Quantifying Greenhouse Gas Emissions from Human Activities in California: Toward Verification of AB-32 Compliance

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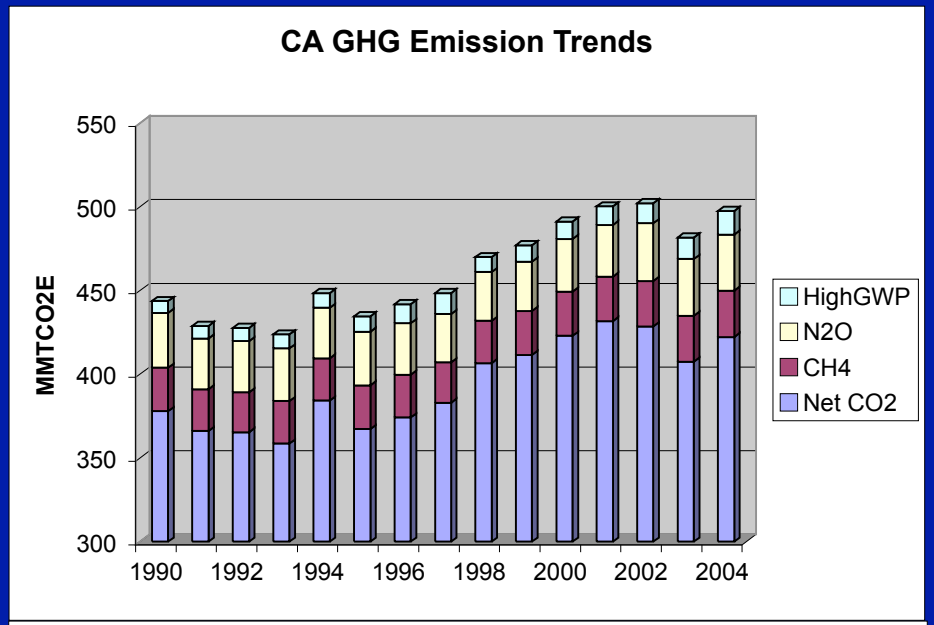
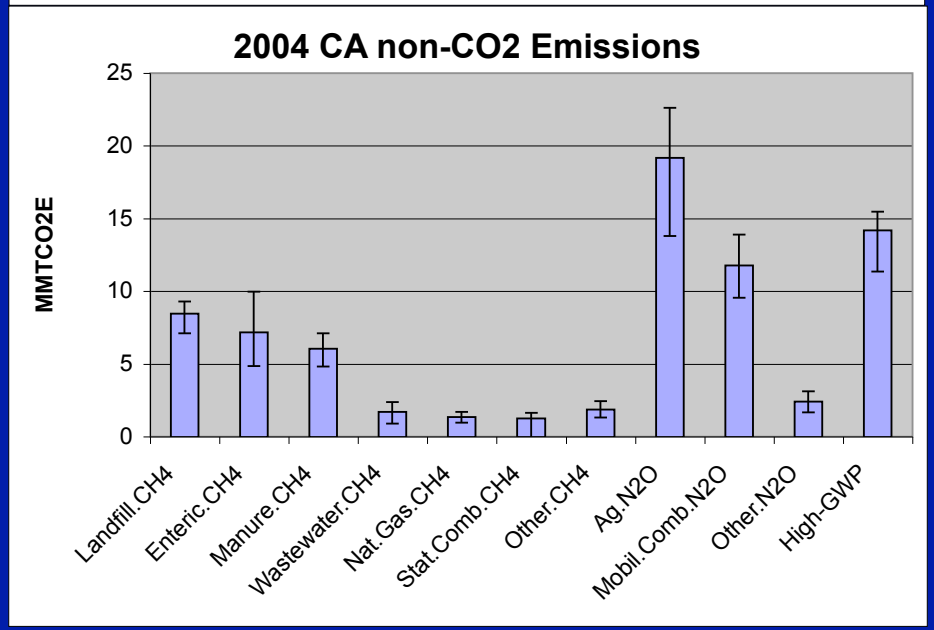
Outline

- Necessity of GHG emissions verification for policies supporting “sustainable well-being”
- Work on California’s GHG emissions
  - The California Greenhouse Gas Emission Measurement Project (CALGEM)
  - Airborne Greenhouse Gas Survey project (AGES)
- Estimates of CO_2, CH_4 & N_2O emissions for Central CA
- Future work
- Conclusions

California GHG Emissions

- 2007, California becomes first state in US to legislate GHG controls
  - AB-32: 1990 levels in 2020
  - The Stick: Quantitative verification of emissions reductions required to assess success of AB-32
  - The Carrot: Verified GHG emission reduction has economic value to drive behavior & innovation
- Non-CO_2 GHG emissions comparable to CO_2 but…
  - Biological sources are not readily metered
  - Uncertainties in inventories are large (even using US average fractional error estimates)
- Atmospheric inverse method provides independent check

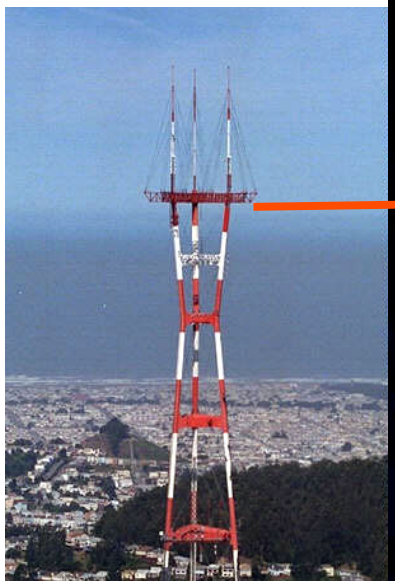




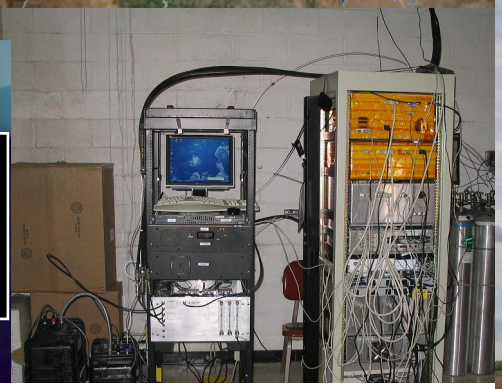
CEC, 2006 ; USEPA, 2007

California Greenhouse Gas Emissions Measurement Project (calgem.lbl.gov)
LBNL - NOAA Collaboration

Sutro Tower (232 m agl) Oceanic + urban



Walnut Grove (483 m agl) Central Valley + Bay Area

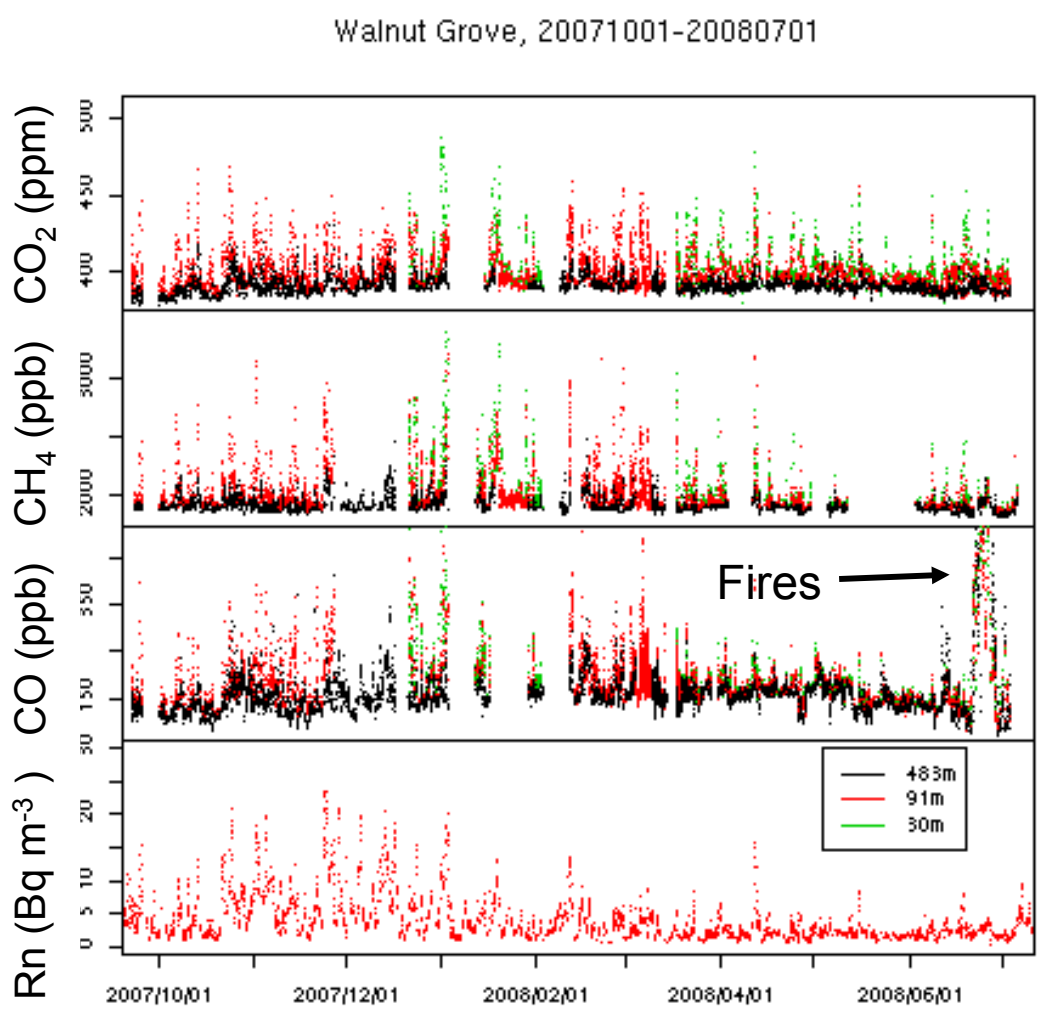


Daily (flasks):
CO2, CO, CH4, N2O
SF6, halocarb, VOC
$^{13}CO_2$, $^{13}CH_4$
Radiocarbon $^{14}CO_2$

Continuous:
CH_4, CO_2, CO, ^{222}Rn

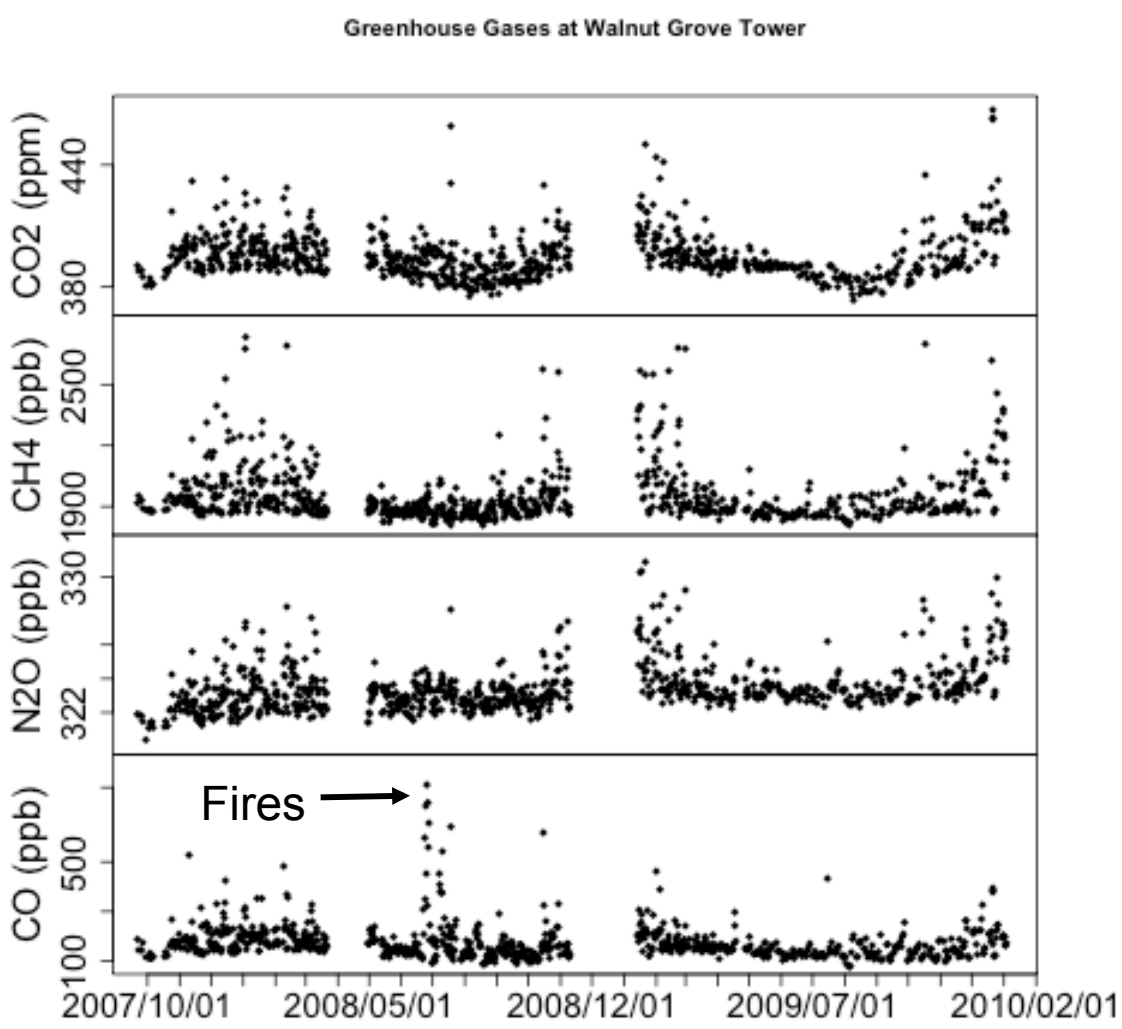
In-situ Measurements at Walnut Grove

- Elevated mixing ratios at 30, 91m indicate strong regional-local emissions
- Strong correlation of diurnal variations in CO_2, CH_4 and ^{222}Rn implicates variations in boundary layer
- Synoptic variations offer opportunity to extract emissions information
- 483 m mixing ratios generally near background levels at night (decouple from surface influence)



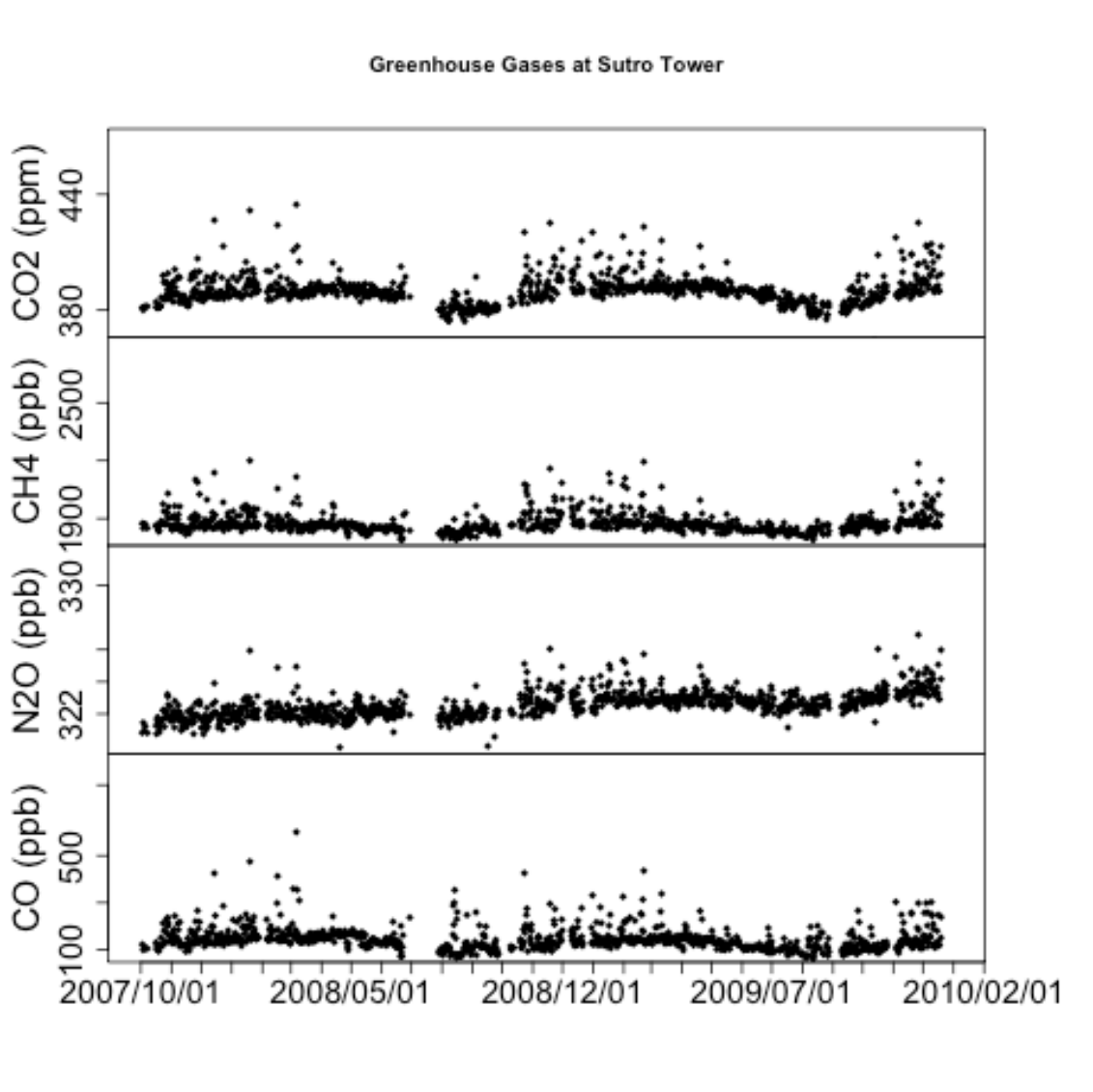
Flask Measurements at Walnut Grove

- Impact of regional emissions present in measured data
- Strong diurnal cycles due to boundary layer variations
- Seasonal cycles due to varied emissions, winds, and boundary layer depth

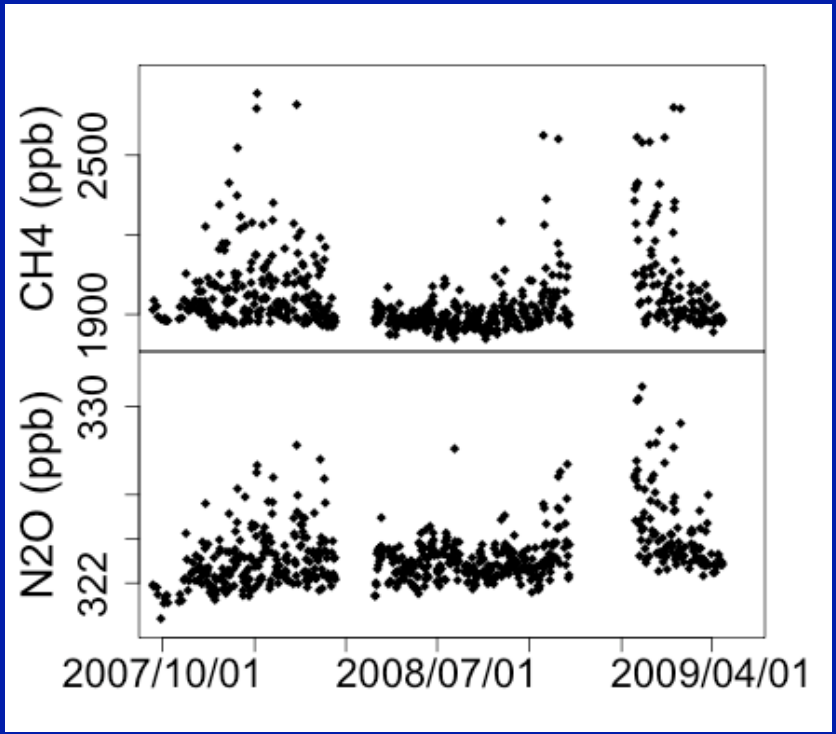


Measurements at Mt. Sutro

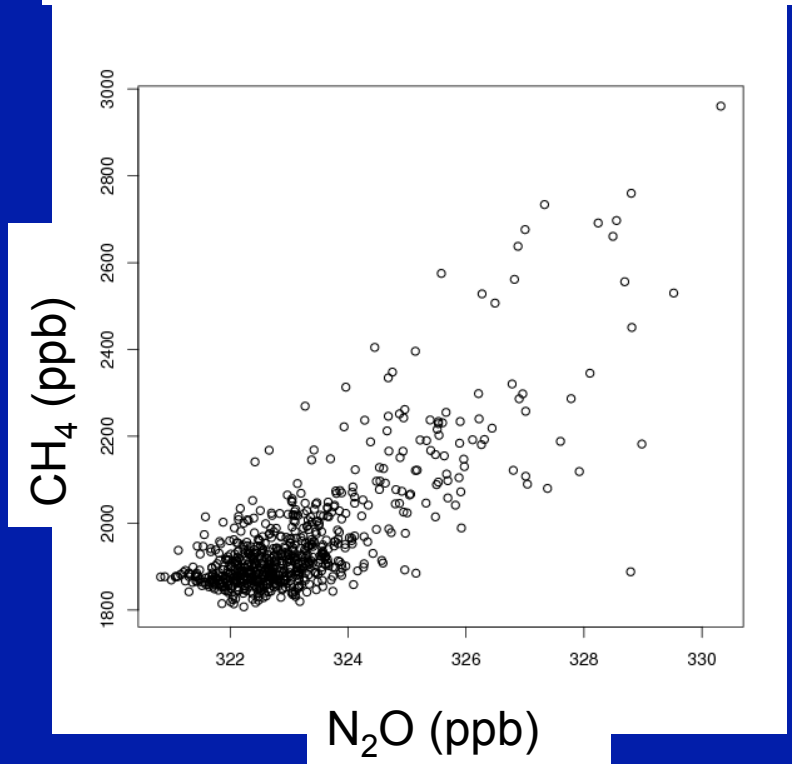
- Comparatively lower GHG signals than at WGC
- Background variations clearly visible
- Local GHG signals present above background during winter correlate with CO



Focus on Walnut Grove CH_4 and N_2O



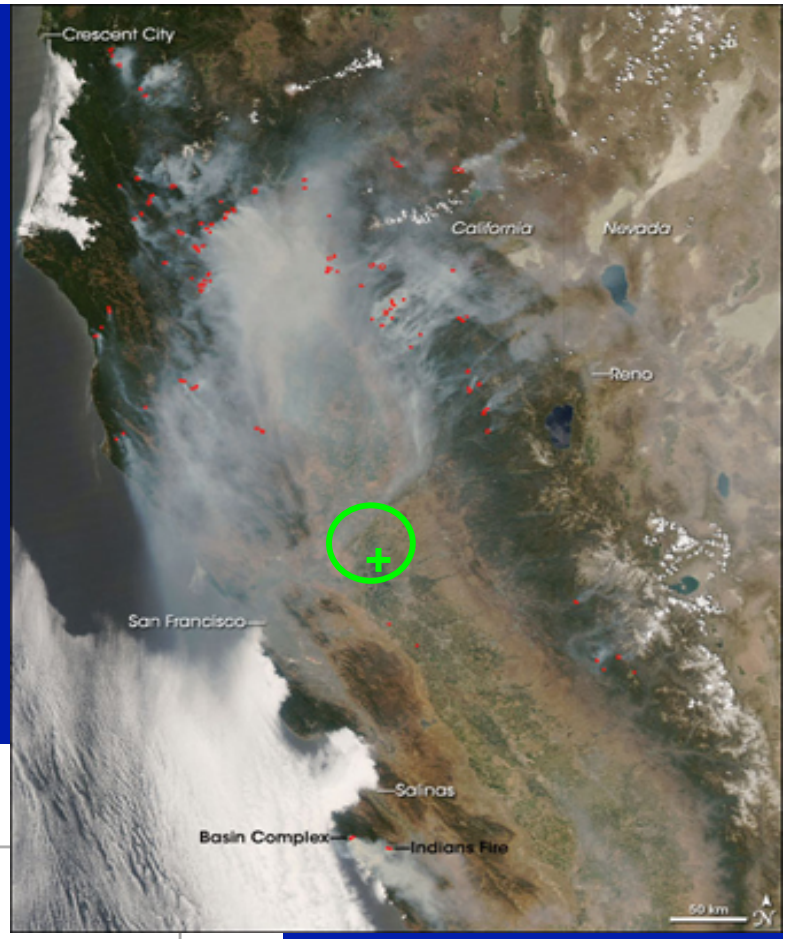
Oct, 2007 - Dec, 2008
WGC 91 m, Well Mixed, 1400 Local

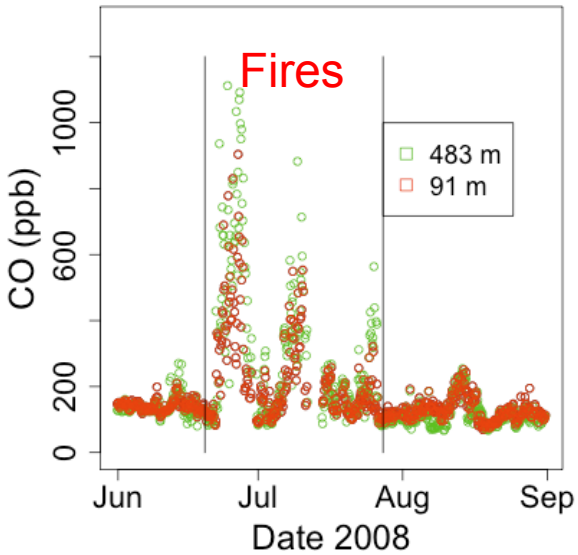


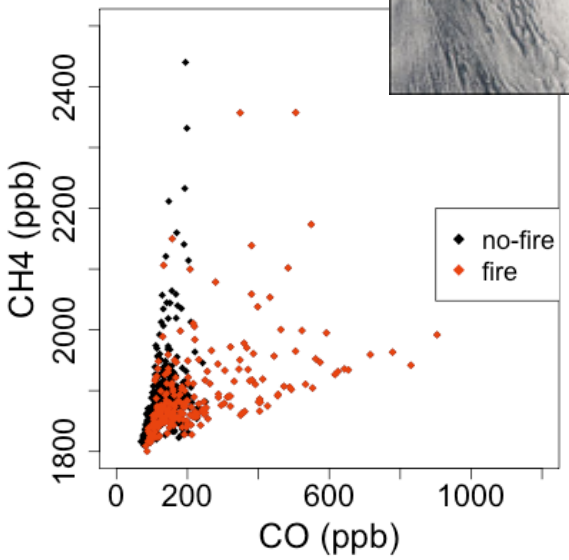
- CH_4 and N_2O share similar patterns
- Strong Central Valley emissions

Fires, Summer 2008

- CO fire signal clearly visible in summer 2008
- 483 m CO > 91 m CO in contrast to most other periods



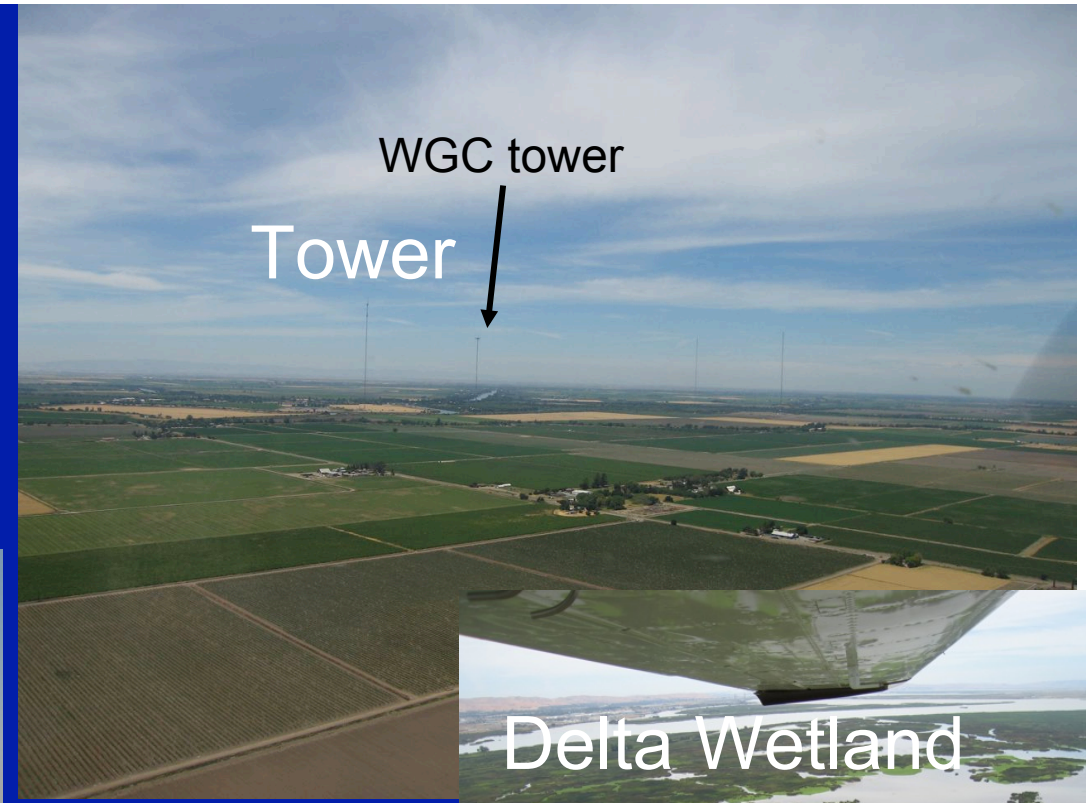


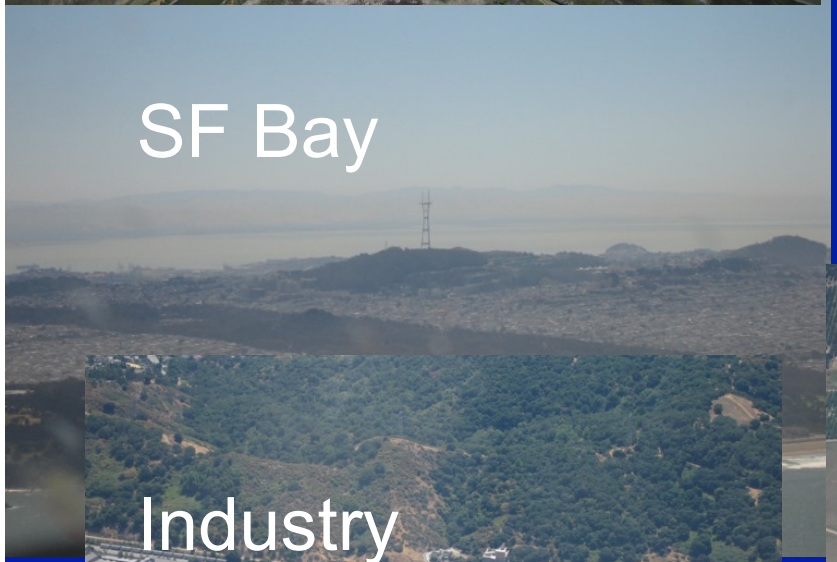


Airborne Greenhouse Gas Survey (AGES)

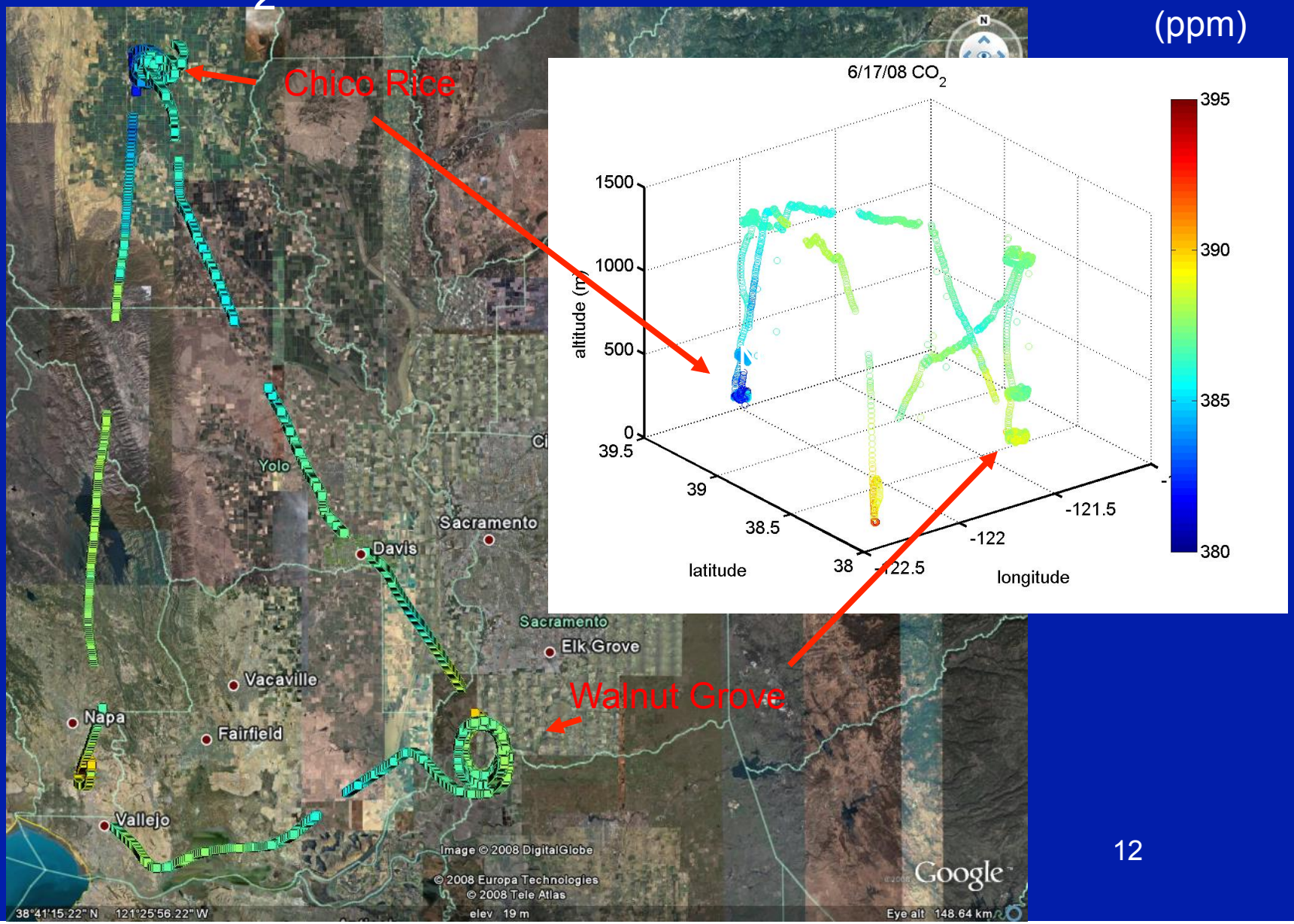
- DOE-SBIR to demonstrate GHG survey capability from small aircraft
- June, 2008 and March, 2009 campaigns from Napa CA
- Instruments
  - Picarro CO_2/CH_4
  - Aerolaser UV Florescence CO
  - Flask sampling for CO_2, CH_4, CO, N2O, $^{14}CO_2$
- Observations of Sac. river delta, Sacramento urban area, and Central Valley agriculture

Aircraft Views

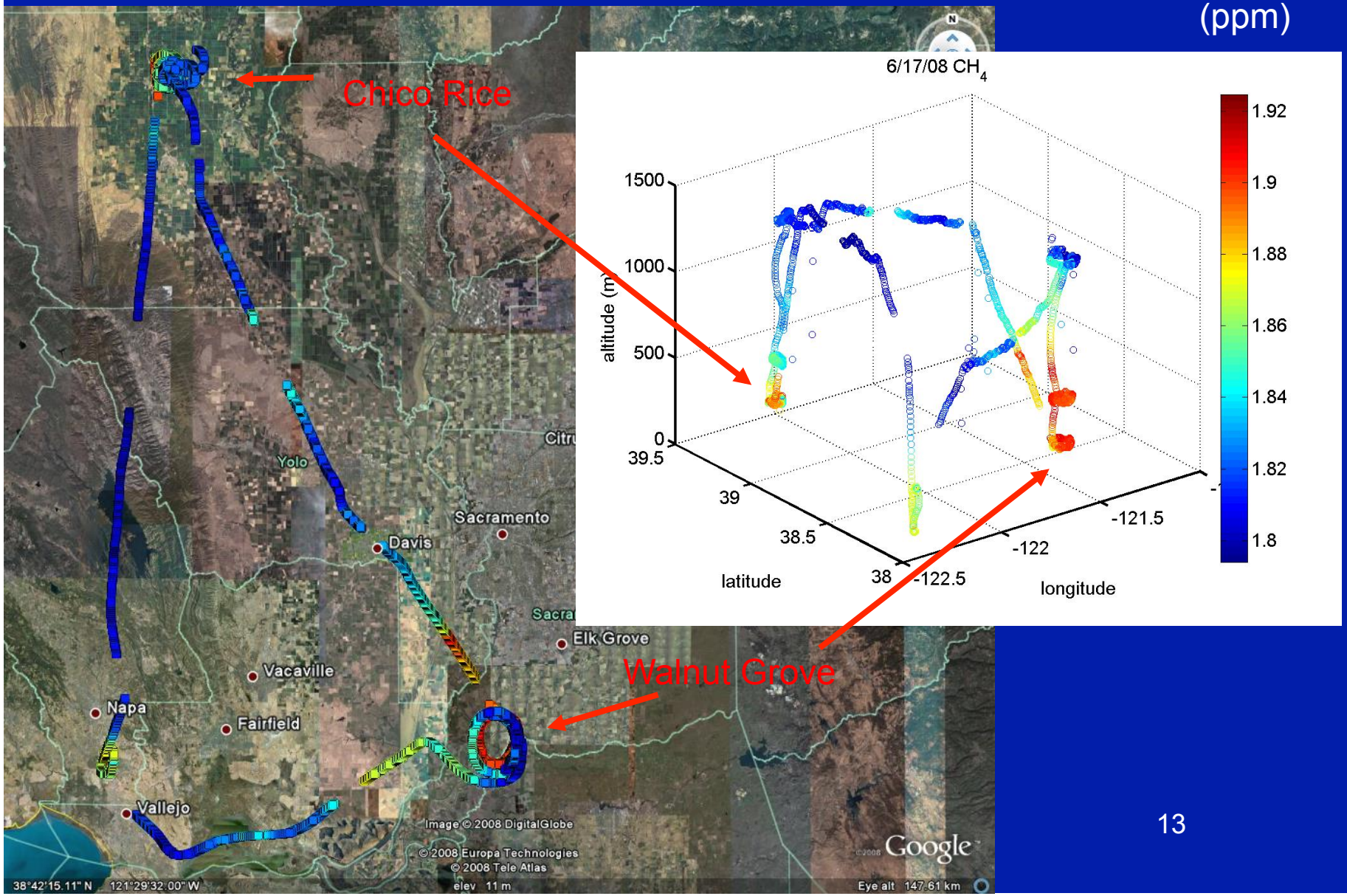




CO_2 Observed over Rice and WGC



CH_4 Observed over Rice and WGC

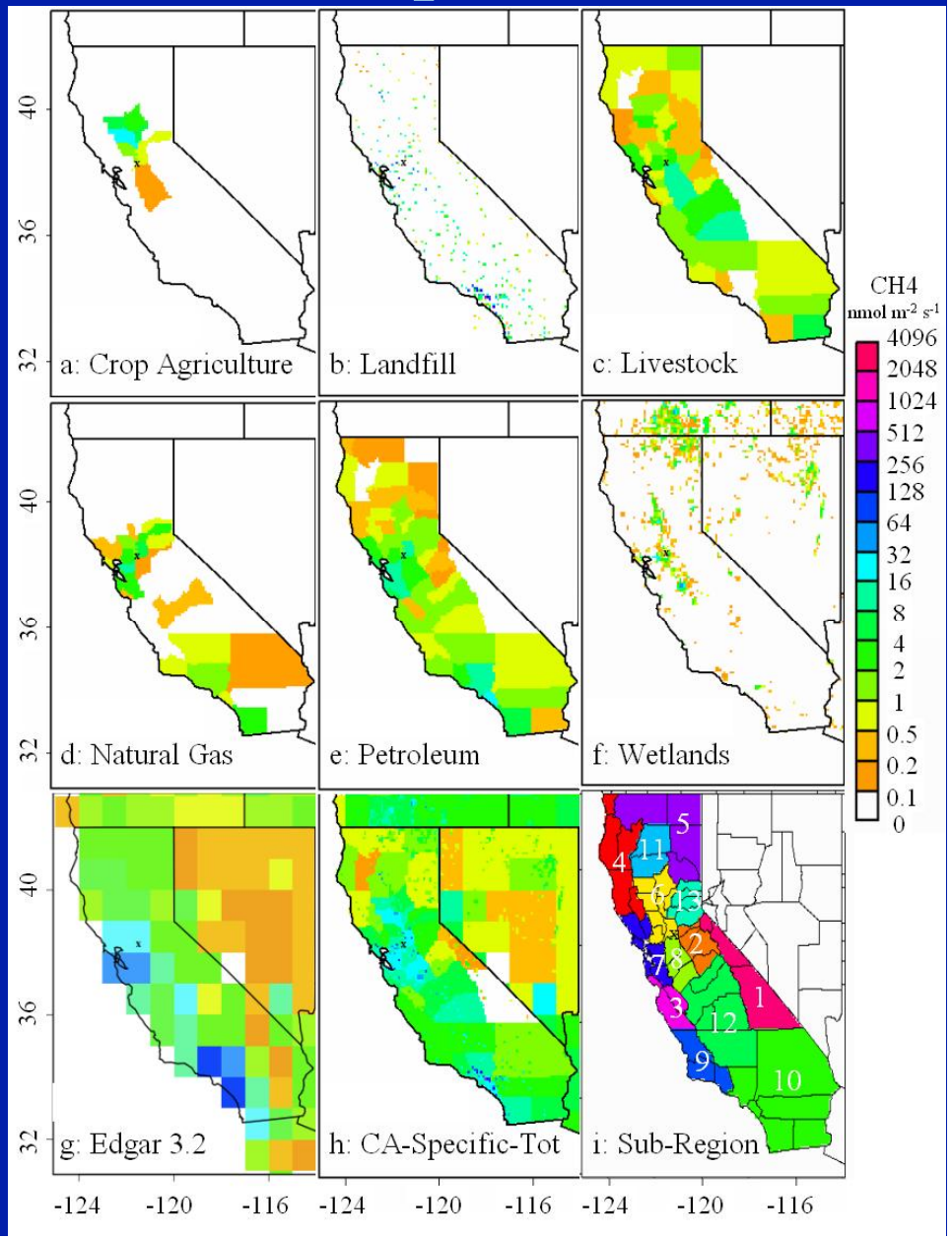


Inverse Model Estimates of Emissions

- Emissions Inventories
- Meteorological Model
- Predicted and Measured CH_4 and N_2O
- Estimated CH_4 Emissions
- Network Design

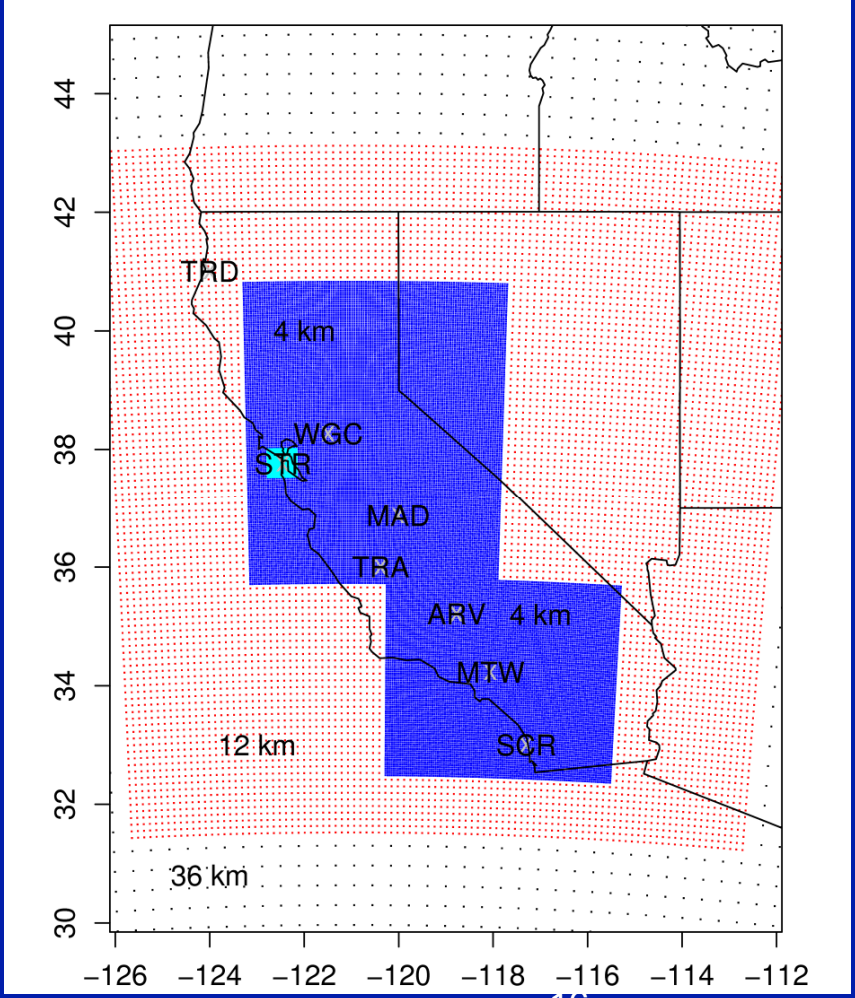
a priori CH_4 Emission Maps

- Crop Agriculture (Salas)
- Landfill (point sources)
- Livestock (USDA)
- Natural gas dist./use
- Petroleum refining and use
- Wetlands (Potter et al.)
- Above sum to CA-specific
- EDGAR3.2 (1x1degree)
  - Landfills and petroleum extraction and refining ~ 2 x CA estimates
- Also: regional subdivision for spatial analysis



Meteorological Model for CA Domain

- Weather Research Forecast Model (WRF)
  - Domains (extension of Zhao et al., 2009):
    - 36 km (W. US), 12 km (CA)
    - 4 km (Central Valley)
    - 1.3 km (Sutro, WGC)
  - NARR boundary forcing and internal nudging
  - Daily runs, hourly output



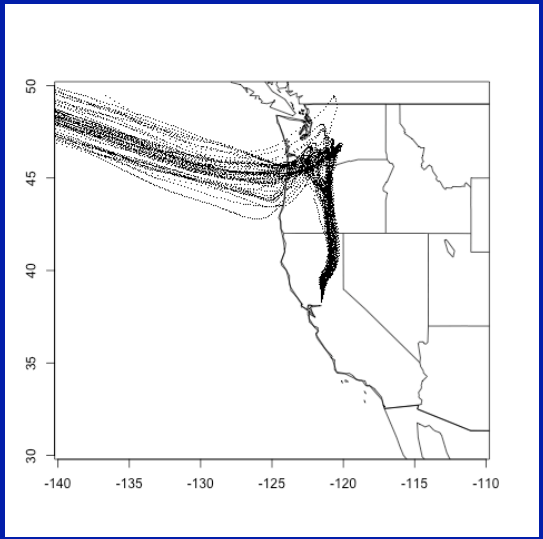
WRF-STILT Footprints for WGC Tower

- Footprint from ensemble of particle trajectories, p

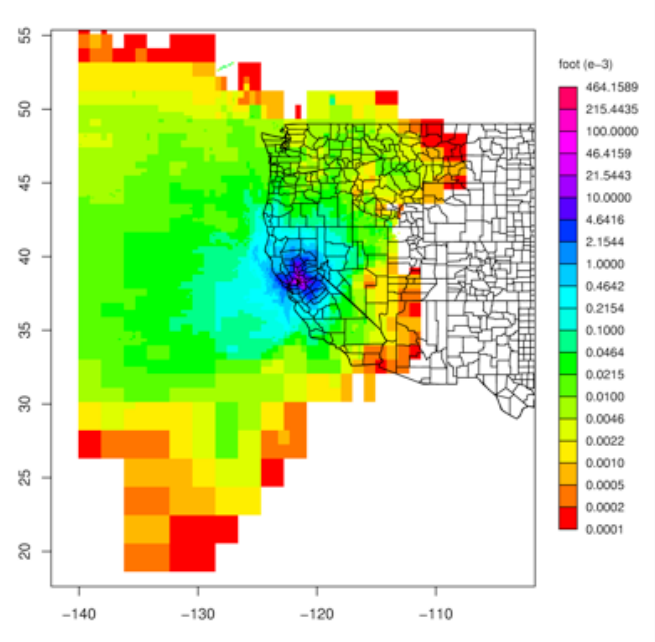
$$f(\underline{X}_r, t_r | x_i, y_j, t_m) \propto \sum_{p=1..N} \left(\frac{\Delta t}{Zi} \right) | i, j, m, p$$

- Largest surface influences (purple) for Bay Area and Central Valley
- Predict local CH_4 signals

$$C_l(\underline{X}_r, t_r) = \sum_{i,j,m} f(\underline{X}_r, t_r | x_i, y_j, t_m) \cdot F(x_i, y_j)$$

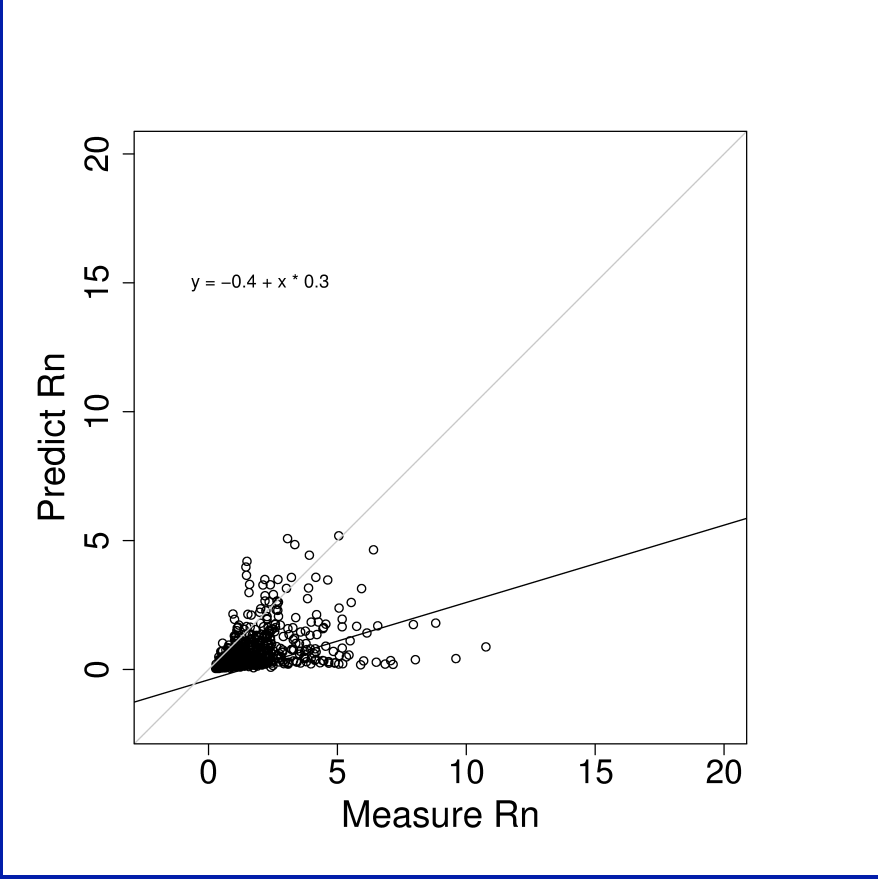


Oct-Dec, 2007 avg. footprint



^{222}Radon to Discriminate Transport Error

- A small fraction of footprints appear to miss boundary layer influence
- Compute predicted ^{222}Rn signal using two emission maps
  - Uniform 1 atom cm^{-2} s^{-1}
  - ^{222}Rn emissions scaled from soil ^{238}U maps
- Compare measured and predicted ^{222}Rn
- Exclude time points with anomalously low predicted:measured ratio
  - 6% data removed in 2008

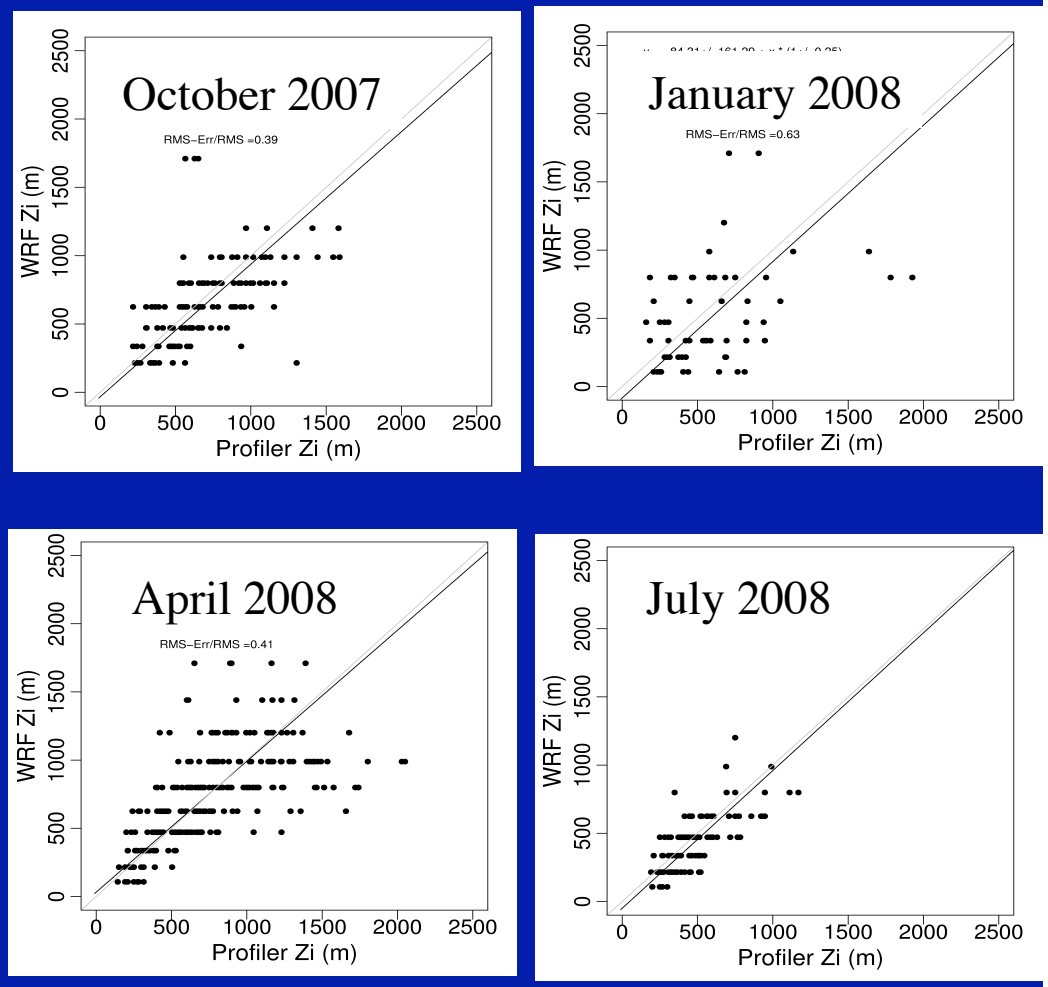


Uncertainty Estimation

- Quantify error sources
- Propagate errors through modeling system to provide quantitative uncertainties
  - Boundary layer ~ 25 %
  - Wind Velocity ~ 10%
  - GHG background ~ 15 %
  - Inventory resolution ~ 8 %
  - Other ~ 8%
- Quadrature sum ~ 32%

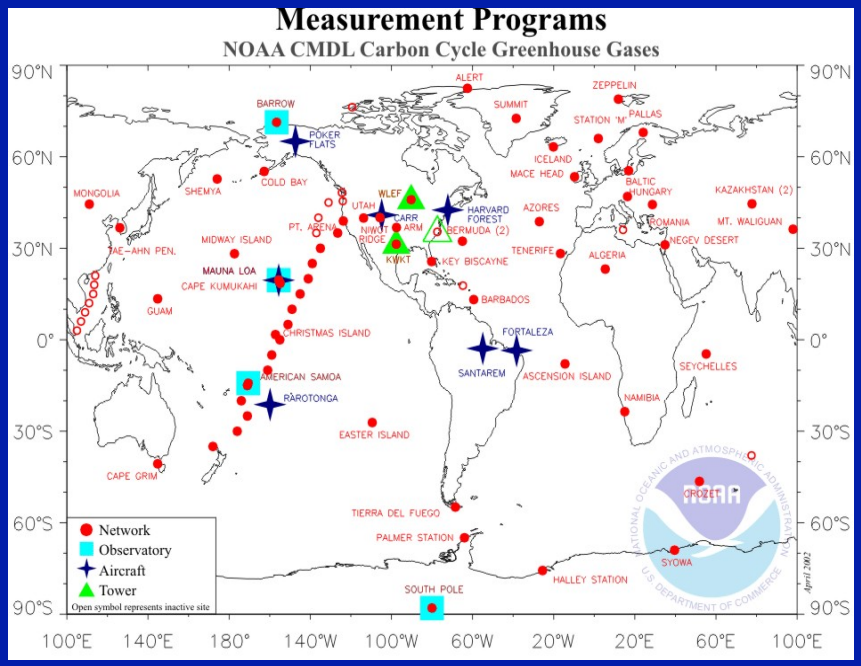
of signal for individual time points

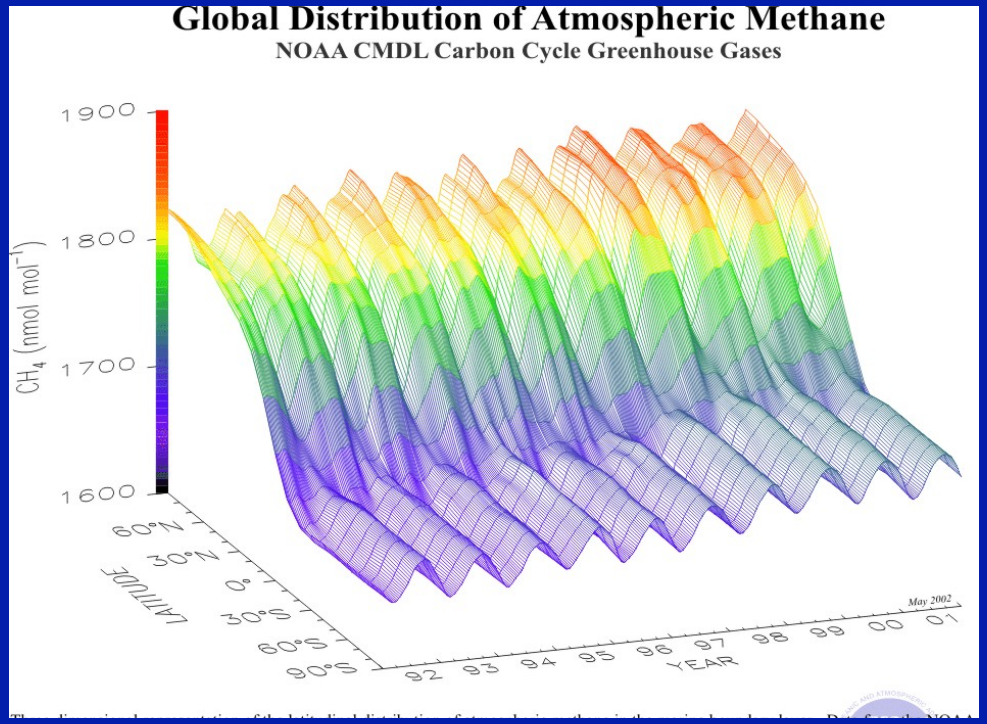
WRF-STILT versus Profiler PBL Depth



Global CH_4 Background

- Global monitoring provides data for emissions estimates
- CH_4 exhibits latitudinal gradient due to northern hemisphere sources

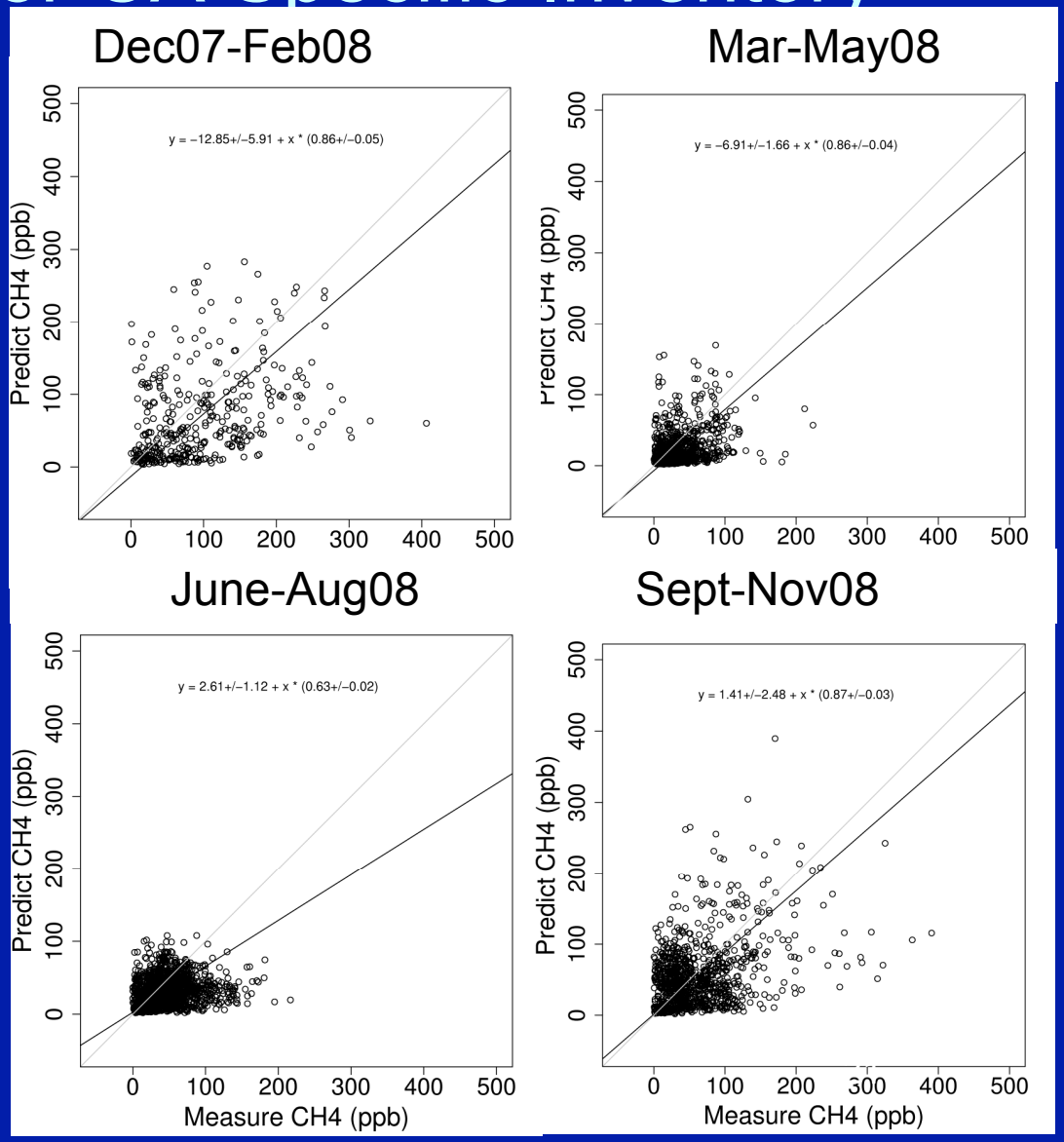




(NOAA-ESRL Global Monitoring)

Compare Measured and Predicted CH_4 by Season for CA Specific Inventory

- Scatter approximately consistent with estimated uncertainties
- CH_4 emissions appear under-estimated in CA inventory for most periods



Bayesian Linear Inverse Model

- Local signal $y = C - C_{bg} \sim \Sigma \lambda_i F_i f + \varepsilon$
  - Write cost function for y depending on both predicted-measured signal mismatch error, S_ε , and posterior-prior mismatch error S_{prior}

$$\underline{J} = (\underline{\underline{y - K\lambda}})^T \underline{\underline{S}}_\varepsilon^{-1} (\underline{\underline{y - K\lambda}}) + (\lambda - \underline{\lambda}_{prior})^T S_{prior}{}^{-1} (\lambda - \underline{\lambda}_{prior})$$

  - If $\varepsilon \sim N(0,\sigma)$, solution and resulting error are algebraic

$$\hat{\underline{\lambda}} = (\underline{\underline{K}}^T \underline{\underline{S}}_\varepsilon^{-1} \underline{\underline{K}})^{-1} (\underline{\underline{K}}^T \underline{\underline{S}}_\varepsilon^{-1} \underline{y} + \underline{\underline{S}}_{prior}^{-1} \underline{\lambda}_{prior})$$

$$\hat{\underline{\underline{S}}}_\lambda = (\underline{\underline{K}}^T \underline{\underline{S}}_\varepsilon^{-1} \underline{\underline{K}} + \underline{\underline{S}}_{prior}^{-1})^{-1}$$

where $K\lambda = \sum_{i,j,m} f(\underline{X}_r, t_r | x_i, y_j, t_m) \cdot F(x_i, y_j, t_m)$

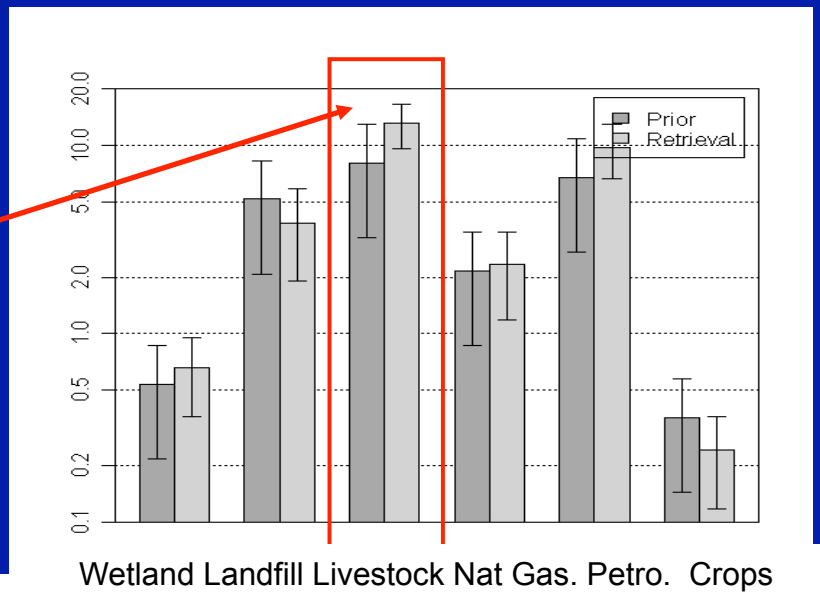
Oct-Dec07: Estimated CH_4 Emissions ($MMT\ CO_{2equiv}\ yr^{-1}$)

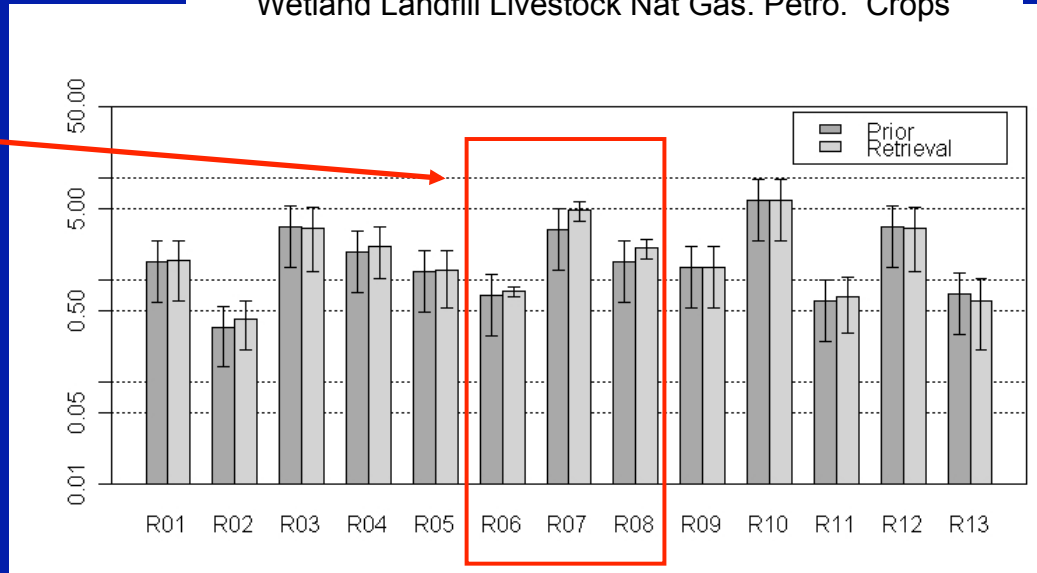
- Baysian estimate of scaling factor for each emission source or region (*a priori* errors assigned at 30%)

- Source analysis: only livestock significantly different from prior (x 1.6 ± 0.15)

- Region analysis:
  - only regions near WGC tower have errors reduced
  - regions 7 & 8 are larger than prior, consistent with source analysis

(Zhao et al., 2009, Journal Geophys. Res.)

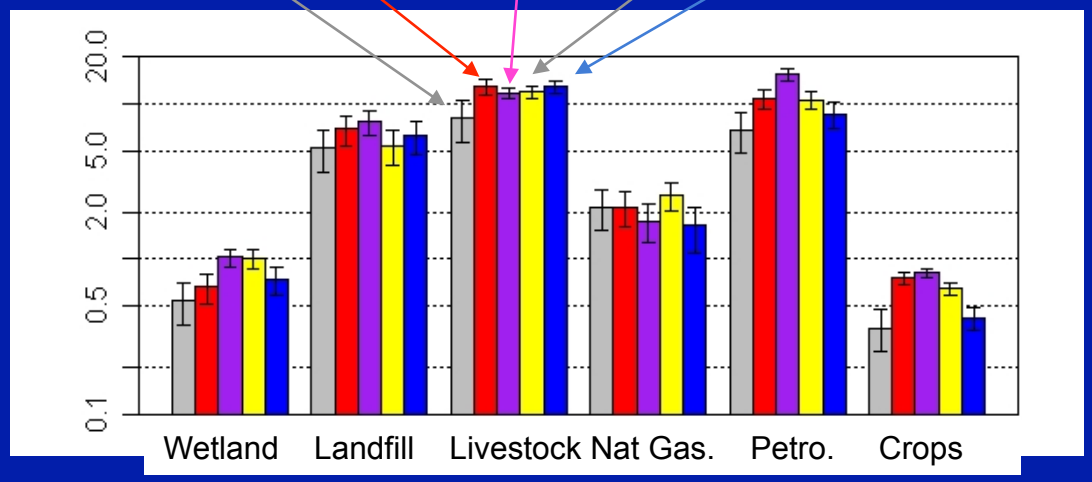




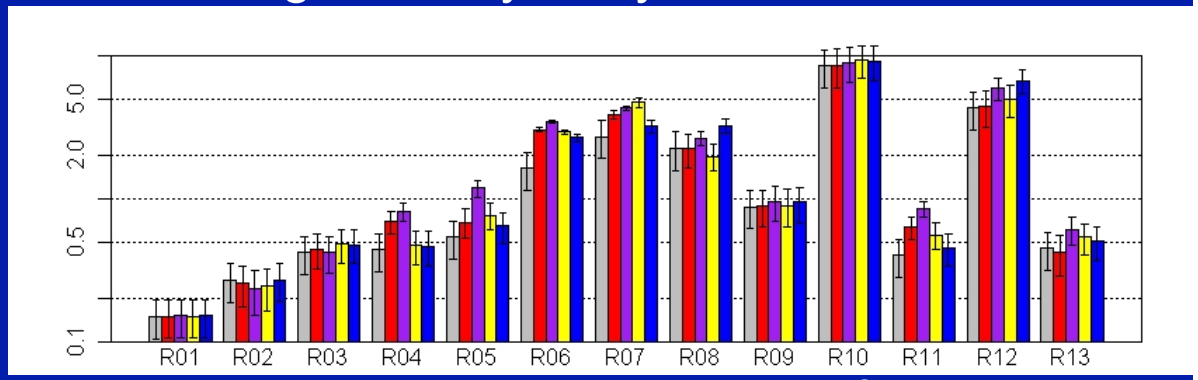
Seasonality in CH_4 Emissions

- Preliminary: Several sources show statistically significantly higher emissions in summer than summer
  - Partially consistent with inventory models
  - Imperfect spatial distributions of sources may bias attribution
  - Region analysis likely more reliable

Source Sector Analysis by Season

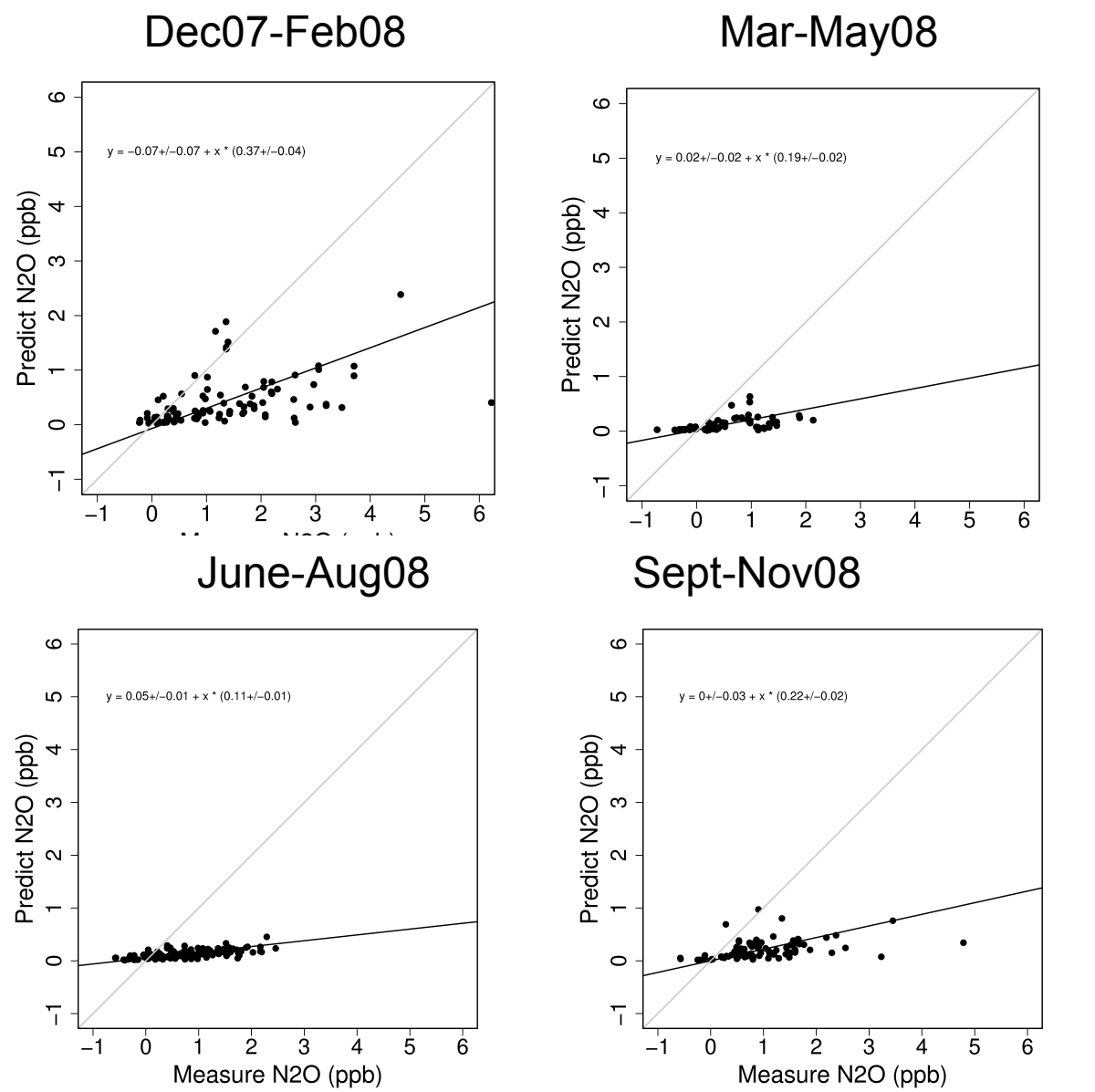


Region Analysis by Season



Measured and Predicted N_2O

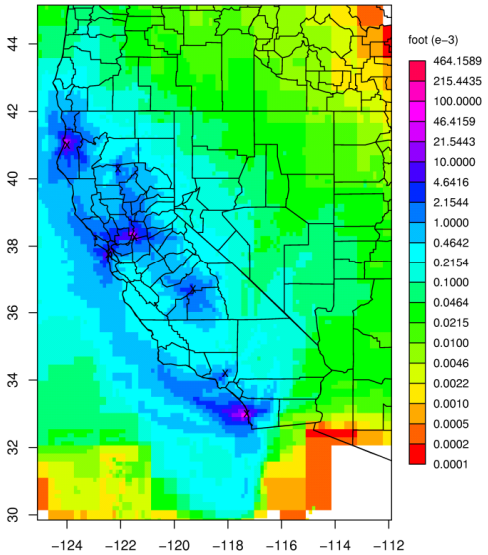
- Compare measured and predicted N_2O using Edgar 3.2 emission inventory
- N_2O flask data is sparse compared to *in situ* CH_4
- Slopes suggest actual emissions 2-8 x higher than inventory

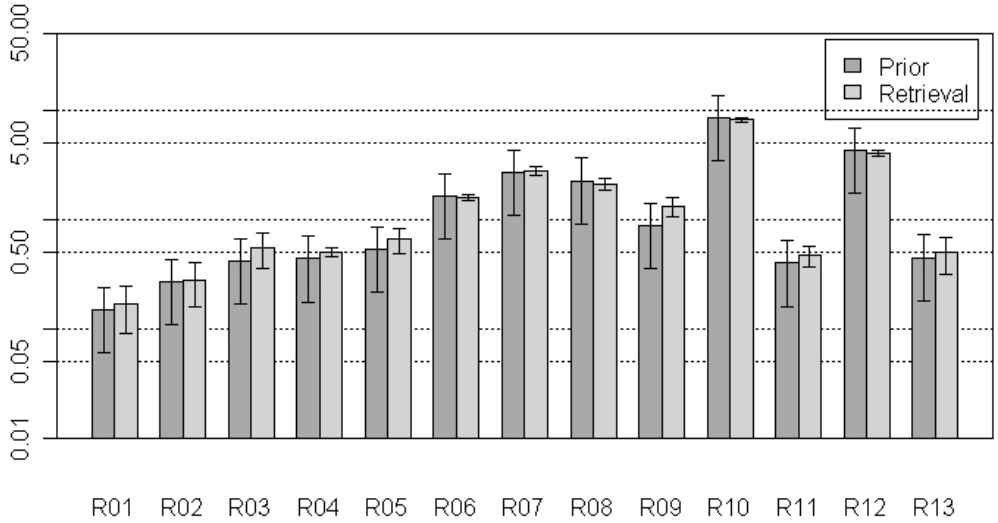


Measurement Network Design

- Estimate effect of seven (3 valley, 4 costal) tower network
- WRF-STILT footprints show predicted regional coverage for Oct, 2007
- Psuedo-data generated from footprints, inventory CH_4 emissions, and 32% random noise as estimated above
- Regional inverse estimates of posterior scaling factors show reduction in uncertainties for most regions

(Fischer, et. al, 2009, CEC)

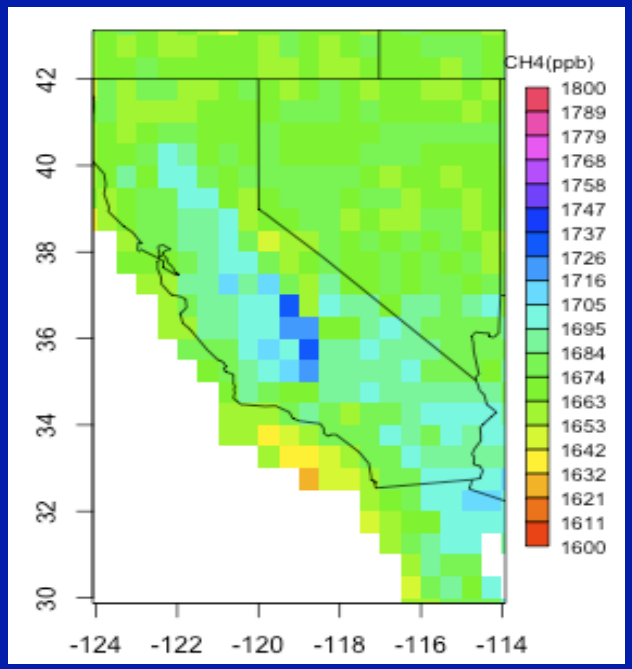




Further Work

- Apply analysis capability to growing network of tower,aircraft and satellite observations over California and Western US
- Incorporate statistical analyses to determine data-driven spatiotemporal distributions for emissions
- Explore data assimilation modeling to improve meteorological errors

SCIAMACHY (ENVISAT) CH_4



(courtesy C. Frankenberg)

Conclusions

- Careful attention to uncertainties essential for quantitative emission inventory assessment
  - Tower-based measurement errors are now small compared to other sources of uncertainty
  - Meteorological uncertainty appears dominant, requiring multiple measurements and methods (e.g., wind profilers, tracer gases)
- Initial inverse estimates of Central California emissions:
  - CA specific CH_4 ~ 20% low; Edgar ~ 20% high (summer?)
  - Edgar 3.2 N_2O emissions appear 2-8 x low
- Tall-tower measurements in valley appear to constrain ~ 100-200km region surrounding tower
  - Network of towers required to capture regional emissions from California
  - Satellite sensors will dramatically increase data density but uncertainty (particularly biases) require careful treatment

Thank You