Atmospheric Measurement and Inverse Modeling to Improve GHG Emission Estimates (ARB 11-306)

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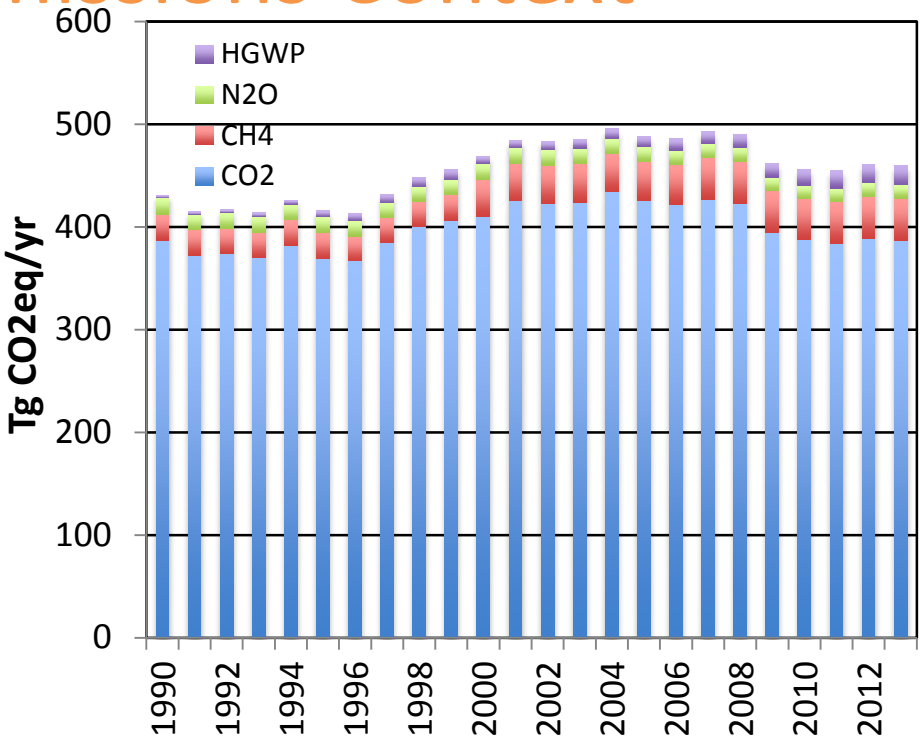
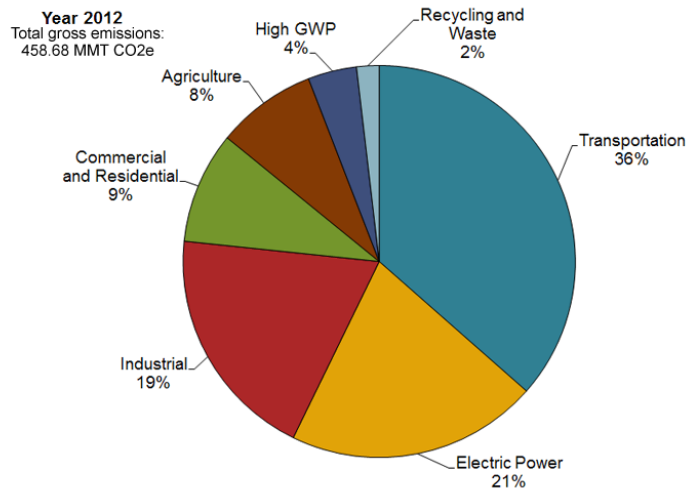
Outline

- Introduction to California GHG emissions
- Approach
  - Collaborative Measurement Network
  - Regional Inverse Modeling Framework
- Results
  - GHG Measurements
  - Atmospheric Transport Evaluation
  - Methane Emissions
  - Nitrous Oxide Emissions
  - Fossil Fuel Carbon Dioxide Emissions
- Summary
- Recommendations

California GHG Emissions Context

- California leading the US and world in responsible action limiting climate change
- "Climate Solutions Act" (AB-32) and Governor's Executive Orders call for matching and reducing (40% to 80%) emissions from 1990 by 2020, 2030, and 2050
- Fossil fuel CO_2 currently dominates (80-90%) total emissions
- Non-CO_2 GHG emissions uncertain and may offer short-term opportunities for mitigation
- Regional, urban, and facility-scale measurements support inventory and mitigation evaluation efforts

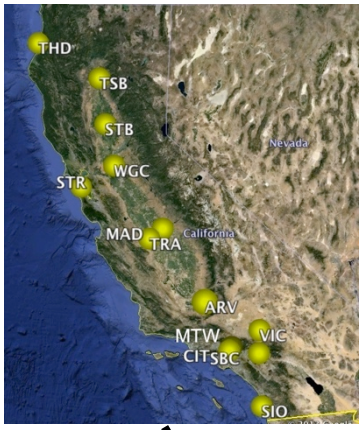


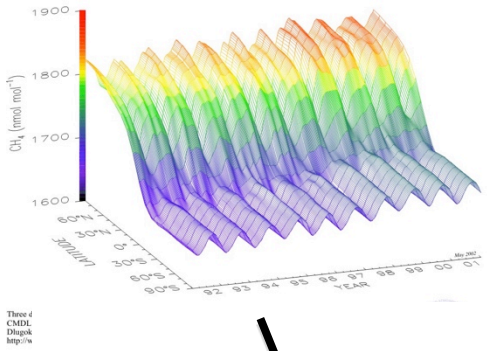


http://www.arb.ca.gov/cc/inventory/background/ghg.htm

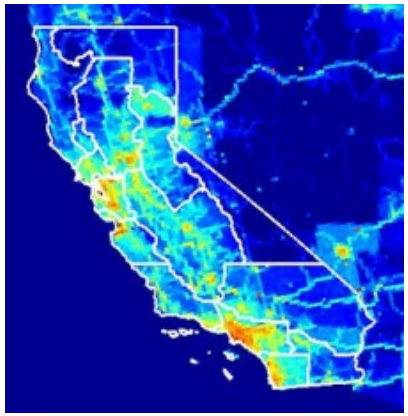
Regional Inverse Emission Estimates

California GHG and GHG Background Inflow





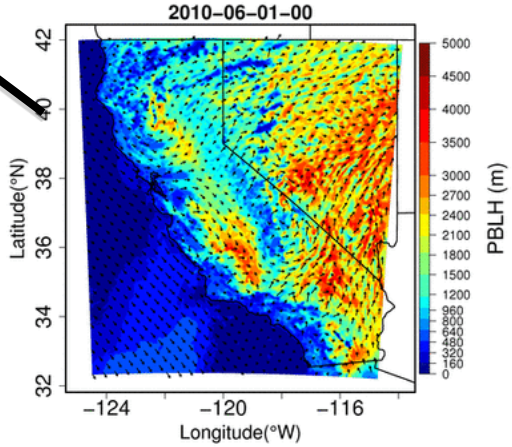
Prior Emission Model



Measured Signals and uncertainties

Predicted Signals and uncertainties

Atmospheric Transport

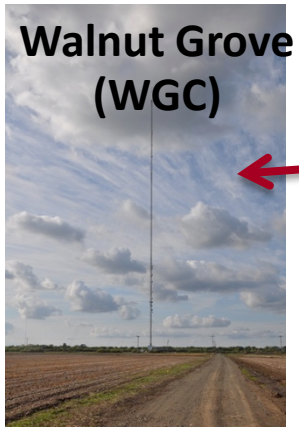


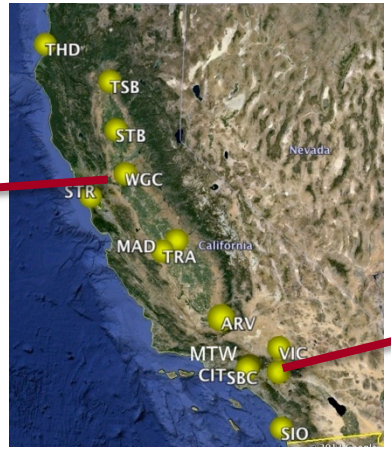
Statistical Estimator of Emissions (e.g., Bayesian)

Improved Emission Estimate

CALGEM GHG Measurements

- Multi-site deployments across California capture rural and urban emissions
- Comprehensive design provides control and calibration all major GHG species (CO_2,CH_4, CO, and N_2O)
- Flask sampling provides full GHG suite + tracers for source identification (e.g., $^{14}CO_2$, VOC, etc.)





San Bernardino
(SBC)

Gas Processing Racks

Calibration Gases

Flask Sampler

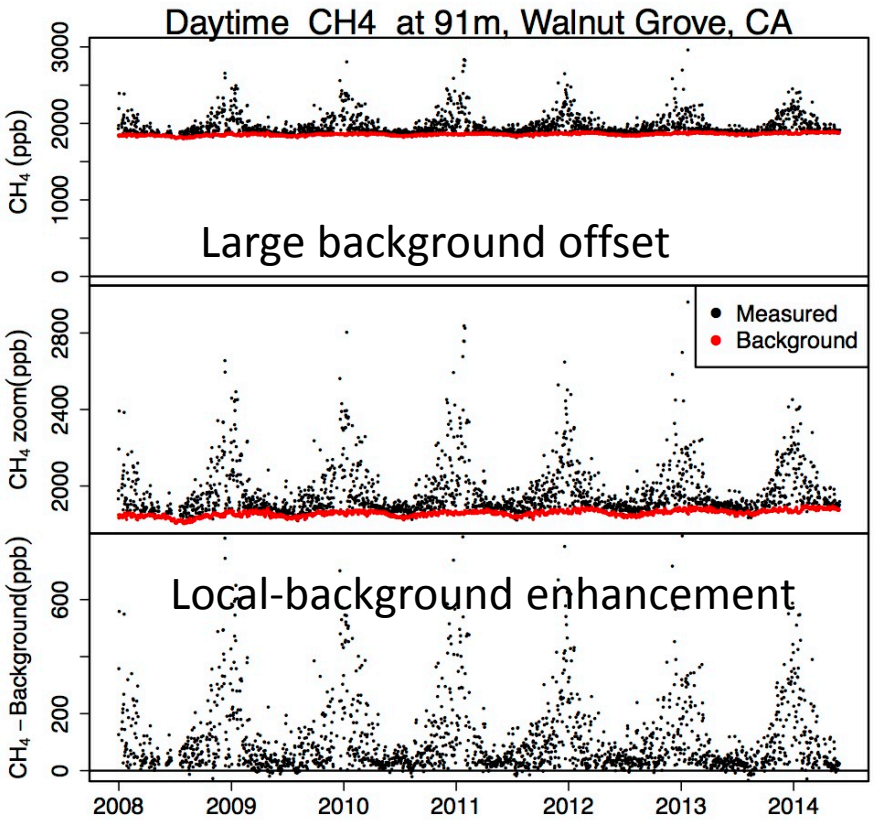
Spectrometers:
CO_2/CH_4
N_2O/CO

Flask Sampler

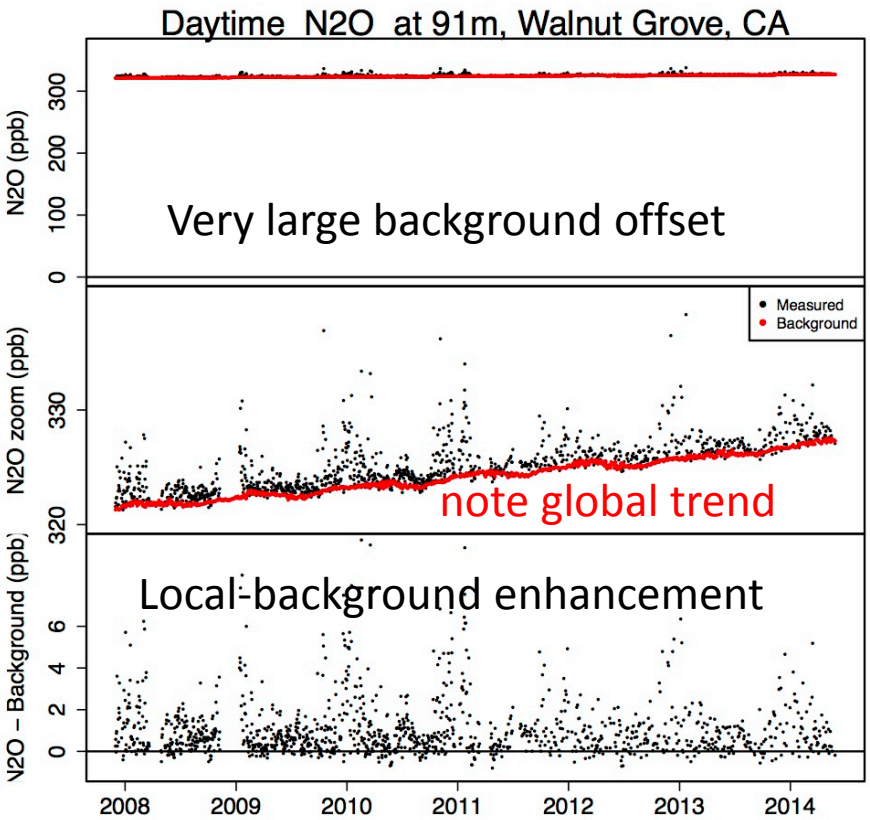
Estimating Local Signals

- Global GHG background inflow dominates local measurement
- California emissions estimated from local-background enhancement
- Accurate local & background GHG measurements essential

Methane

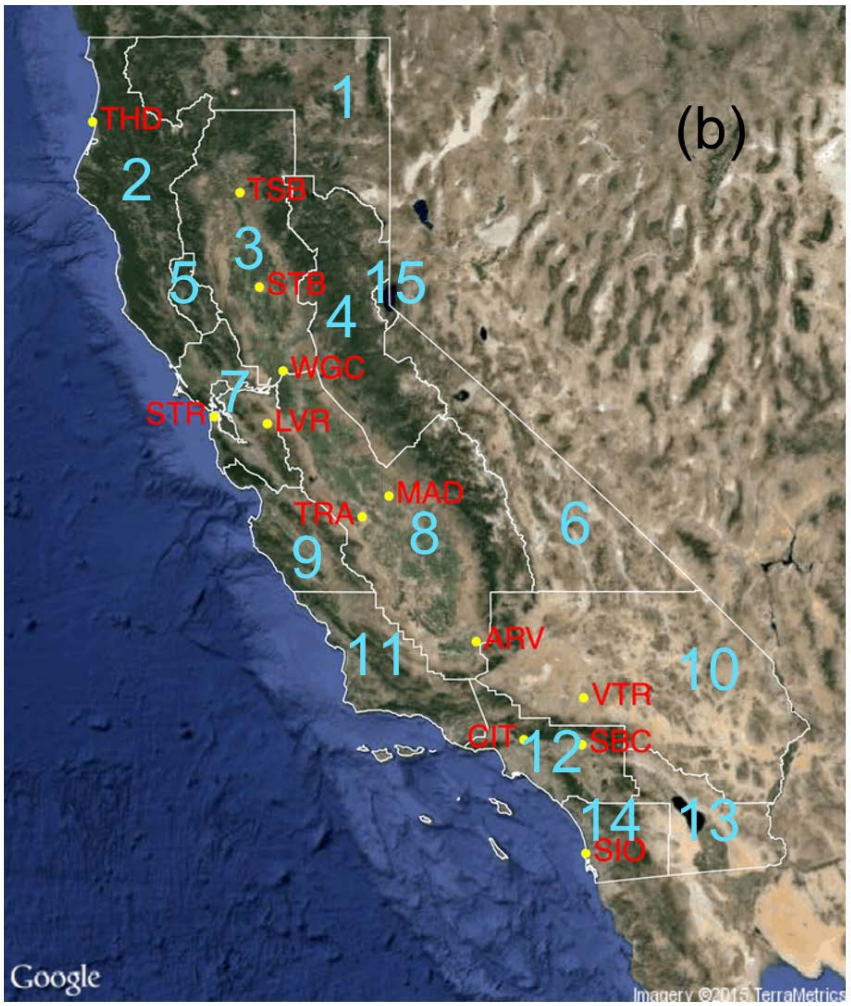


Nitrous Oxide



California GHG Measurement Network

Measurement Sites with CA Air Basins



- Collaborative GHG measurement sites
  - 6 CARB anchor sites (CO_2, CH_4, CO, N_2O)
  - CH_4 measurements at 13 sites
  - N_2O at 6 sites (STB, WGC, STR, ARV, CIT, SBC)
  - Fossil fuel CO_2 at 3 sites (WGC, CIT, SBC)

Development of Hierarchical Bayesian Inversion Method

- Develop a hierarchical Bayesian inversion (HBI) method to estimate emissions (CH_4 and N_2O for 0.3° pixels)

Posterior Probability in Hierarchy *(Jeong et al. [2016], in press)*

$$\underbrace{p(\boldsymbol{\lambda}, \boldsymbol{\mu}_\lambda, \boldsymbol{\sigma}_\lambda, \boldsymbol{\sigma}_R, \eta, \tau | \boldsymbol{y})}_{\text{Posterior probability: most probable emissions}} \propto \underbrace{p(\boldsymbol{y} | \boldsymbol{\lambda}, \boldsymbol{\sigma}_R, \eta, \tau)}_{\text{Likelihood: atmospheric data}} \underbrace{p(\boldsymbol{\lambda} | \boldsymbol{\mu}_\lambda, \boldsymbol{\sigma}_\lambda) p(\boldsymbol{\mu}_\lambda) p(\boldsymbol{\sigma}_\lambda) p(\boldsymbol{\sigma}_R) p(\eta) p(\tau)}_{\text{Prior probability in hierarchy: } a\ priori \text{ knowledge (e.g., GHG inventory)}}$$

Parameters to Be Solved

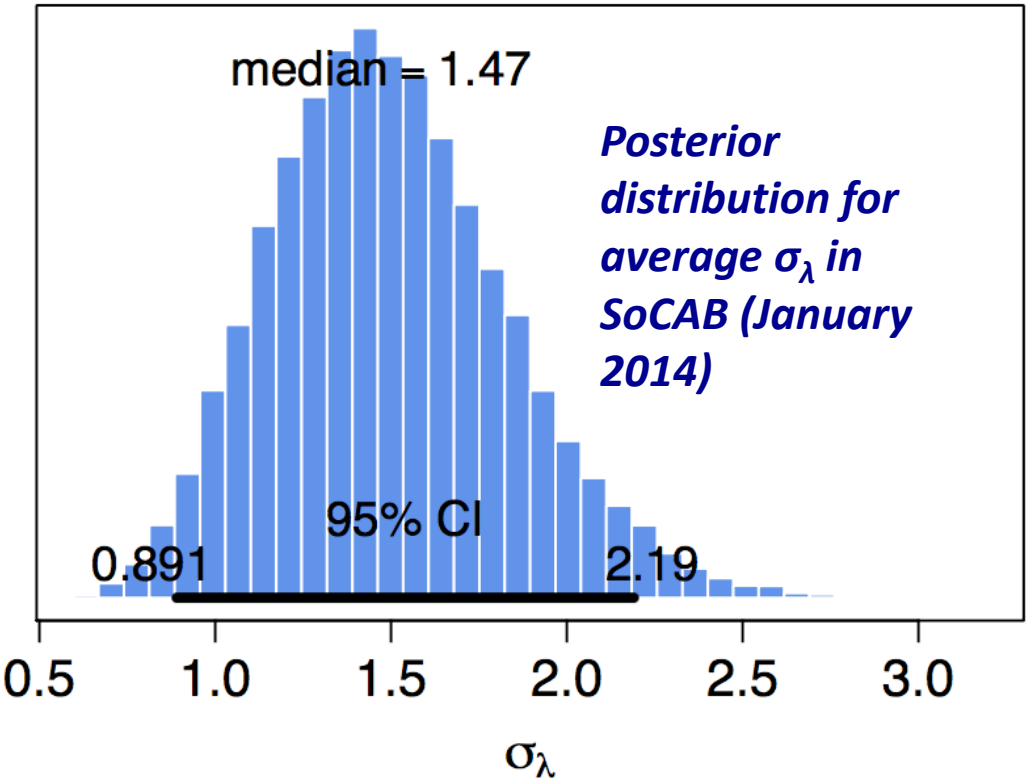
$$\boldsymbol{\Theta} = \{\boldsymbol{\lambda}, \boldsymbol{\mu}_\lambda, \boldsymbol{\sigma}_\lambda, \boldsymbol{\sigma}_R, \eta, \tau\}$$

In HBI, these parameters are optimized as opposed to using fixed values ***(e.g., Jeong et al. [2013]).***

λ: scaling factor for emissions
y: measurements - p(**y**|**λ**,**R**)~*N*(**Kλ**,**R**) where **K** is prediction and **R** is model-measurement covariance [Jeong et al., 2013]
$\boldsymbol{\mu}_\lambda$: prior mean for **λ**; $\boldsymbol{\sigma}_\lambda$: prior error for **λ**
$\boldsymbol{\sigma}_R$, η, τ: parameters for **R**

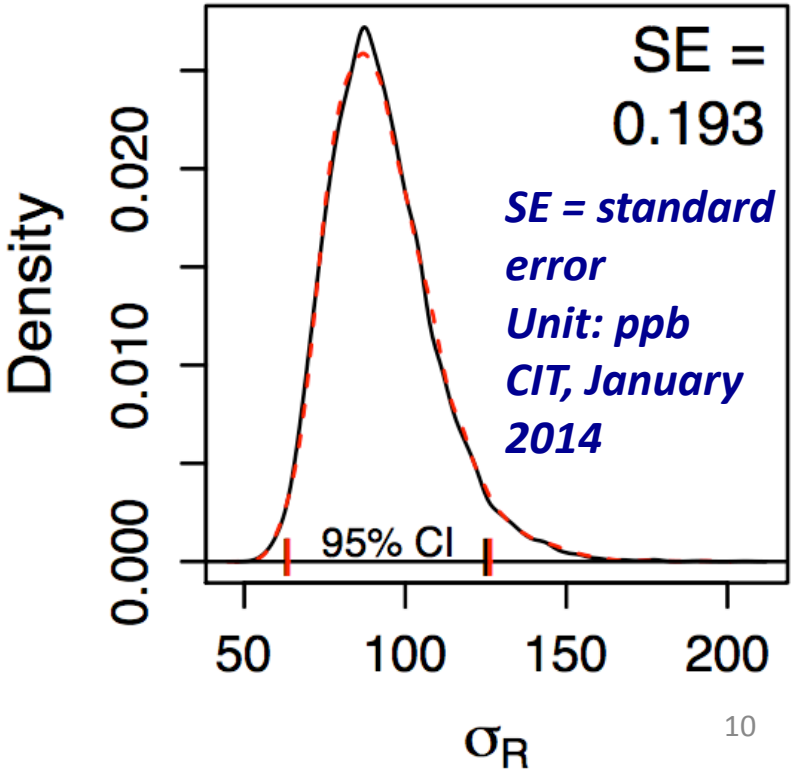
Parameter Estimation Example Using HBI

Examples of estimated region-averaged prior uncertainty for CH_4 (SoCAB) – prior uncertainty was fixed in previous work and is optimized in Jeong et al. [2016]



Estimated model-measurement uncertainty for CH_4 (in ppb) at CIT

In Jeong et al. [2016], model-measurement uncertainty is also optimized

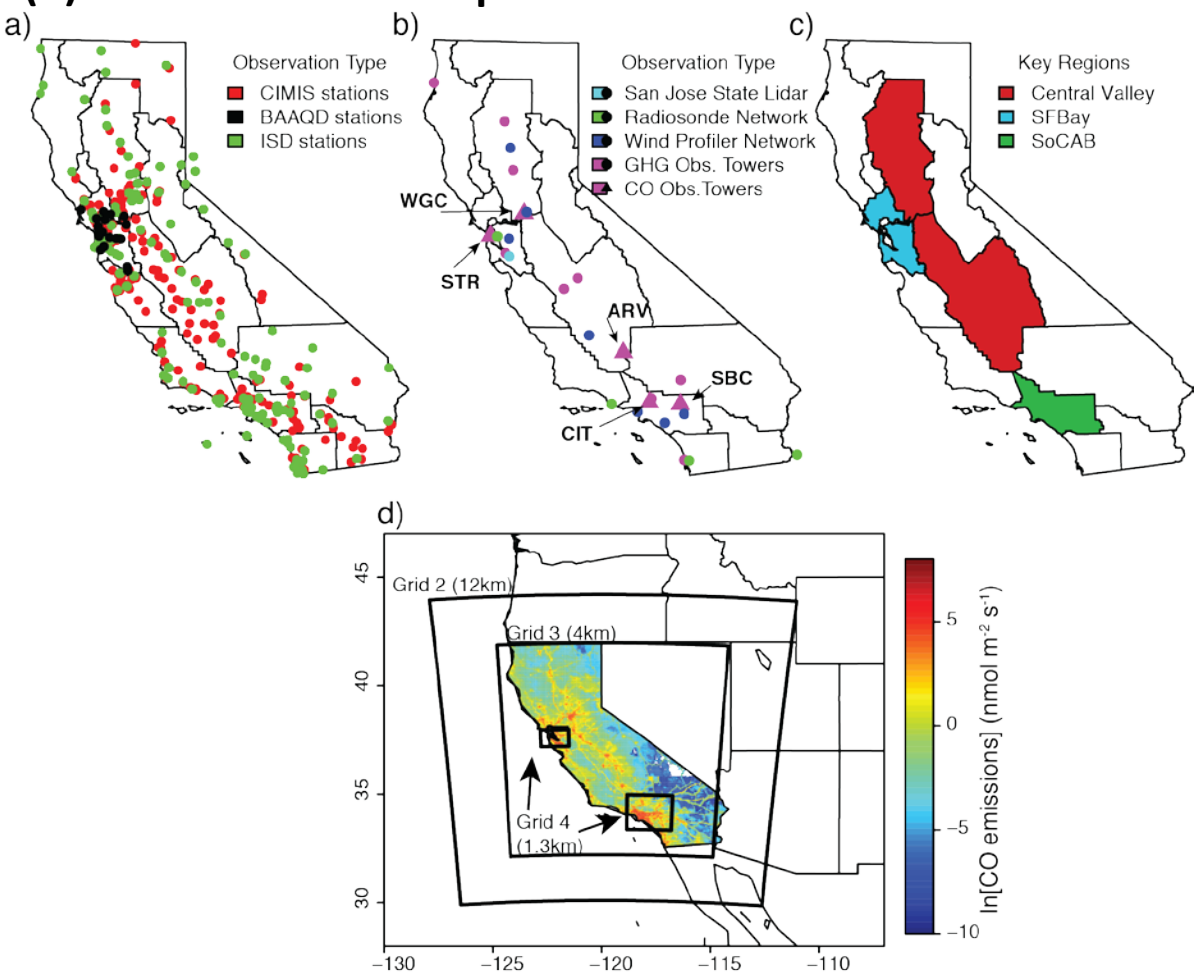


ATMOSPHERIC TRANSPORT

Evaluation Using Carbon Monoxide Measurements

Evaluation of Atmospheric Transport

(a) Locations of meteorological stations, (b) tower sites with radiosondes and wind profilers, (c) key regions, and (d) WRF domains with prior CO emissions from CARB

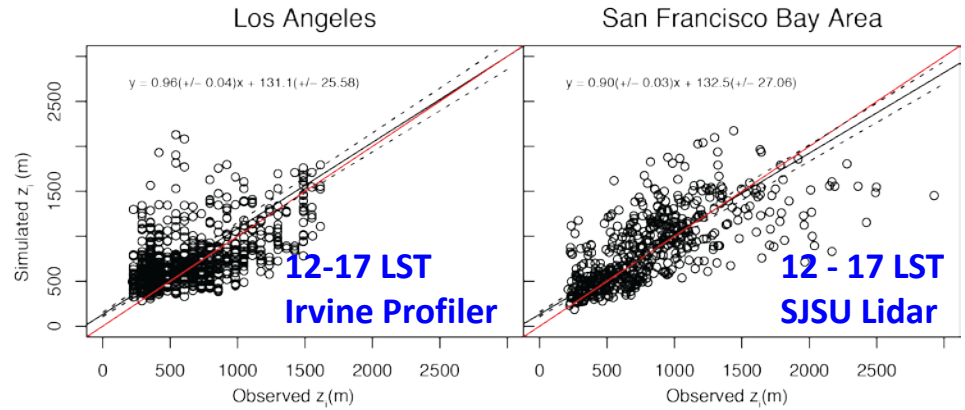


- Transport model (WRF-STILT) is assessed using a combination of meteorological and carbon monoxide (CO) measurements coupled with the gridded CARB CO emission inventory

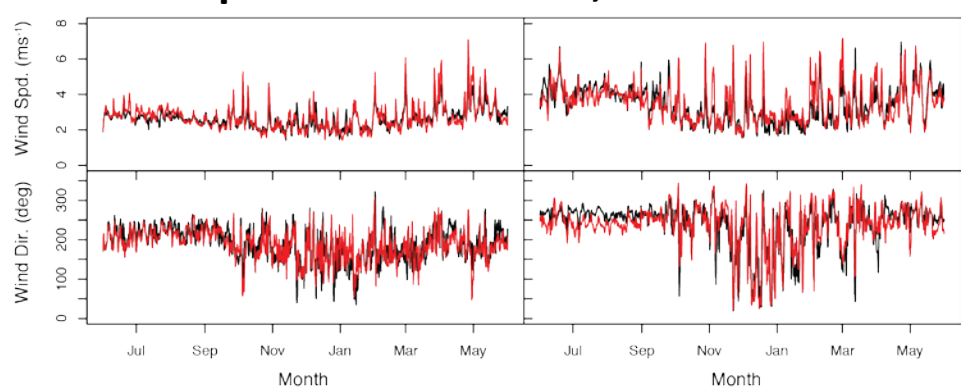
Evaluation of Key Transport Variables

- Numerous observations from surface, profiler, Lidar, and radiosonde stations across California were used
- WRF configurations were selected to minimize meteorological biases in winds and boundary layer
- The seasonal mean biases in wind speed (< ~ 0.5 m/s), direction (< ~ 15°), and boundary layer height (< ~ 200 m) were generally small

Simulated vs. observed boundary layer for LA and San Francisco Bay Area (2013 -2014)

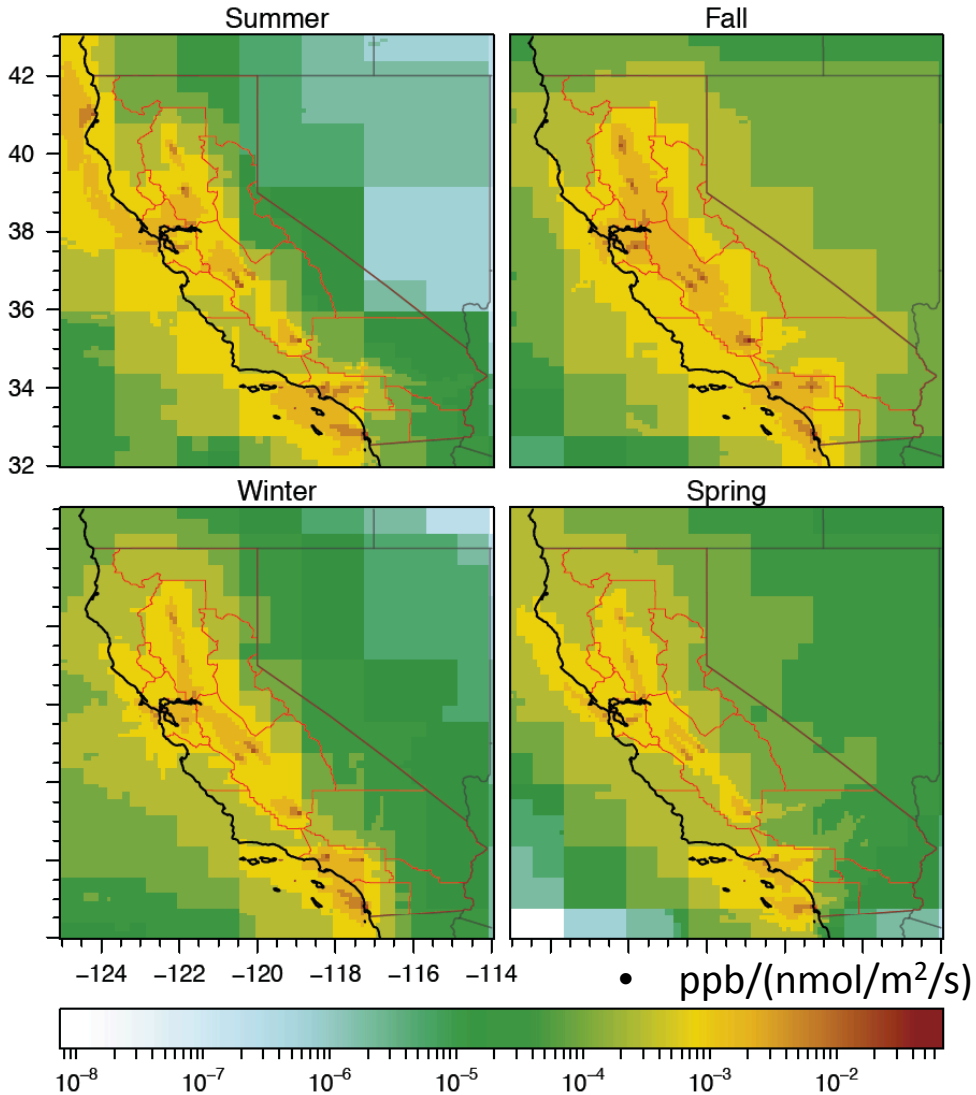


Simulated (red) and observed (black) surface wind speed and direction, CIT and STR



Data from surface stations within 50 km of CIT and STR used

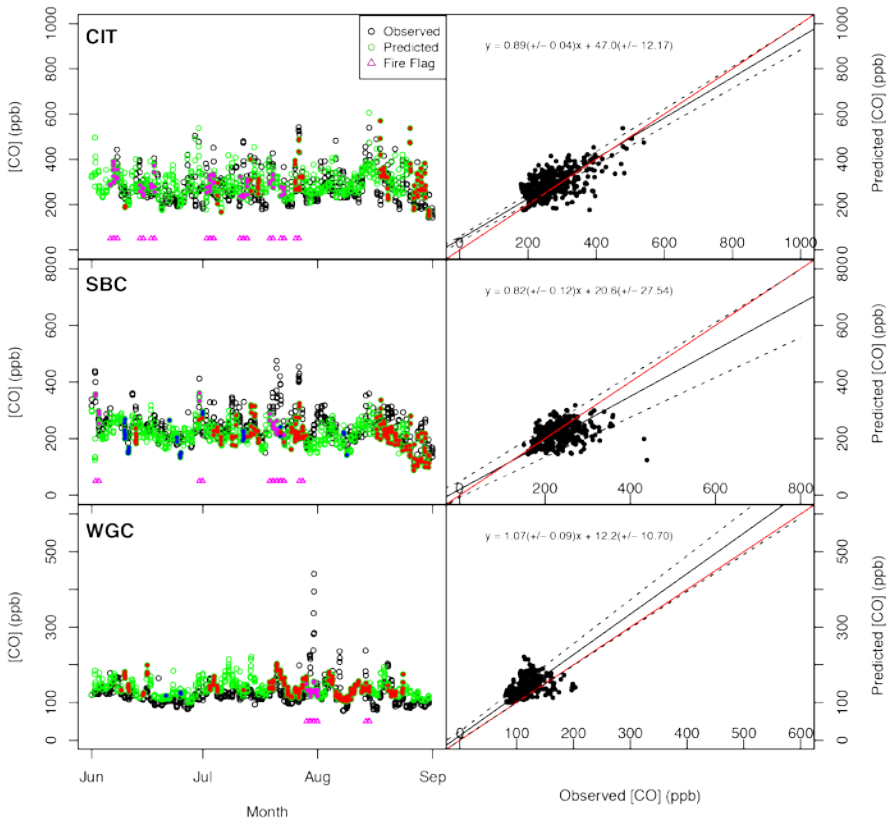
Footprint Simulations from Selected WRF-STILT Configuration (2013 – 2014)

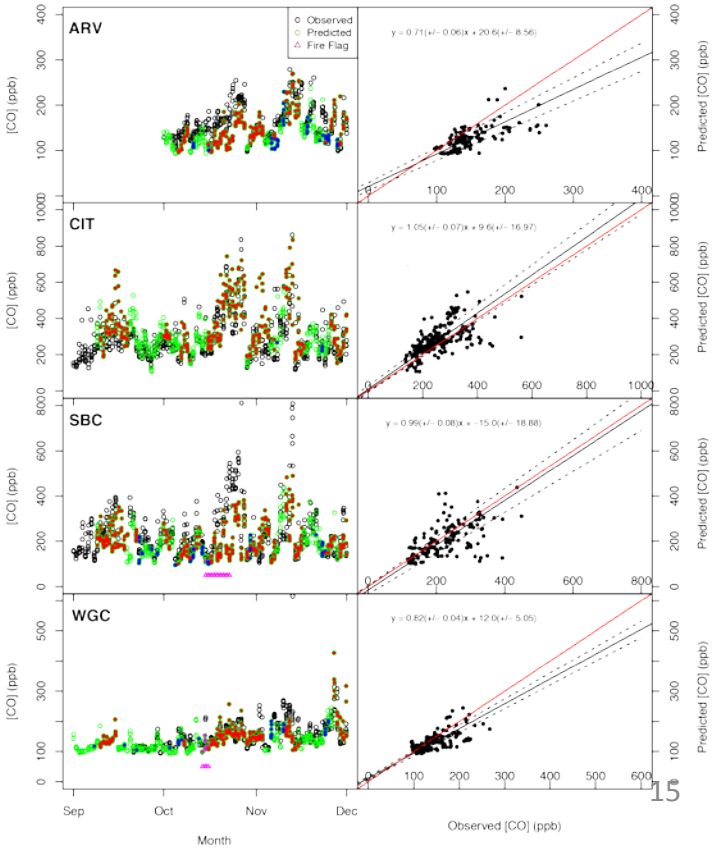


- Footprint represents the sensitivity of concentration to a unit emission change
  - Multiplication of footprint with emissions yields mixing ratio concentration
- The seasonal footprints shown represent the most complete sensitivity maps in California
  - Full annual cycle in time
  - 13 sites in space

Comparison of Predicted vs. Measured CO for Summer and Fall

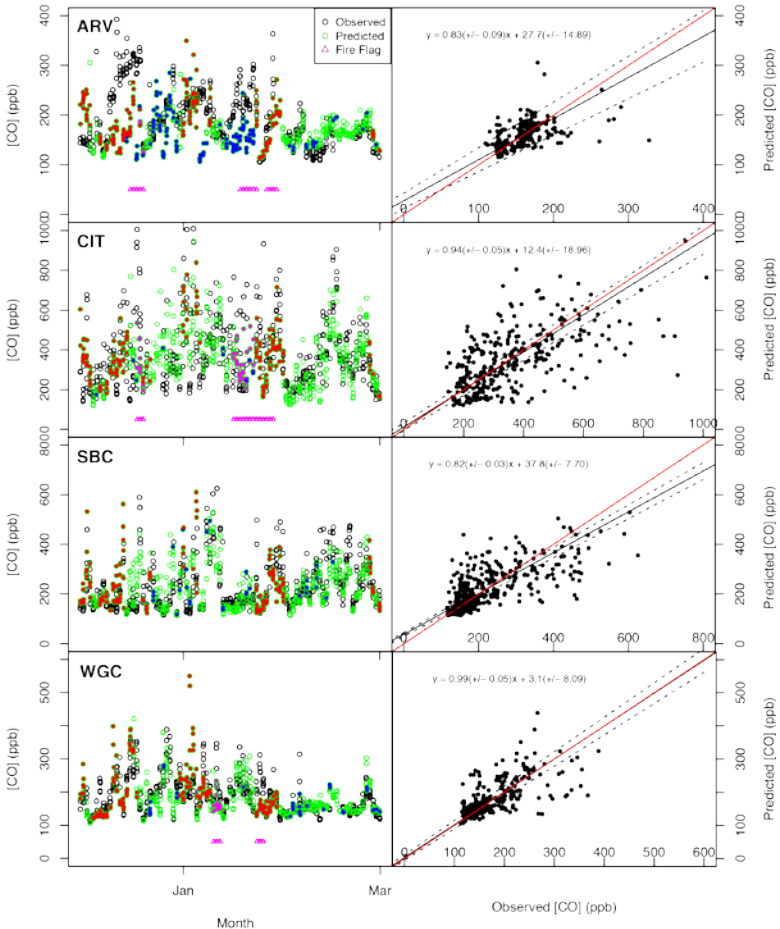
- Regression of predicted and measured CO yields near-unity slopes for the majority of sites and seasons (Bagley et al., in review)
- A subset of sites/seasons exhibit larger (~ 30%) uncertainty, when weak winds combined with complex terrain (e.g., South Central Valley)

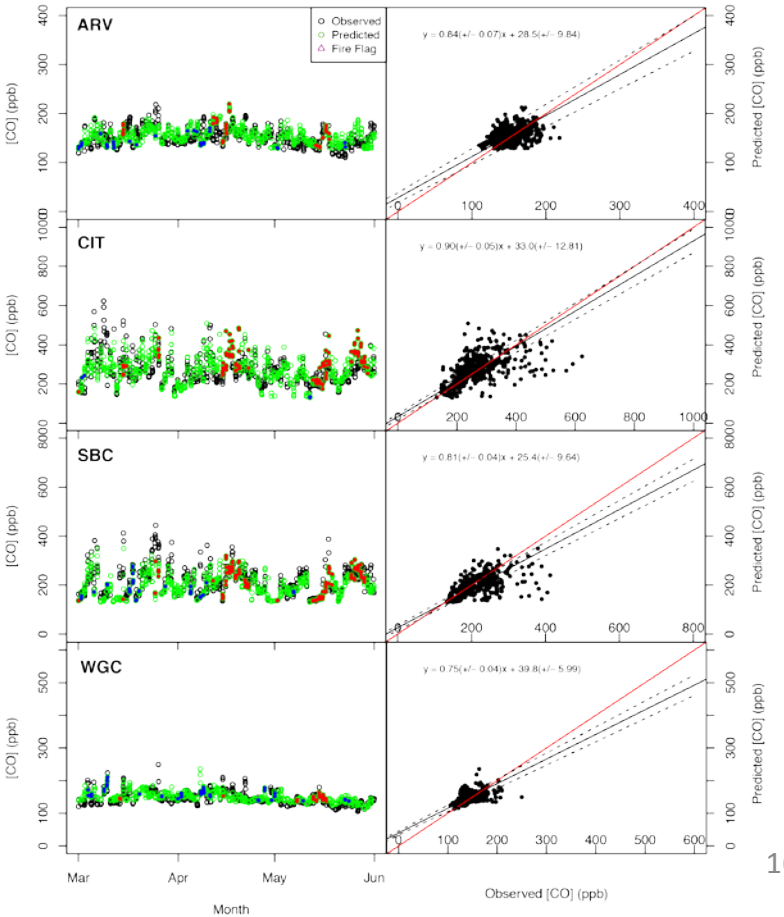




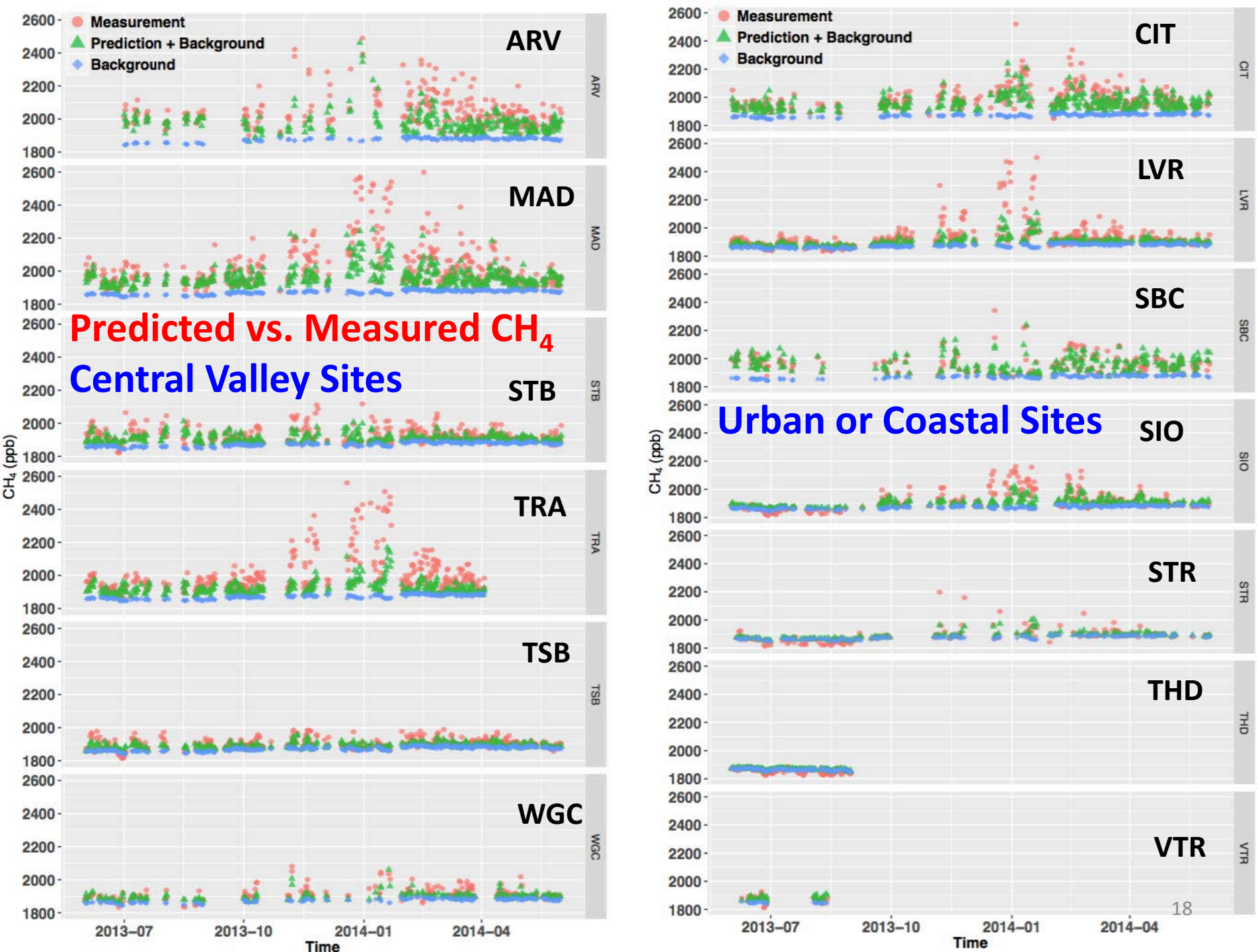
Comparison of Predicted vs. Measured CO for Winter and Spring

- WRF-STILT simulations are sufficient to estimate emissions of CO and other GHGs with similar emission patterns to within 10% ± 10% (95% CI) on annual timescales across California





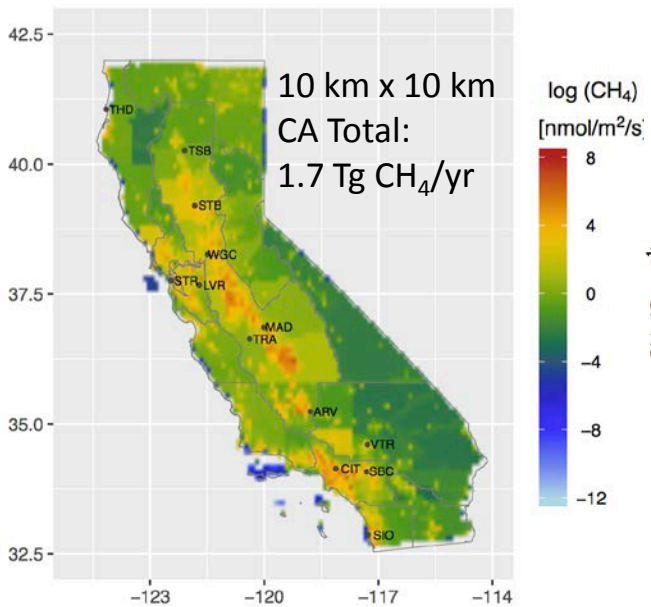
METHANE


Measurement
Prediction + Background
Background
ARV
MAD
STB
TRA
TSB
WGC
CIT
LVR
SBC
SIO
STR
THD
VTR
Predicted vs. Measured CH_4
Central Valley Sites
Urban or Coastal Sites
CH_4 (ppb)
2600
2400
2200
2000
1800
2013–07
2013–10
2014–01
2014–04
Time

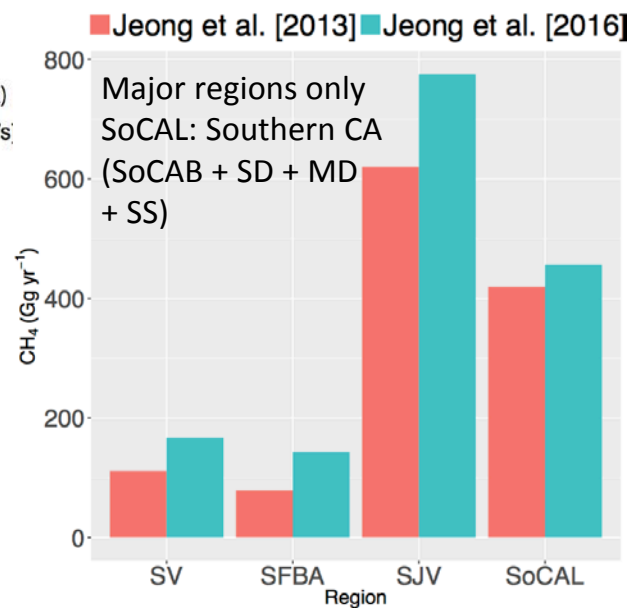
Prior Emission Maps

- High-resolution CH_4 prior emission map scaled by CARB inventory (year 2012, version March 2014; most recent version at the time of analysis) by sector with adjustments for regions [Jeong et al., 2016]
- Includes seasonal emissions from wetland and rice CH_4
- The new prior emissions are higher than those (for 2008) in Jeong et al. [2013] by ~30%
- Central Valley and major urban regions (SoCAB & SFBA) account for 55 and 29%
- Livestock is the largest source sector in the prior (52%)

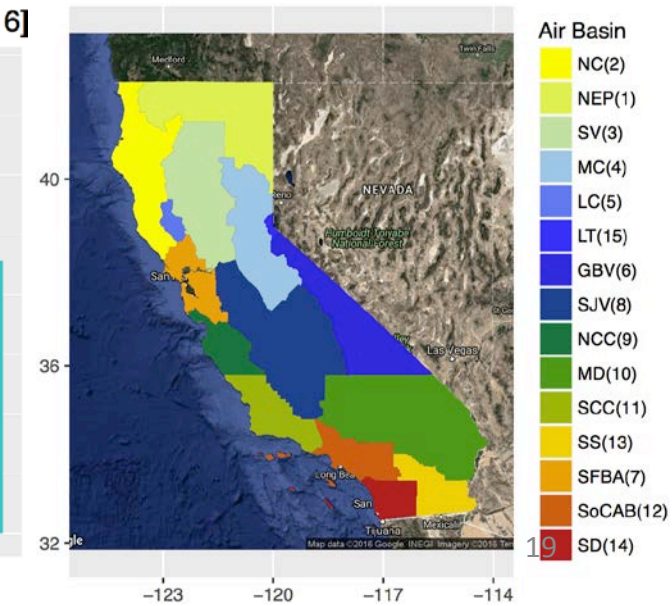
State Total Emission



2008 vs. 2012 Emissions

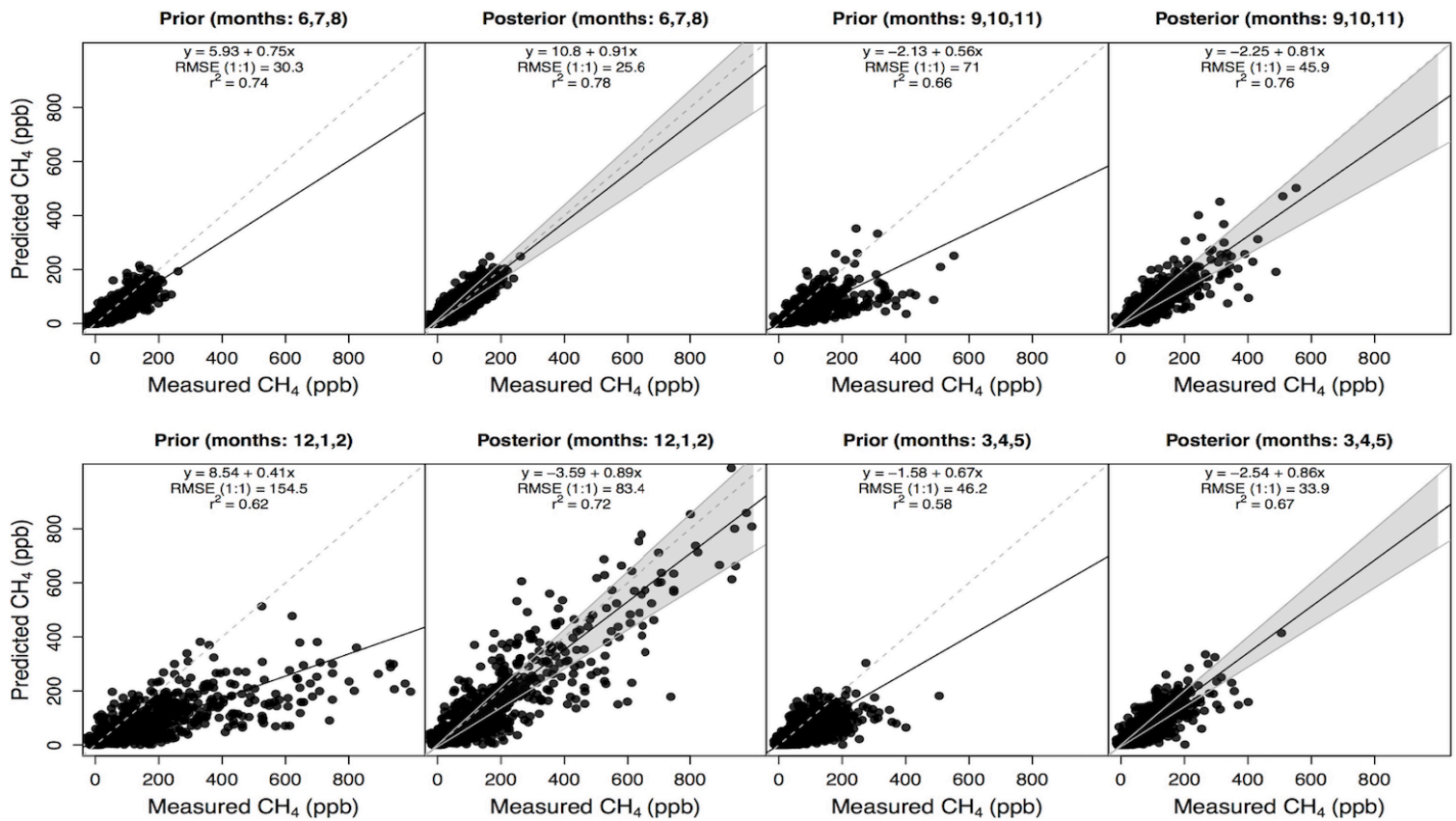


CA Air Basins



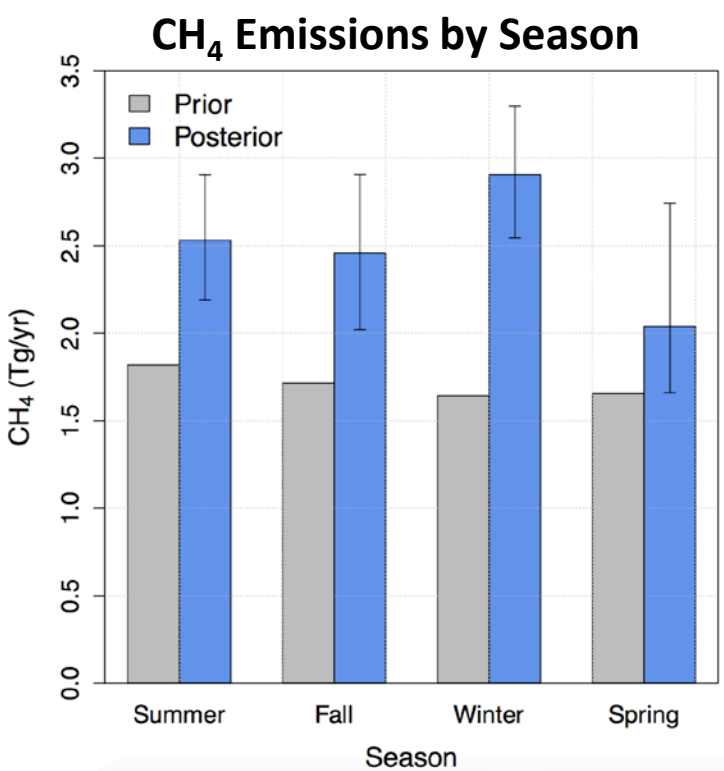
Comparison of Predictions vs. Measurements by Season

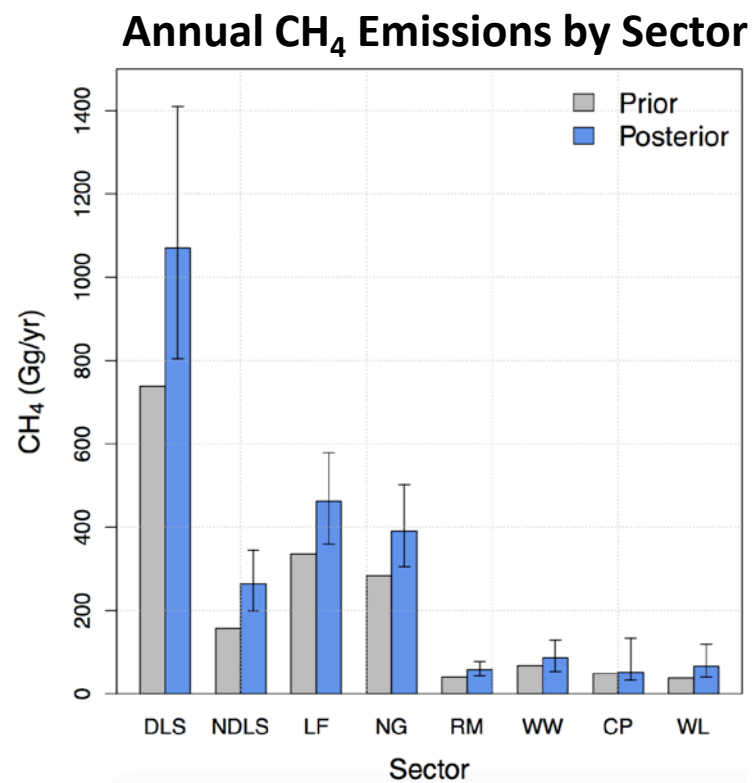
- After inversion, RMS errors and best-fit slopes are improved (shaded region = 95% CI region)
- Best-fit slopes are derived from the median values of the posterior emissions (25000 Markov chain Monte Carlo (MCMC) samples used)



CH_4 Emission by Season and Sector

- State annual anthropogenic CH_4 emissions are 2.42 ± 0.49 Tg CH_4/yr (at 95% CI), 1.2 - 1.8x the CARB inventory (1.64 Tg CH_4/yr in 2013, 1.0 – 1.6x the inventory if corrected for the 10% transport bias; Jeong et al. [2016])
- Given the posterior errors, the posterior emissions are greater than the prior across seasons, but only with weak seasonality
- Livestock sector is likely the major contributor to the state total CH_4, in agreement with CARB's inventory

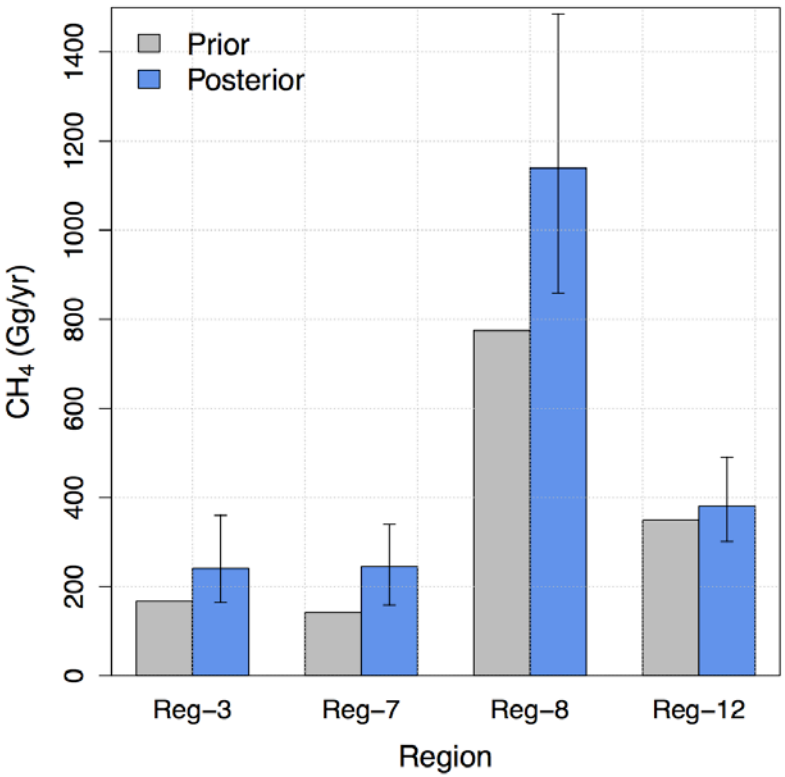


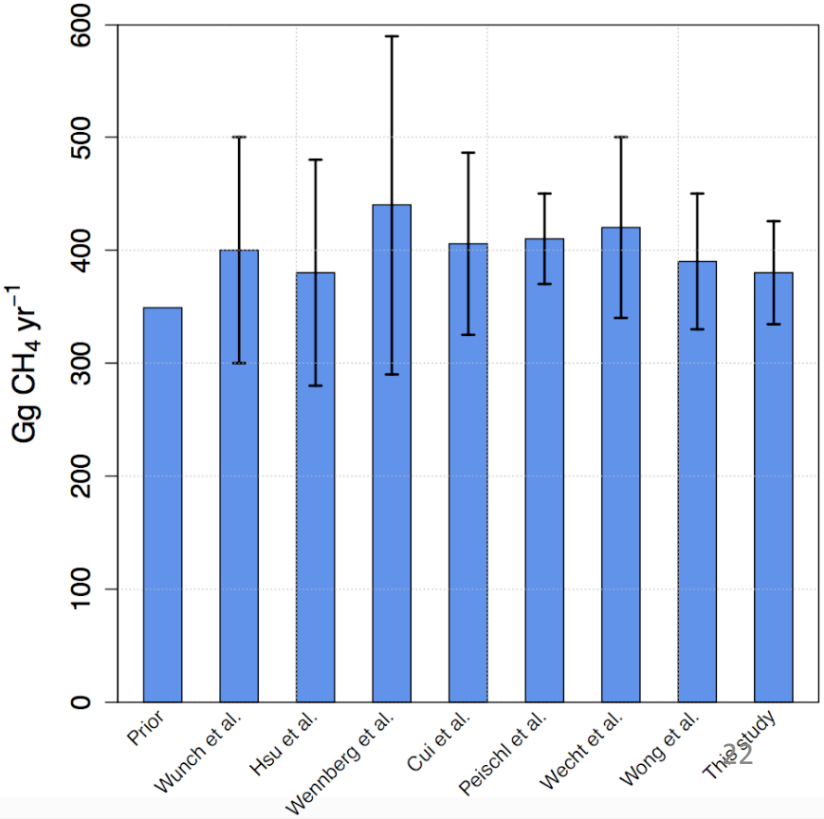


Estimated Regional CH_4 Emissions

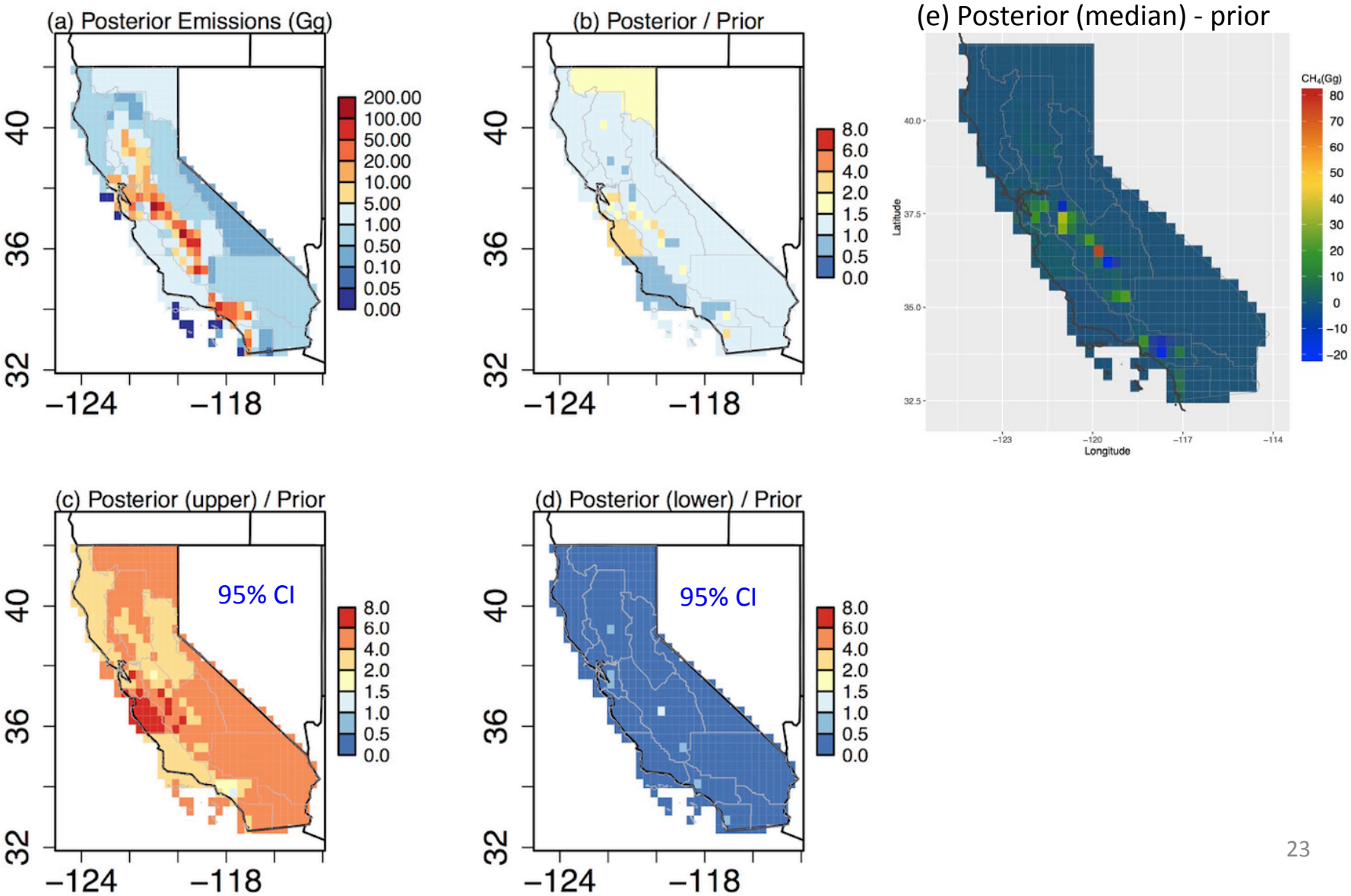
- Posterior CH_4 emissions from the Central Valley and urban regions (SF Bay and SoCAB) account for ~58% and 26% of the posterior total, respectively

- Consistent results in SoCAB with those from recent studies suggests the robustness of the inversion method developed in Jeong et al. [2016]



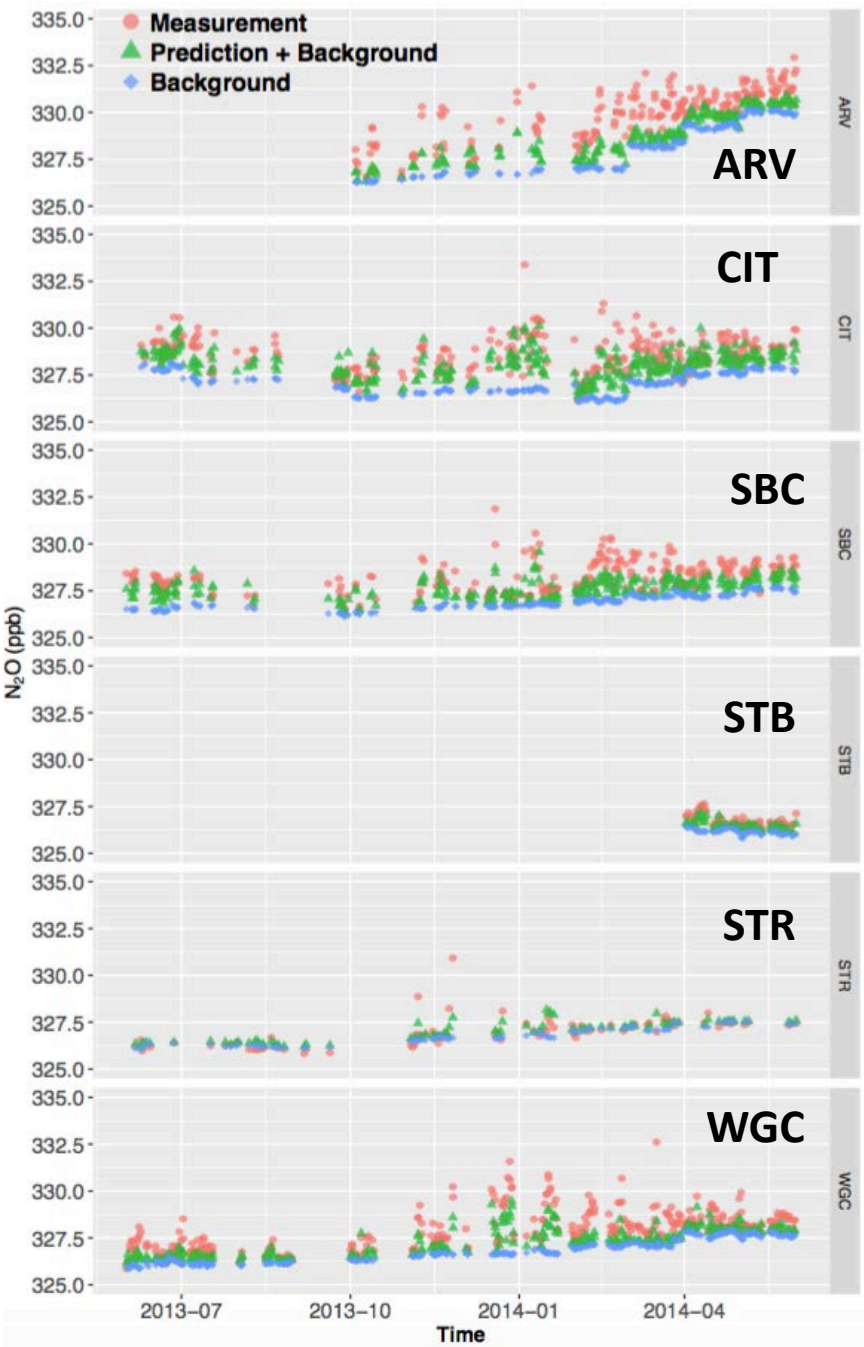


Map of Estimated CH_4 Emissions

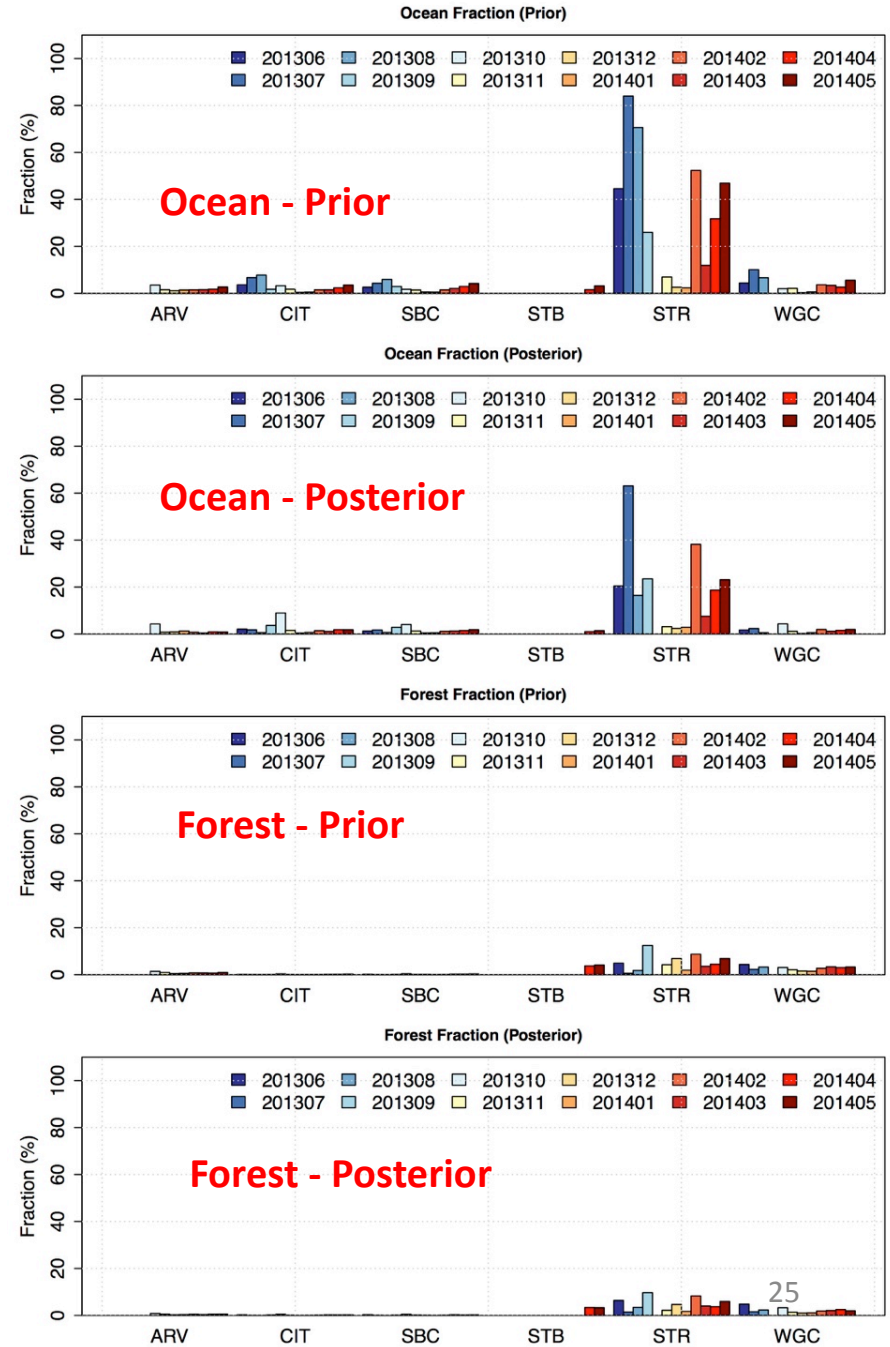


NITROUS OXIDE

Measured vs. Predicted N_2O



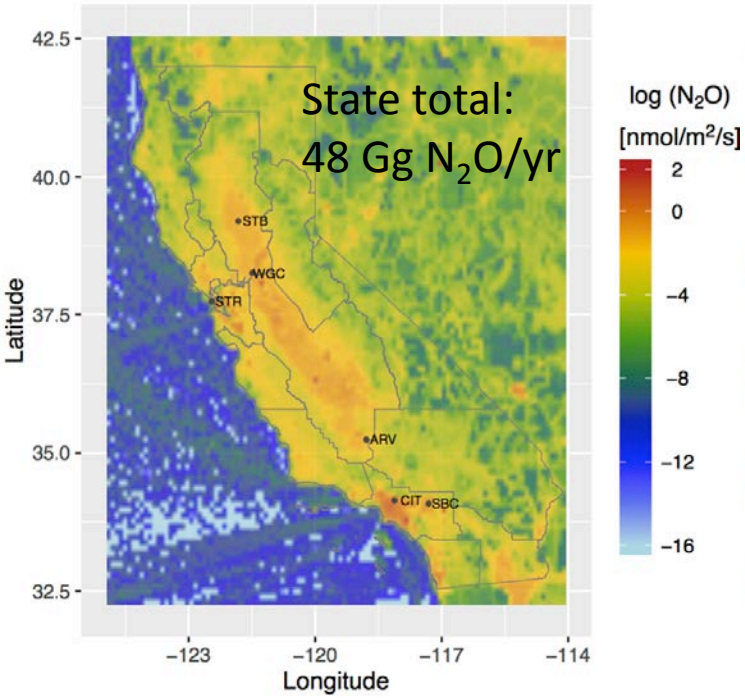
Ratio of Ocean and Forest N_2O



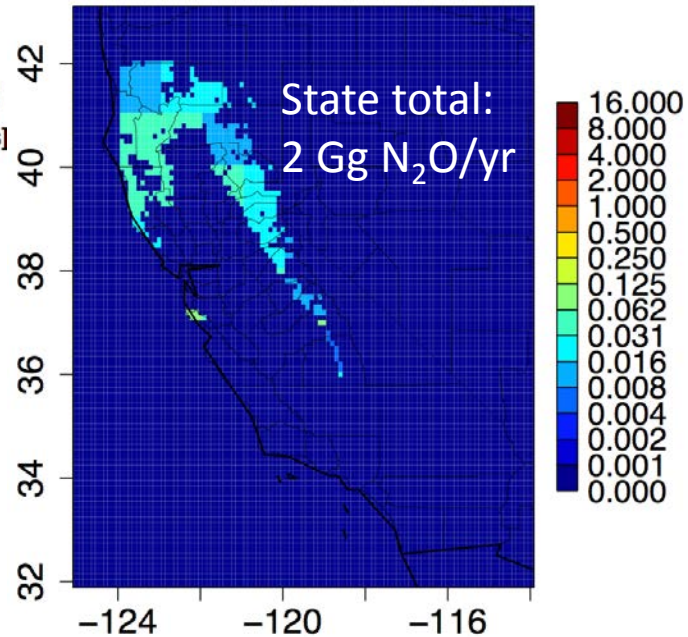
Prior Emissions

- Anthropogenic N_2O prior emission maps are generated from EDGAR scaled by CARB inventory (Year 2012; year 2012, version March 2014; most recent version at the time of analysis) by sector
- The Central Valley and major urban regions (SoCAB & SFBA) account for 46% and 26% of the state total, respectively
- The largest emissions from agricultural soils (41% of the total) followed by industrial processes and product use (20%) and manure management (20%)

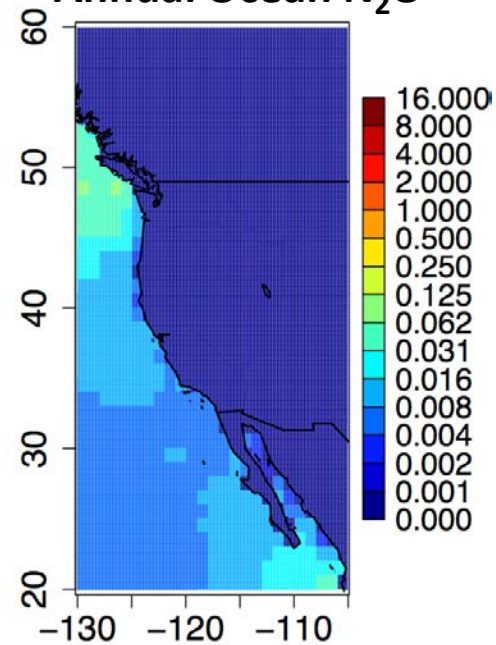
Annual Anthropogenic N_2O



Annual Forest N_2O

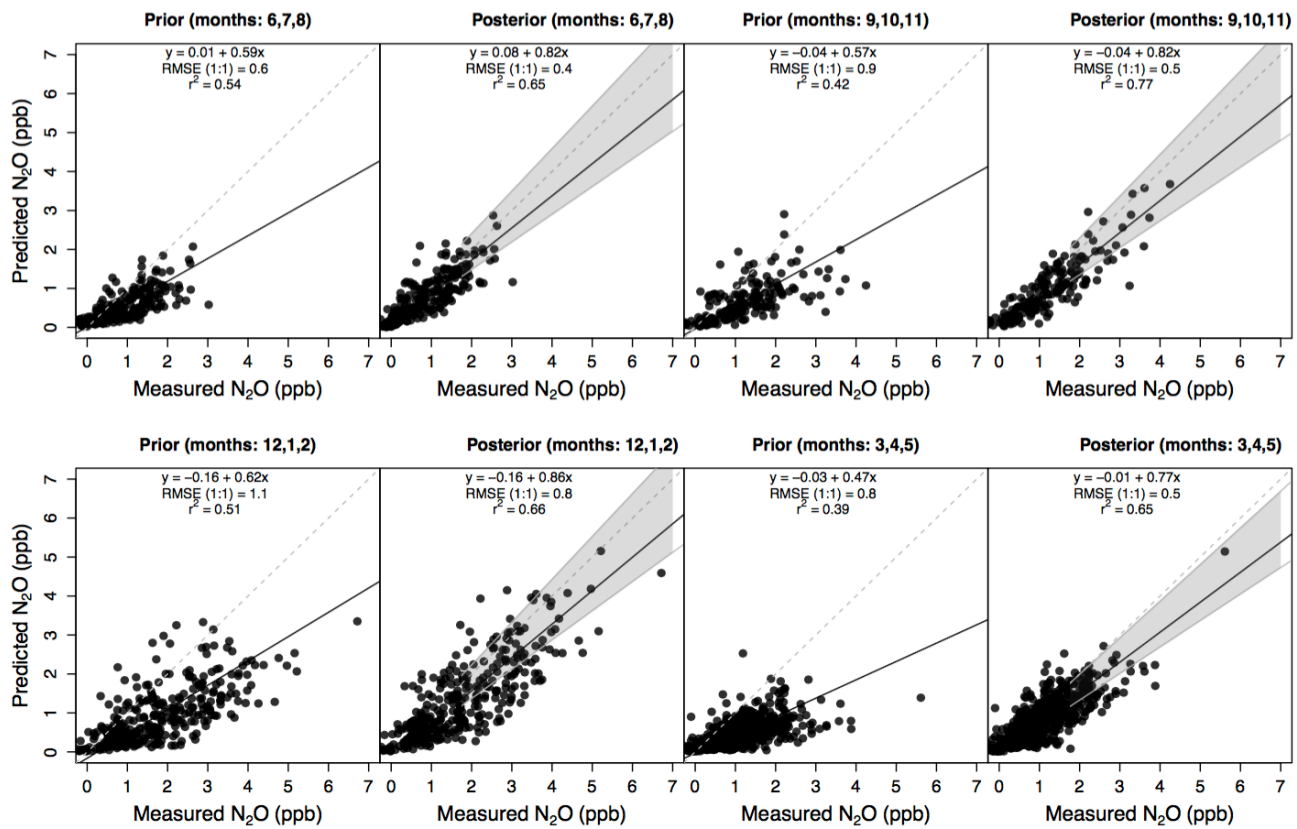


Annual Ocean N_2O



Comparison of Predictions vs. Measurements by Season

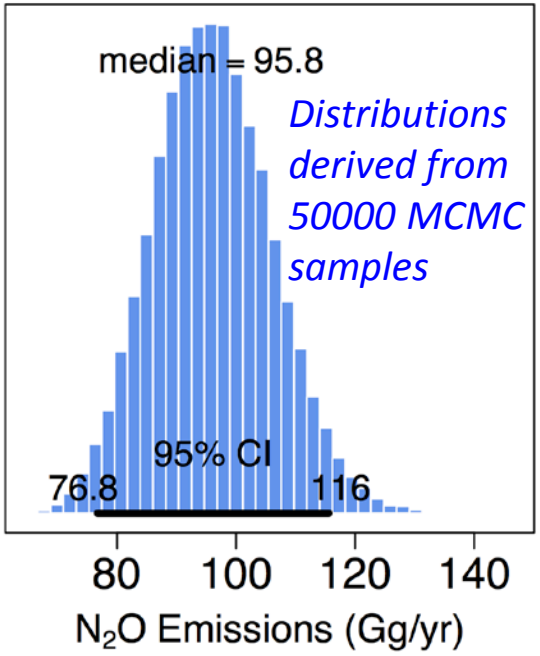
- After inversion, RMS errors and best-fit slopes are improved (shaded region = 95% CI region)
- Best-fit slopes are derived from the median values of the posterior emissions (50000 MCMC samples used)



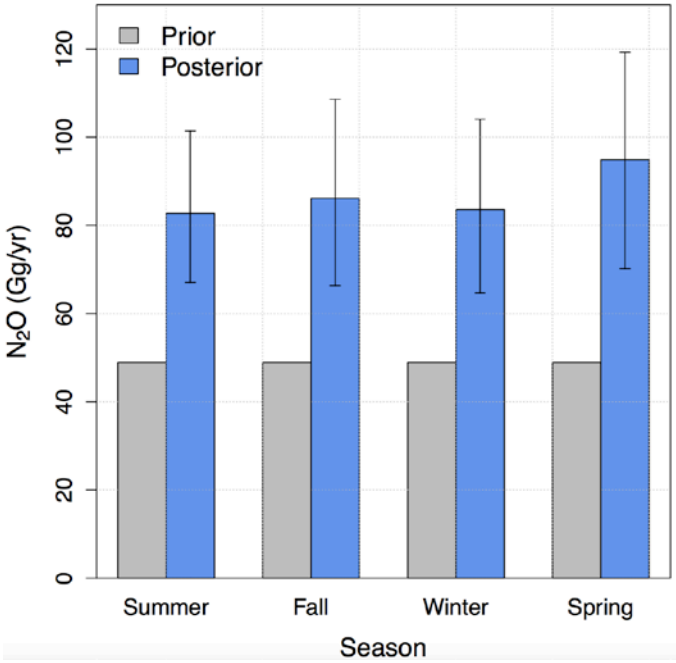
State Anthropogenic N_2O Emissions

- State annual anthropogenic N_2O emissions are 1.5 – 2.5 times (95% CI) the CARB inventory (44 Gg N_2O/yr in 2013; 1.3 - 2.3x the inventory if corrected for the 10% transport bias)
- Seasonal variations in California's N_2O emissions are likely smaller than for interior portions of the continental US, similar results to Jeong et al. [2012]

Example posterior distribution for state total N_2O from HBI (May 2014)



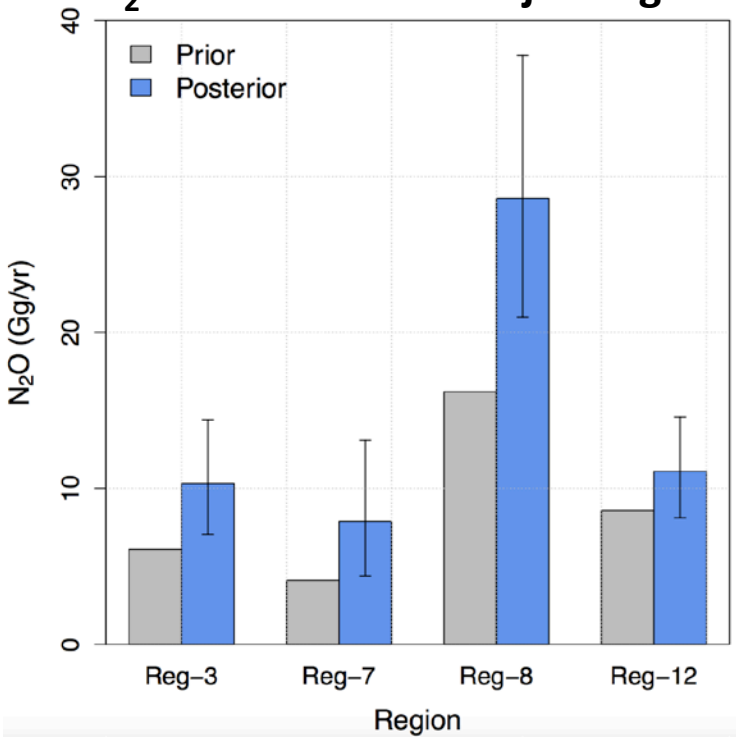
Statewide anthropogenic N_2O emissions by season



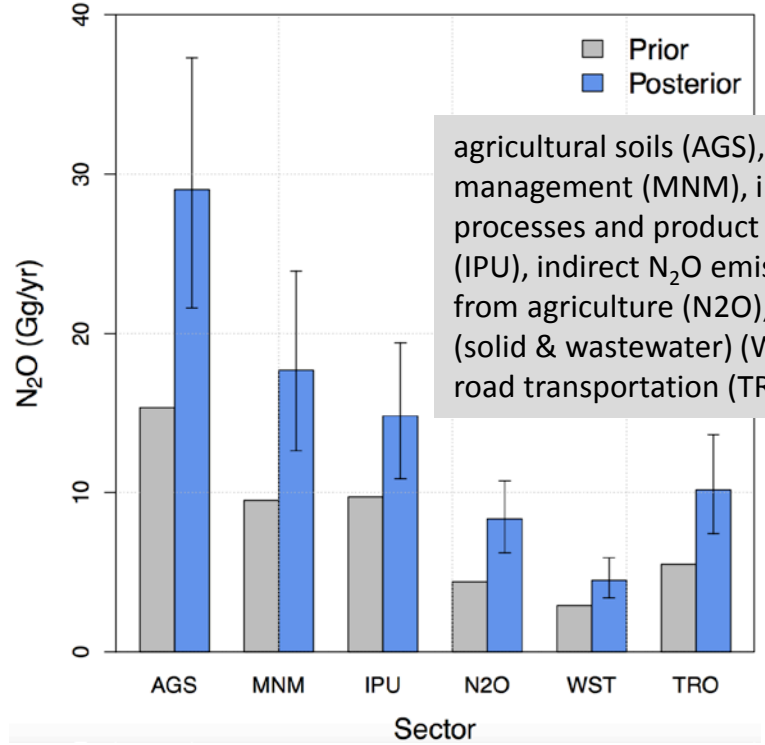
Annual Anthropogenic Emissions by Major Region and Sector

- Central Valley emissions are 1.4 – 2.2 times (95% CI) the prior (22 Gg N_2O/yr)
- Emissions from two major urban regions (SoCAB & SFBA) are 1.1 – 2.0 times (95% CI) the prior (12.7 Gg N_2O/yr)
- Actual emissions in the Central Valley dominated by agricultural soil and manure management appears to be higher than the prior

N_2O Emissions for Major Regions

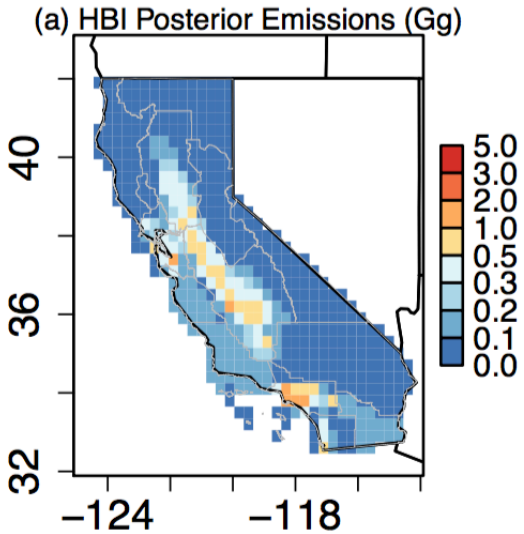


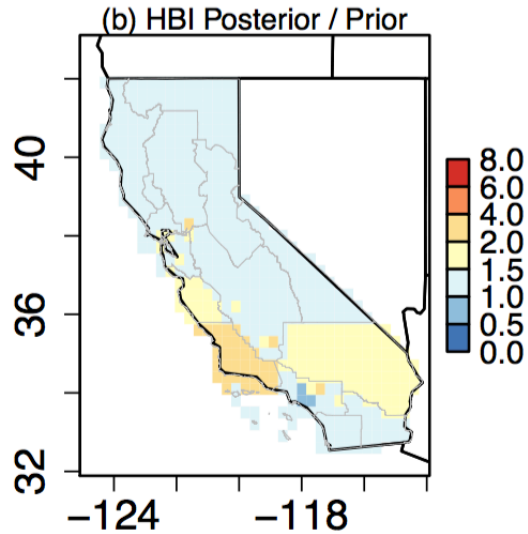
N_2O Emissions by Sector

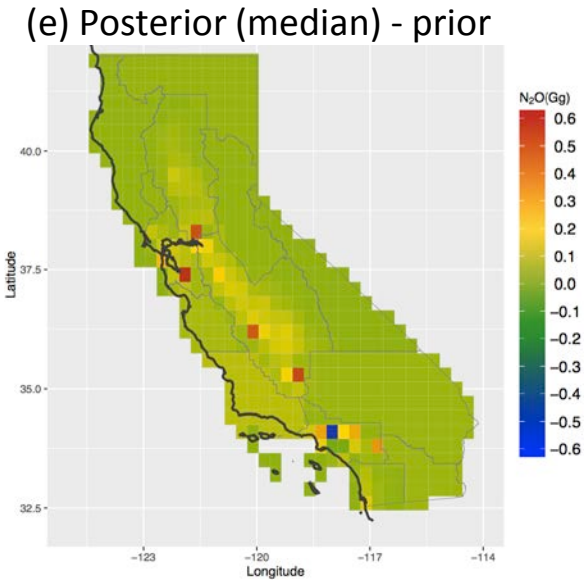


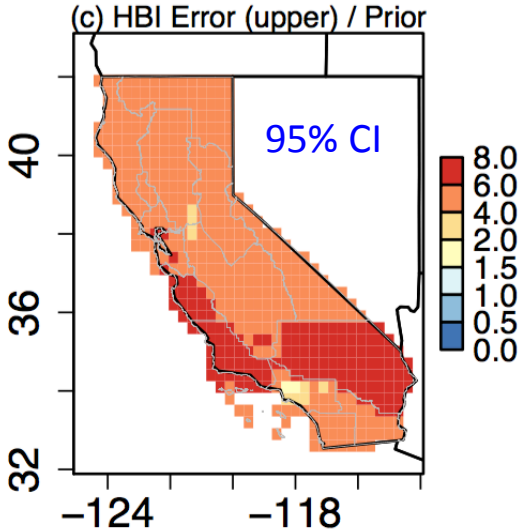
agricultural soils (AGS), manure management (MNM), industrial processes and product use (IPU), indirect N_2O emissions from agriculture (N2O), waste (solid & wastewater) (WST), road transportation (TRO)

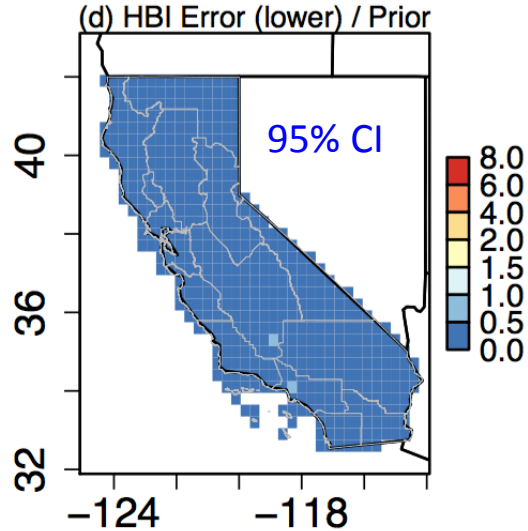
Estimated Anthropogenic N_2O Emissions









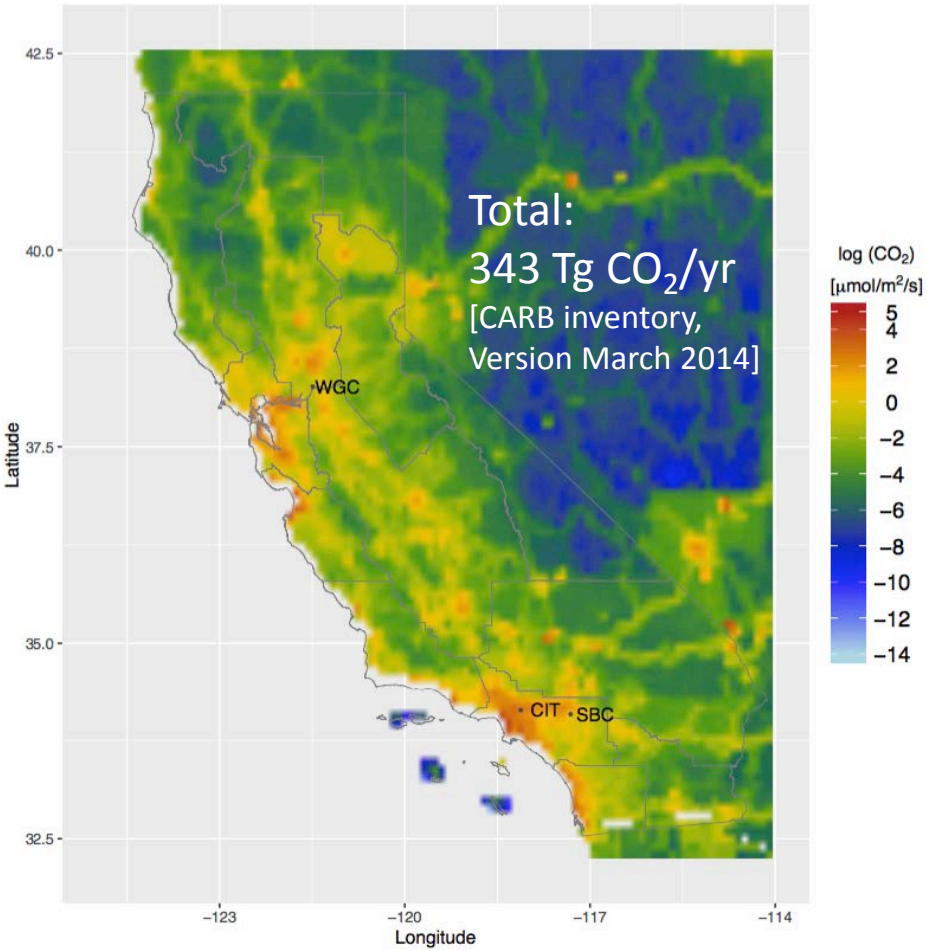


FOSSIL FUEL CO_2

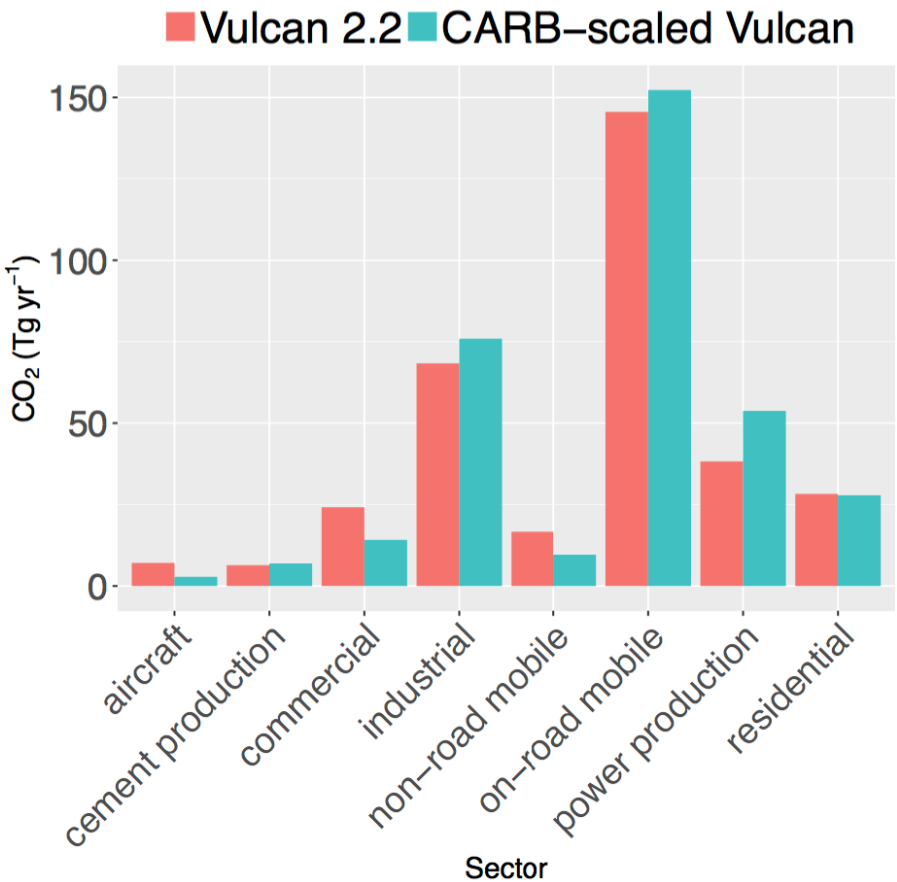
Fossil Fuel CO_2 Prior Emissions

- Vulcan 2.2 $ffCO_2$ emissions are scaled to CARB 2012 inventory by sector

CARB-scaled Vulcan $ffCO_2$ Emissions Used in Inversion

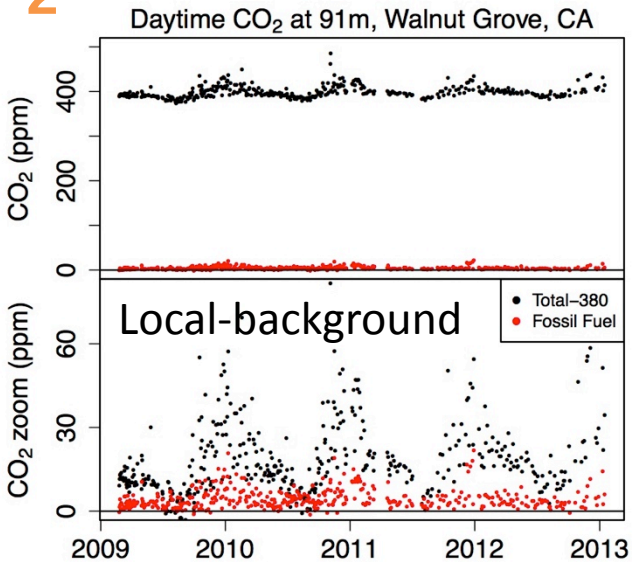


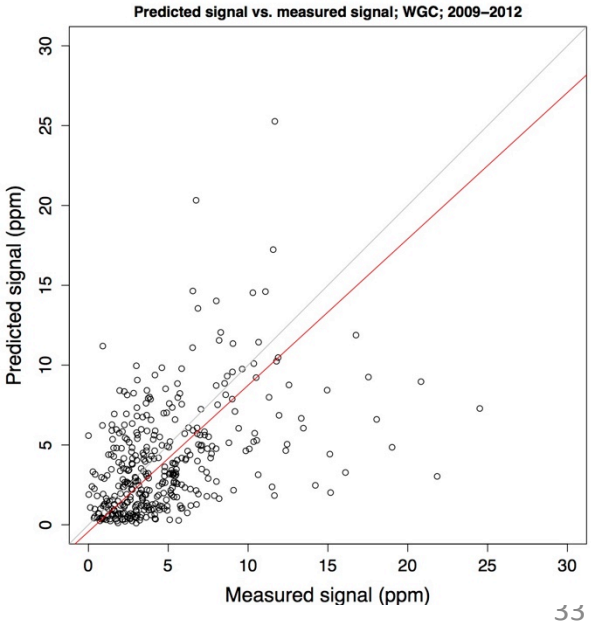
Comparison of Original Vulcan 2.2 vs. CARB-scaled Vulcan $ffCO_2$ by Sector



Estimated Fossil Fuel CO_2 Emissions

- Radiocarbon $^{14}CO_2$ provides sensitive (~ 1 ppm) measure of atmosphere fossil fuel (^{14}C free) CO_2
- Compare local signals with WRF-STILT-VULCAN scaled to CARB (2013) inventory by year
- Walnut Grove 2009-2012: model-measurement comparison match to +/- 10% (results from individual years more variable (e.g., +10 to -25%)
- Measurements for single year 2013-2014 from San Bernardino (- 26 +/- 8%) and Caltech (-9 +/- 4%) similar





RESEARCH SUMMARY AND RECOMMENDATIONS

Summary

- Increased ARB capacity for State-wide GHG inventory assessment
  - Continued multi-species GHG measurements at Walnut Grove
  - Implemented measurements at a new site in San Bernardino
  - Combined 13 sites in collaborative CA-wide network

- Optimized NCAR Weather Research Forecast WRF) model
  - Selected WRF physics to match with meteorological measurements and evaluated residual random error and biases
  - Compared measured and predicted carbon monoxide signals to estimate GHG signal prediction errors

Summary (cont'd)

- Estimated CH_4, N_2O, and fossil fuel CO_2 emissions for CA (compared with a recent ARB inventory for year 2013, version April 2015)
  - CH_4 slightly higher (1.0- 1.6 times) than the 2013 ARB inventory (Jeong et al., 2016)
    - Livestock emissions are likely the largest source, consistent with CARB inventory
    - Actual natural gas/petroleum production emissions are likely higher than the prior while posterior emissions from the other sectors are slightly higher or similar to the prior
  - N_2O emissions higher (1.3 – 2.3 times) than 2013 CARB inventory
    - Likely higher emissions than the prior in the agricultural soil (1.4 – 2.4x the prior) and manure management (1.3 – 2.5x) sectors
    - Non-agricultural sources in CA are also important (~36% of the total posterior emissions)
  - $ffCO_2$ approximately consistent with 2013 CARB inventory
    - On-road mobile is likely the largest source sector

Recommendations for Further Work

- Expand work on inventory-based estimation of CA GHG emissions
  - Perform 1st first order uncertainty analysis (e.g., US Environmental Protection Agency)
  - Create spatiotemporally disaggregated GHG emission inventories for all major species.
- Continue developing GHG and meteorological capabilities
  - Implement wind profiling and boundary layer mixing height observations near measurement sites to refine/evaluate meteorological models
  - Add multi-species tracer gas measurements (e.g., ethane and other alkanes, stable isotopes, 14CO2) for source sector attribution
  - Incorporate available satellite and ground-based full-column and airborne GHG observations