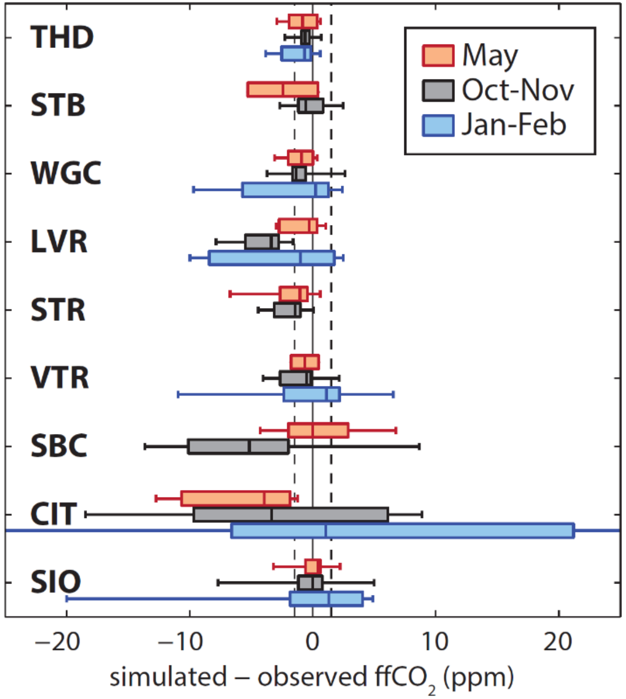



# Most observations (66%) were matched within 2-σ ±3.0 ppm measurement uncertainty in the simulations




Simulated – Observed Difference in $ffCO_2$ (ppm)



# Inverse estimates of $ffCO_2$ emissions are consistent with Vulcan and California Air Resources Board inventories

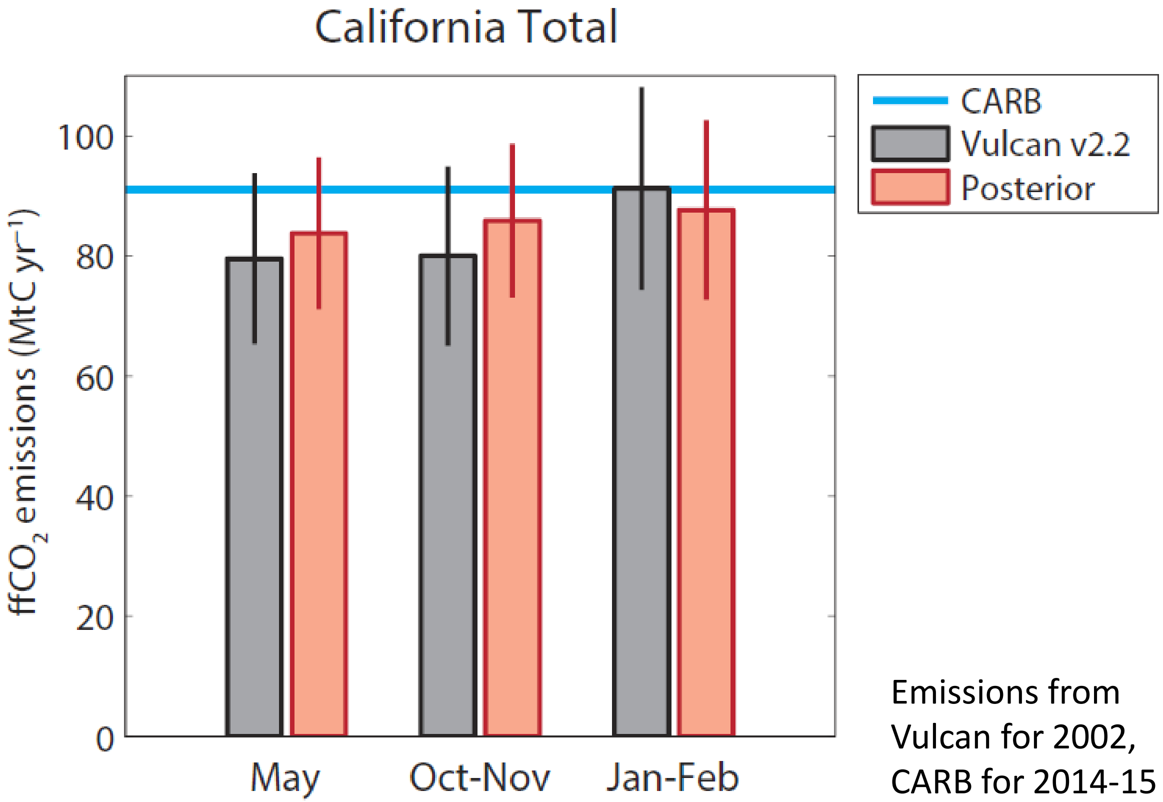
**Emissions of 84-88 MtC/yr are estimated using observations**

**Slightly greater than Vulcan inventory except in Jan-Feb**

**Error bars show 95% confidence bounds, ±12 to ±15 MtC/yr**

**196 observations used**
**18 outliers removed**

**In-state emissions excluding aircraft and shipping emissions**




Emissions from Vulcan for 2002, CARB for 2014-15

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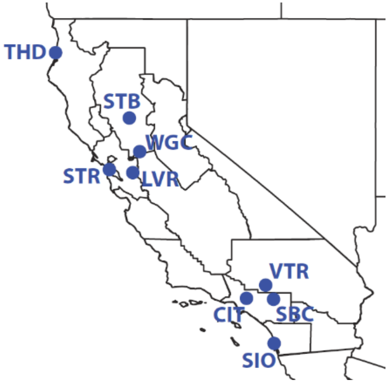
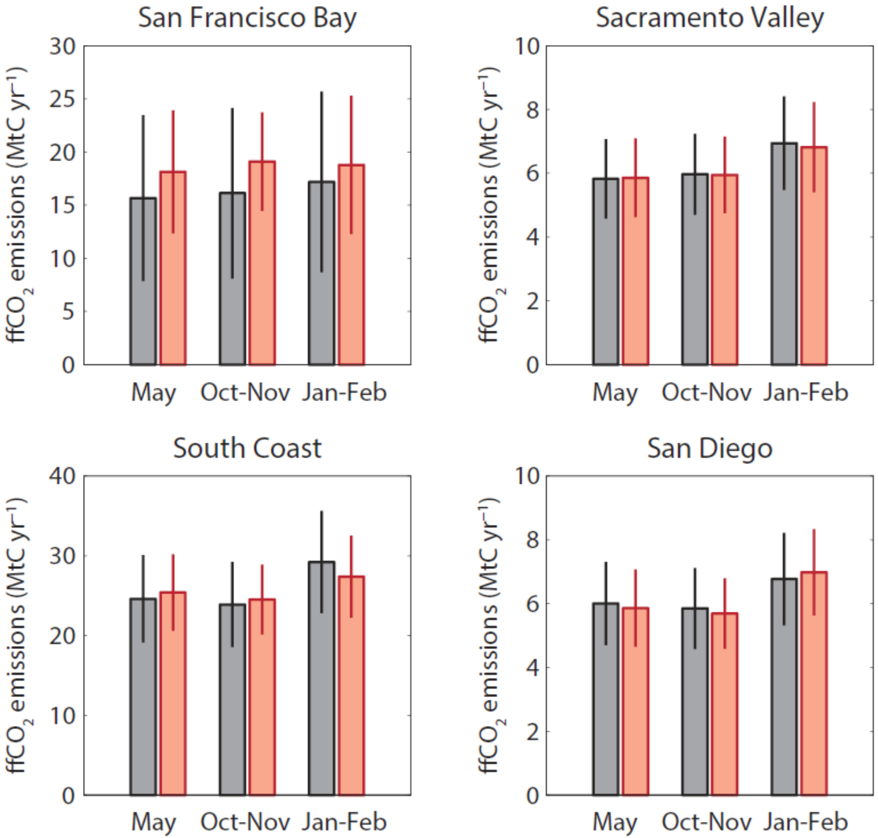
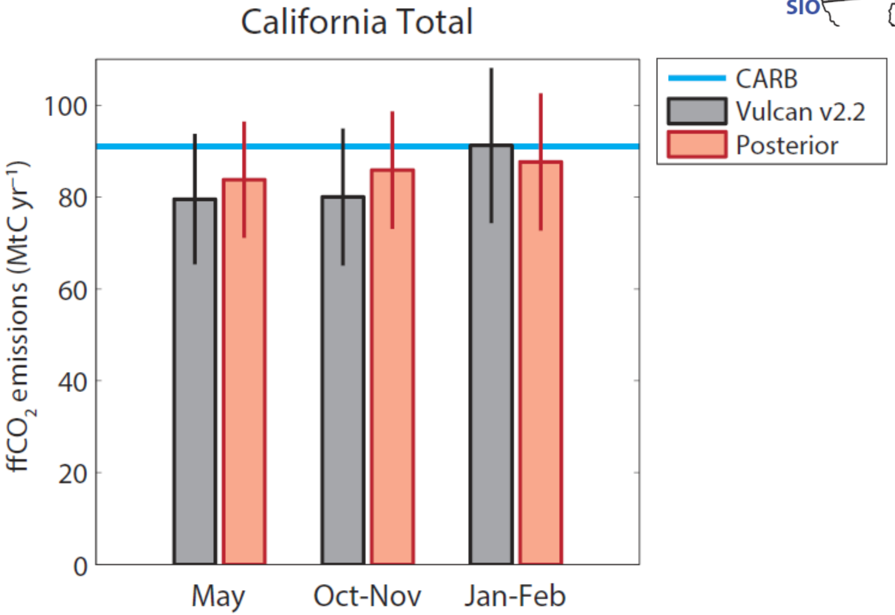
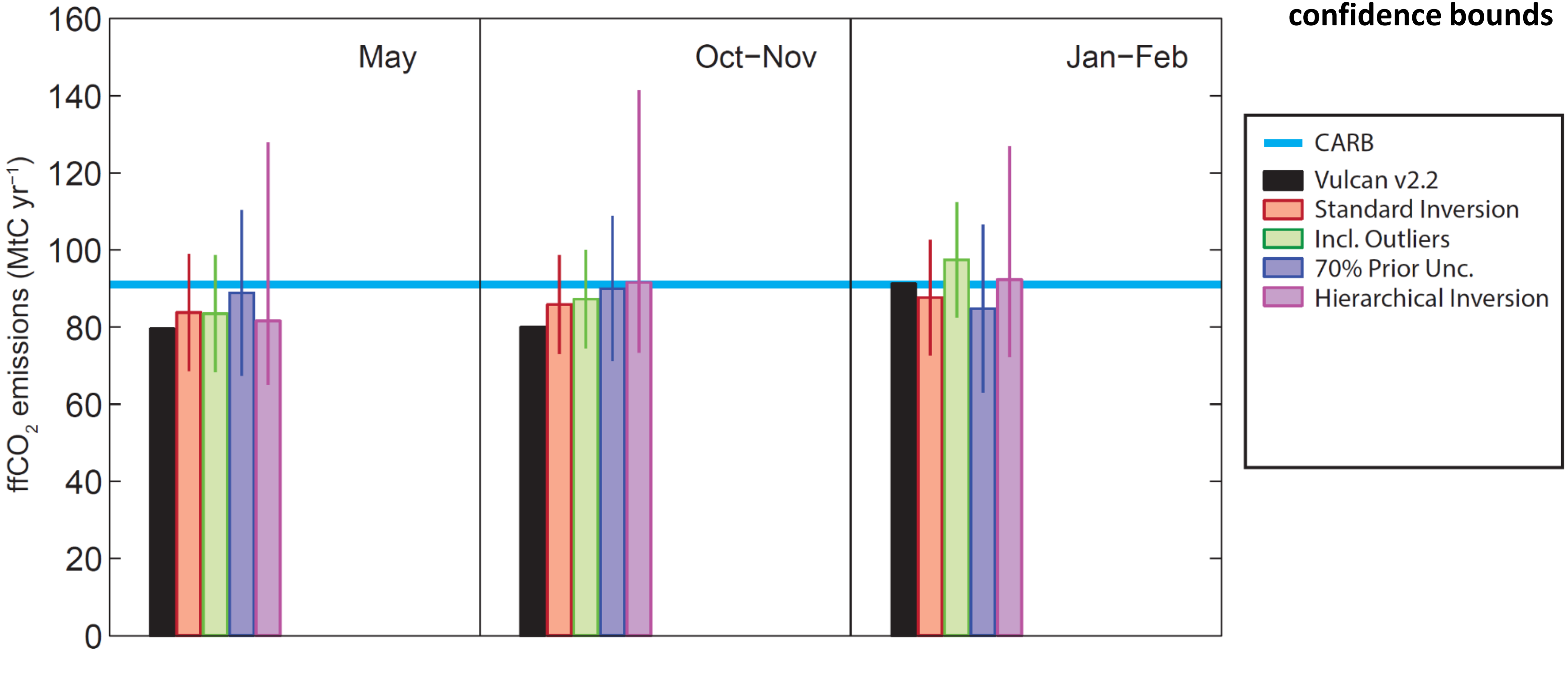


# Inverse estimates do not change significantly in sensitivity tests

**Error bars show 95% confidence bounds**



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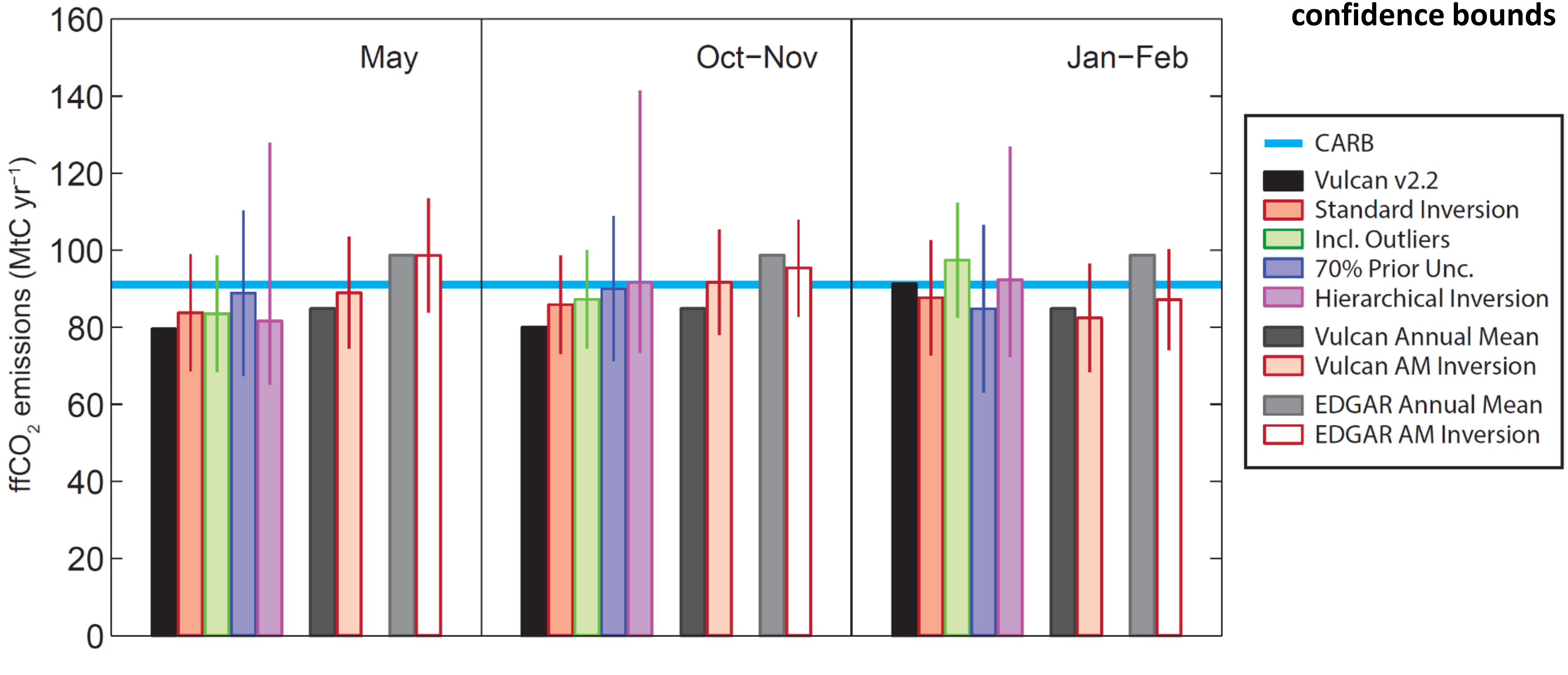
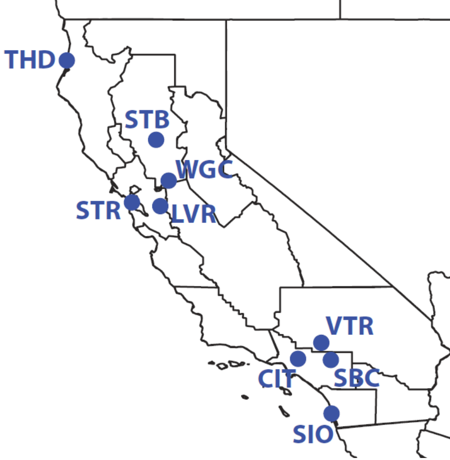
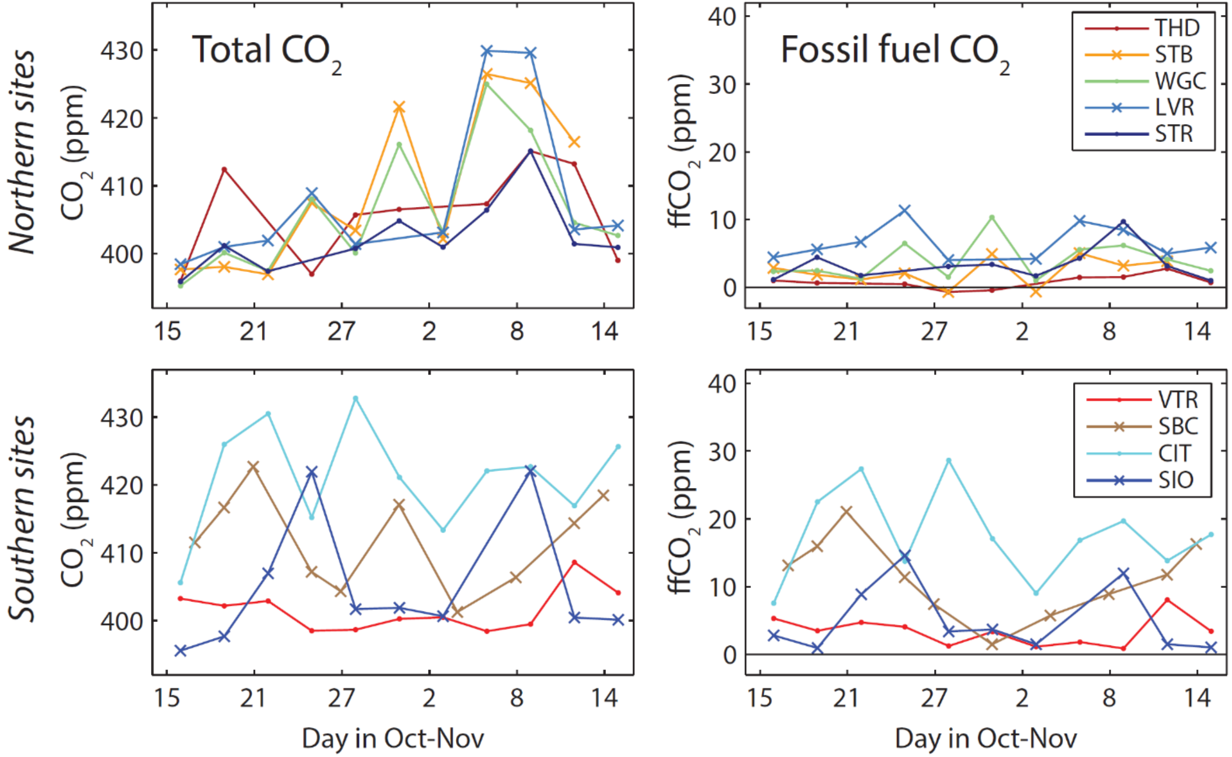


# Only part of the $CO_2$ variability is caused by $ffCO_2$, showing respiration was also a strong source of $CO_2$




**bio$CO_2$ can make a substantial contribution to excess $CO_2$, even in urban areas (e.g. Pataki et al. 2007, Graven et al. 2009, Miller, LA Megacities)**

**Data from Oct-Nov 2014 campaign**

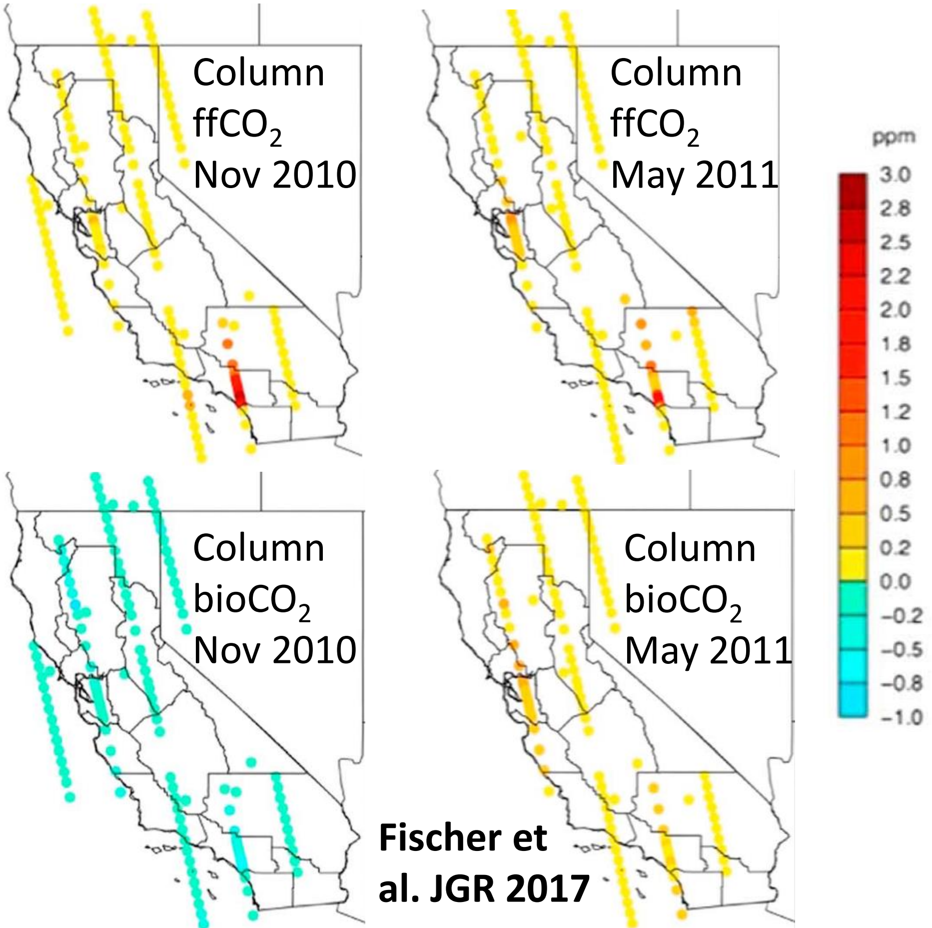
# California $CO_2$ inversion OSSEs incorporating tower and OCO-2 pseudo data

Synthetic inversions for regional $ffCO_2$ and $bioCO_2$ pseudo data with WRF-STILT

Including XCO2 has relatively little impact on $ffCO_2$ flux estimate but improves $bioCO_2$ flux estimate

Effects of simulated biases in XCO2 data are reduced when both tower and XCO2 included in inversion

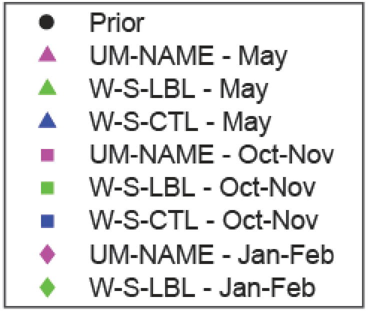
OSSEs provide (optimistic) estimate of posterior uncertainty achievable: for state-total $ffCO_2$ emissions about ±16% in real inversion vs about ±10% in OSSE




Fischer et al. JGR 2017

# California $ffCO_2$ inversion OSSEs to explore uncertainties, incorporating tower sites only

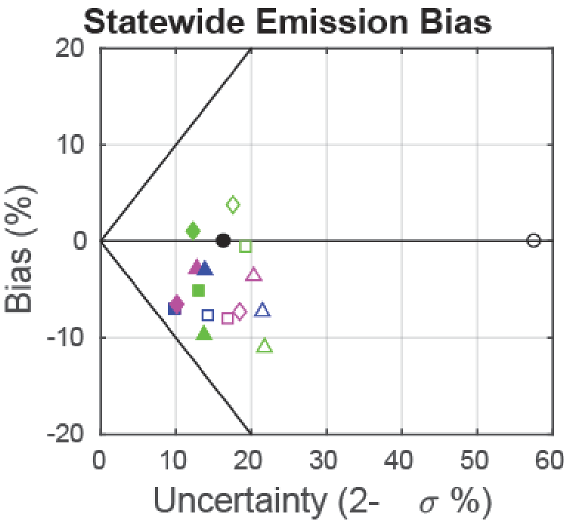
*Brophy et al. in prep*




## Spatial Representation

**Truth: Vulcan, annual mean**

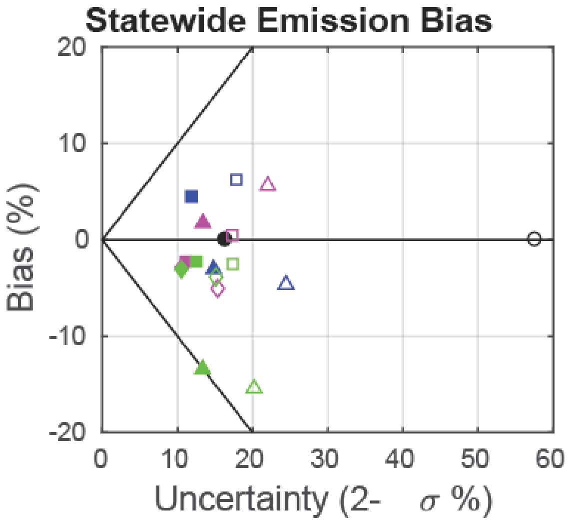
**Prior: EDGAR, regional scaling**




## Temporal Representation

**Truth: Vulcan, annual mean**

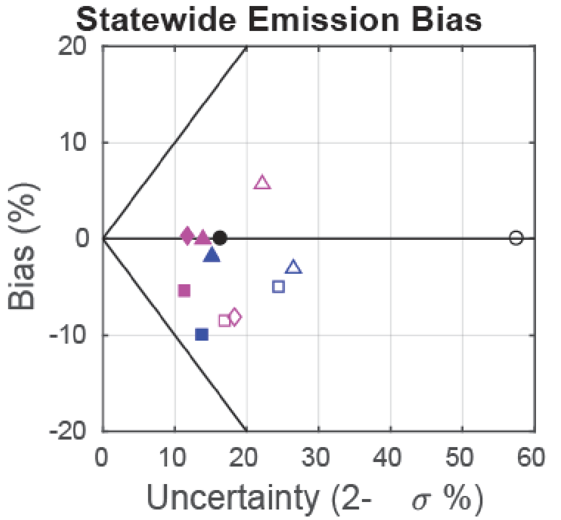
**Prior: Vulcan, time-varying**




## Transport

**Truth: EDGAR, W-S-LBL**

**Prior: EDGAR, other model**



# Needs for $ffCO_2$ inversions and CHE, a few thoughts

- Nuclear power plant $^{14}C$ emissions data/estimates with high temporal resolution and good accuracy
- Estimated $CO_2$ emissions from fossil/non-fossil, different fuel types, different sectors, and simulations as separate tracers
- Estimated biospheric fluxes (esp. NBP and Rh) with high spatial and temporal resolution
- Simulations using several atmospheric models and emission models
- Tests of inversions, uncertainty contributions, and emissions change detection with OSSEs
- More polluted observation sites

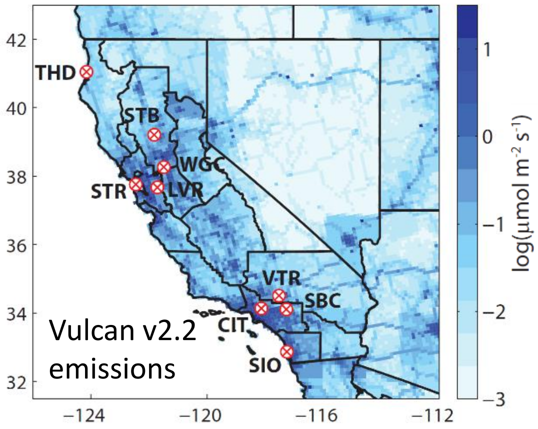
# Summary:

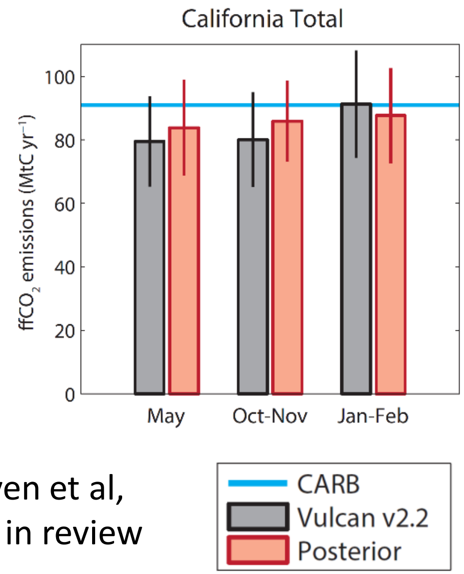
Observations provide tentative independent validation of $ffCO_2$ emission inventories in California

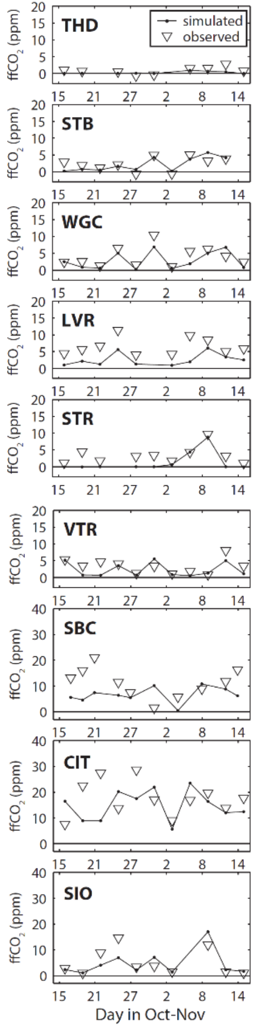
Inverse estimates are 84 to 88 MtC/yr, with 95% confidence of ±15 to ±17 %

Long-term observations could potentially validate target reductions by 2030 in California (40% for all GHGs)

More observational coverage and method development could improve observation-based emissions estimates




Graven et al, ERL, in review

# Previous evaluation of California ff$CO_2$ emissions using atmospheric measurements

- 6 aircraft flights in LA South Coast area in May-June 2010 (Brioude et al. 2013), $CO_2$:CO flux ratio inversion method
  Posterior estimate 15-44% higher than Vulcan annual mean

- 2 aircraft flights in Sacramento area in Feb-Mar 2009 (Turnbull et al. 2011)
  Mass balance method, $\Delta^{14}CO_2$ and CO-based estimates of ff$CO_2$
  Posterior estimate 20% higher than Vulcan annual mean, with ~100% uncertainty

Ongoing work in California by various groups, including $\Delta^{14}CO_2$ measurements at a few sites

# Observational networks for $^{14}C$ in $CO_2$

- $^{14}C$ in $CO_2$ has been measured by global networks
- Recent expansion to urban / polluted sites
- Some sites are discontinued
- More sustained and coordinated observations needed