From Wells to Burners: Methane Emissions from California Natural Gas

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- Problem Overview
  - Significance of Natural Gas (NG) Methane
  - Bottom-up Estimates of California NG methane emissions
- CALGEM-NG measurements
  - Regional NG Emission Measurements for SF Bay Area
  - UCD Airborne Measurements of NG Facilities
  - LBNL Mobile Plume Integration (MPI) Measurements
  - LBNL Residential Building and Appliance Measurements
- Summary and Recommendations

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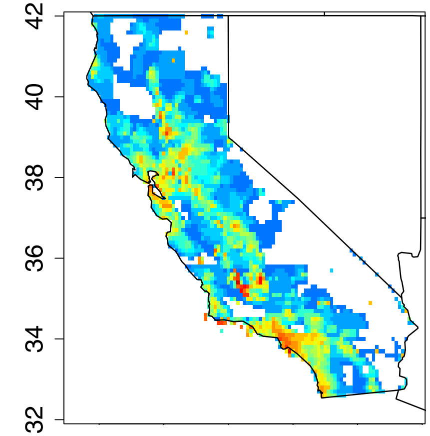
Problem Overview

- Natural gas provides ~40% of California fossil fuel energy
- Methane is a potent short lived climate pollutant
  - 3% of well-to-burner NG leaked as methane approximately doubles climate forcing of remaining 97% gas combusted to CO_2 on 20 year timescale
- CA and US now moving to control CH_4 emissions
  - 10-20% of California's total methane emissions likely from NG
  - Entire production to consumption chain susceptible to emissions
  - Measurements now fill some gaps in understanding across NG infrastructure

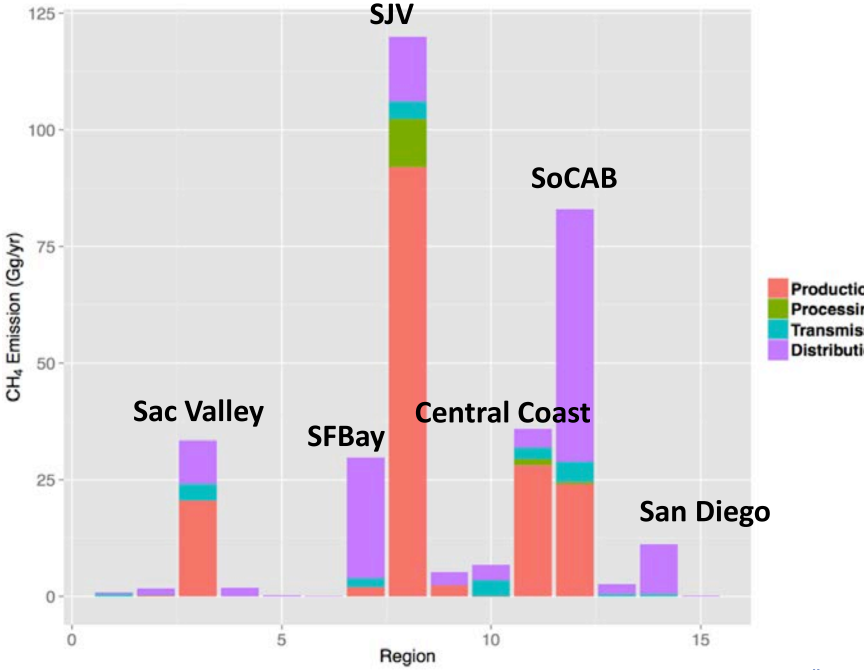
Bottom-up Natural Gas CH_4 Emissions

- Map emissions w/ 2010/2011 US-EPA emission factors and CA specific GIS activity data
  - Production: Dry gas and petroleum wells
  - Transmission, compression, and storage
  - Distribution & consumption
- Estimated NG emissions ~ 330 Gg CH4 yr^{-1} (-20% to + 30% @ 95%)
  - Top-down studies in SoCAB suggest higher NG emissions (Peischl et al., 2013, Wunch et al., 2016)
  - 2016 US-EPA estimates increase production but decrease distribution emissions
  - NG is still small fraction of total California CH_4 emissions

CALGEM-NG Methane Flux (nmol m^{-2} s^{-1})



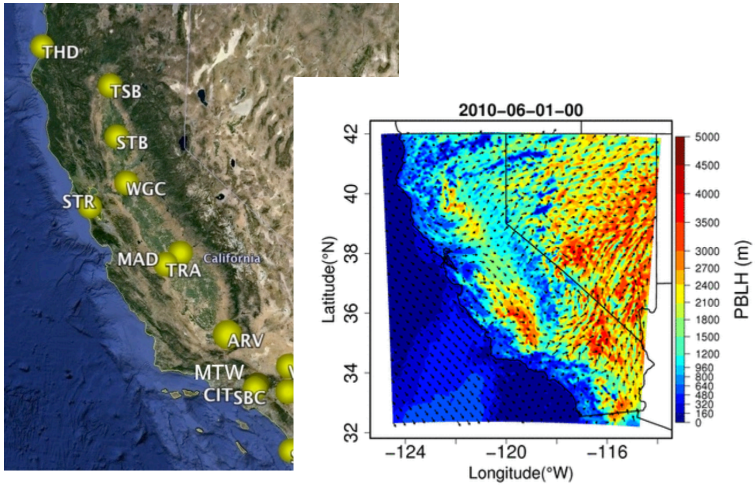
(Jeong et al., 2014)



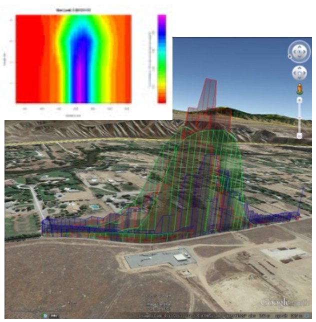
CALGEM-NG CH_4 Measurements

- Regional Emissions
  - Tower measurements
  - Atmospheric Inversions
- Large Facilities
  - Aircraft Observations
- Localized Sources
  - Mobile Plume Integration
  - Building Studies

Collaborative tower measurements
Atmospheric Regional Inverse Modeling



LBNL Plume Integration



UC Davis Mass-balance

UC Irvine VOC

LBNL Building Science

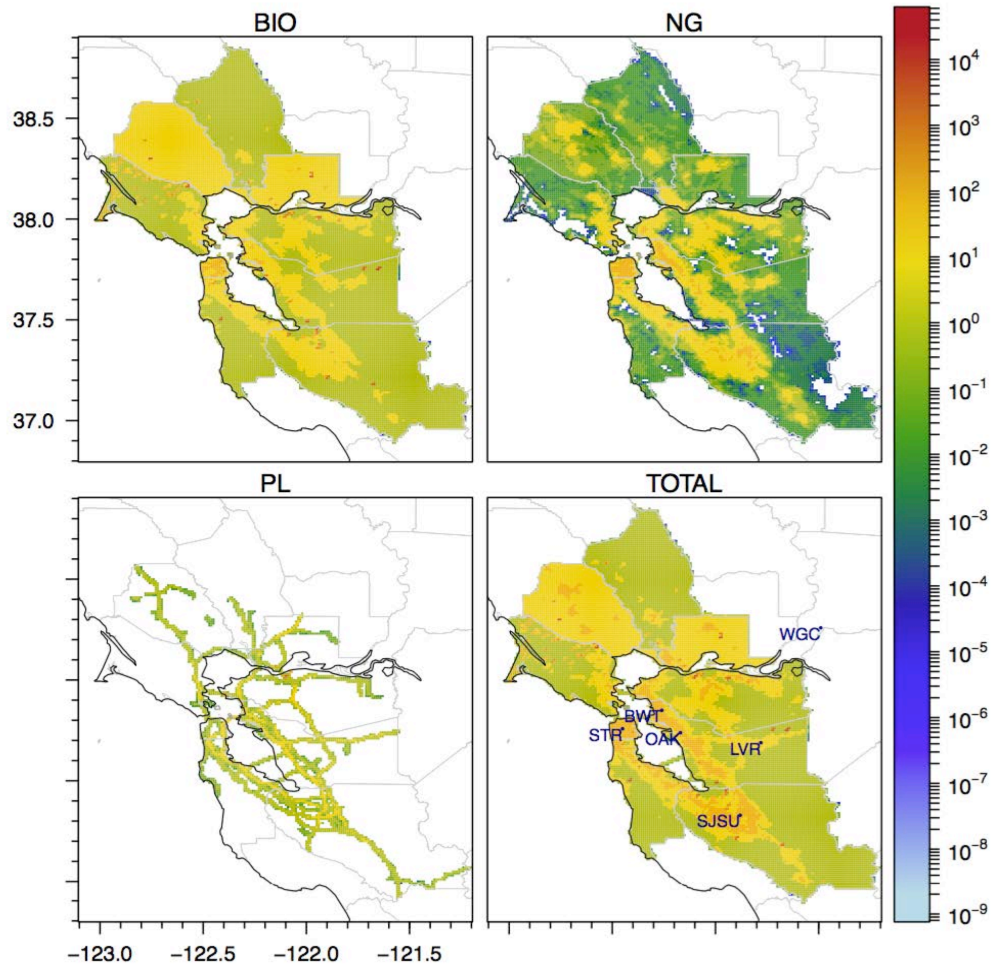
Regional NG Emission Estimate for San Francisco Bay Area

- Oct-Dec, 2015 sampling at six collaborative sites
  - CH_4, ethane, pentane, toluene, CO, and other VOC
  - Livermore hourly CH4 & VOC
  - Daily flask sampling at other sites analyzed at NOAA and UCI
- Fossil VOC:CH_4 compositions adopted from PG&E gas reporting, airborne measurements, and previous mobile source studies (e.g., Kirchstetter et al., 1996)

SFBA Biological and Fossil CH_4 Sources

- Biological sources
  - Landfill 51%
  - Livestock 15%
  - Wastewater 6%
  - Wetland 3%
- Fossil sources
  - NG distribution 15% (0.2% NG consumption)
  - Mobil and refining 4%

SF Bay CH4 Emissions at 1 km



Sector Specific SFBay CH_4 Inversion

$$\begin{bmatrix} C_{CH_4} - C^*_{bg} \\ C_{C_2H_6} - C^*_{bg} \\ C_{iC_5H_{12}} - C^*_{bg} \\ C_{nC_5H_{12}} - C^*_{bg} \\ C_{C_7H_8} - C^*_{bg} \end{bmatrix} = \begin{bmatrix} FE_{S\backslash NG_{PL}} & FE_{NG} & FE_{PL} \\ 0 & FE_{NG} f^*_{C_2H_{6NG}} & FE_{PL} f^*_{C_2H_{6PL}} \\ 0 & 0 & FE_{PL} f^*_{iC_5H_{12PL}} \\ 0 & 0 & FE_{PL} f^*_{nC_5H_{12PL}} \\ 0 & 0 & FE_{PL} f^*_{C_7H_{8PL}} \end{bmatrix} \begin{bmatrix} \lambda_{S\backslash NG\_PL} \\ \lambda_{NG} \\ \lambda_{PL} \end{bmatrix}$$

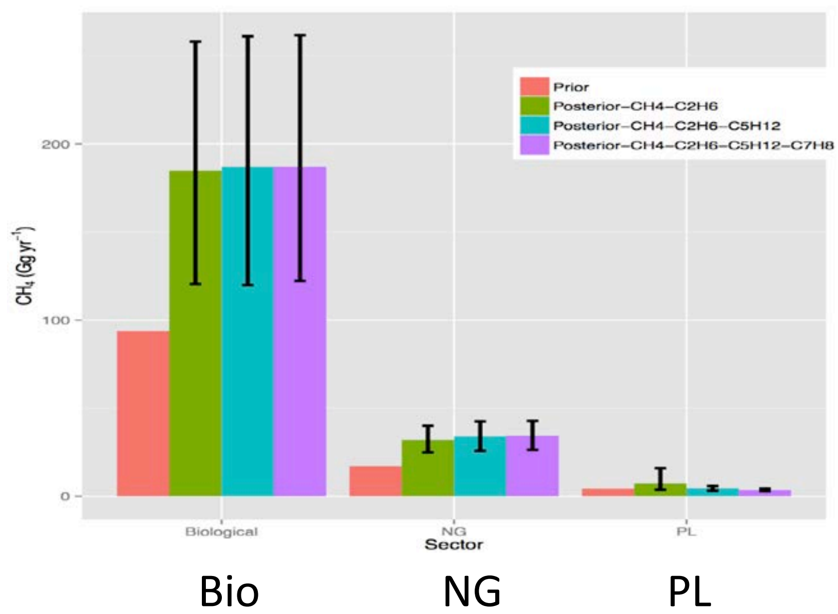
- Inversion of biological, NG, and petroleum CH_4 emissions constrained by CH_4 and VOCs
- Hirarchical Bayesian estimates optimize background offsets, VOC source compositions, and emission scaling factors

Preliminary results:

1) Biological CH_4 dominates
2) NG emissions higher than prior at 0.3-0.5% SFBA NG consumption (Jeong et al., in prep)

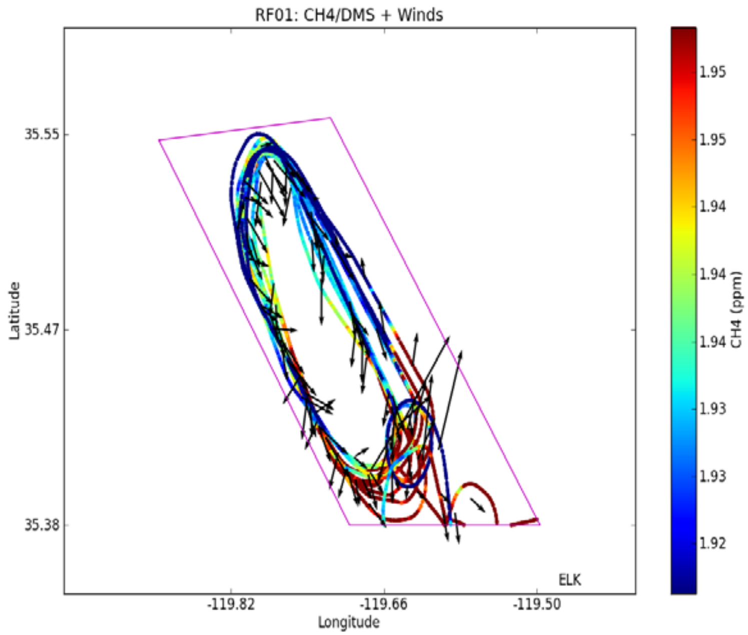
- Approach amenable to sustained observations in other locations

Posterior CH_4 by Sector



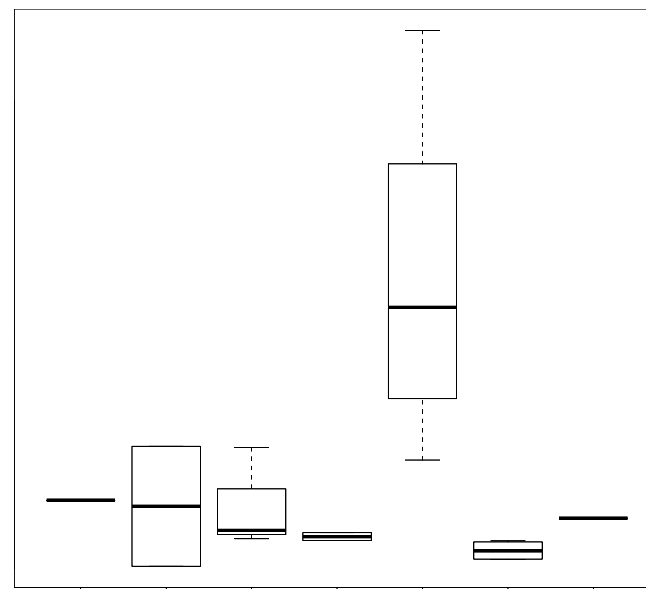
Facility Specific Emissions
San Joaquin Valley Production

- UCD Airborne mass balance measurements
- Example: April, 2014 Belridge South petroleum production field w/ steam injection
  - Clear downwind enhancements of CH_4 and ethane
- Emissions estimated from mass balance flight 1900 +/- 700 kg CH_4 hr^{-1} (17 +/- 6 Gg CH_4 yr^{-1})
- Bottom-up 15 – 20 Gg CH_4 yr^{-1}
- Collaborative observations of Kern River/Front fields show emissions varied with well completion (Leifer et al., in prep)



Facility Level Emissions: Natural Gas Storage

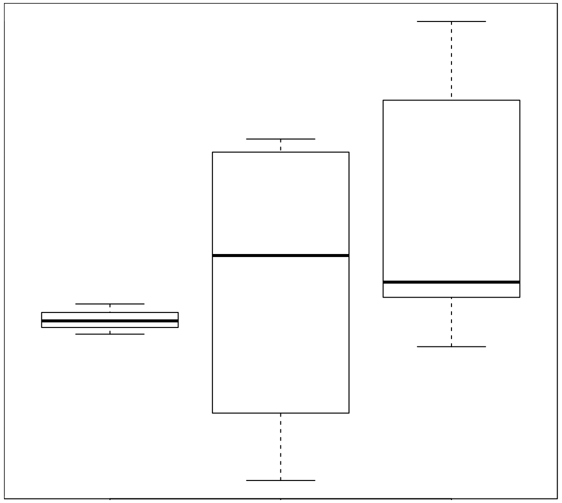
- UCD Airborne mass balance measurements
  - Four sites observed 3-8 times from June, 2014 – May, 2016 (+ four others recently)
  - Emissions vary from ND to > 400 kg CH_4 hr^{-1}
  - Median emissions ~ 1 – 2 x annual voluntary reporting
  - C_2H_6:CH_4 ~ 5% by vol., - consistent w/ NG
  - Single point failures carry high risk: Oct,2015-Feb, 2016 Aliso Canyon well failure ~ 30% annual total CA fossil CH_4 emissions



(Mehrota et. al., in prep)

Facility Level Emissions: Petroleum Refining

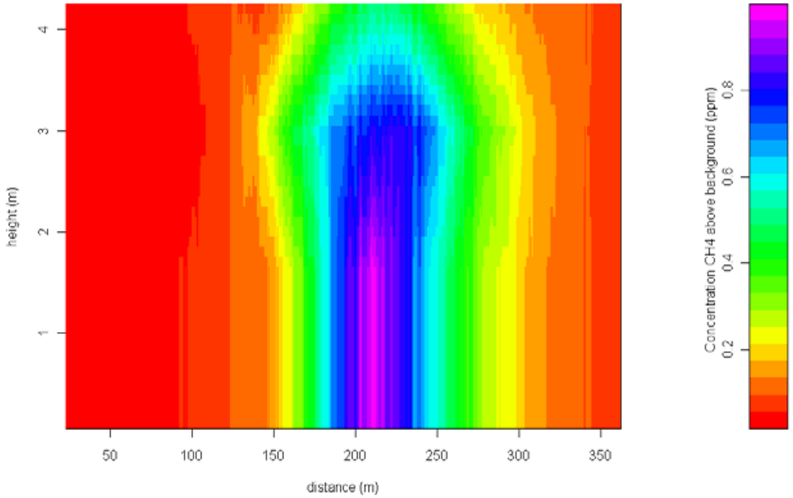
- UCD Airborne mass balance measurements
  - Three refineries observed 3-5 times from Feb, 2015 – May, 2016
  - Emissions varied by site and date ~ 30 - 700 kg CH_4 hr^{-1}
  - Median emissions exceed annual emissions (4-25 x) reported to US-EPA
  - $C2H6:CH_4$ 6-10% by vol.



(Mehrota et. al., in prep)

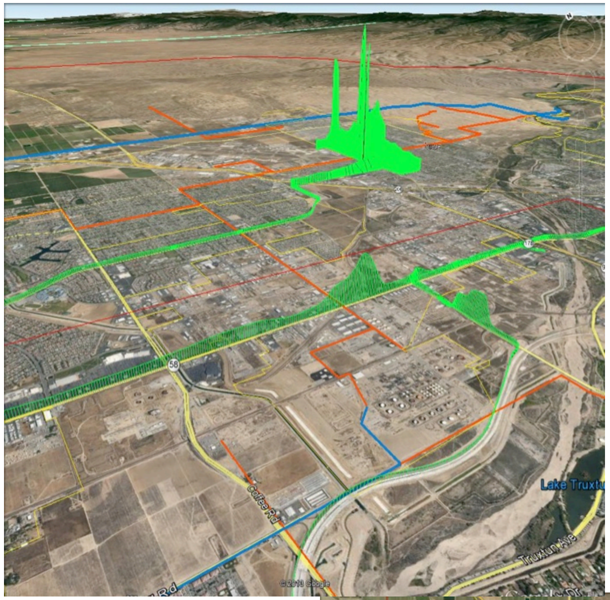
Localized Source Emissions
LBNL Mobile Plume Integration (MPI)

- Cross-wind integral of CH_4 enhancement flux quantifies localized plume emission
  - Sample inlets can be set to 4-8 m above ground
  - Multi-analyzer system w/ $^{13}CH_4$ allows NG attribution for strong plumes
  - Anemometry of wind velocity
  - Tests at LBNL and local utilities show 30% accuracy with 3 passes with steady winds & small obstructions

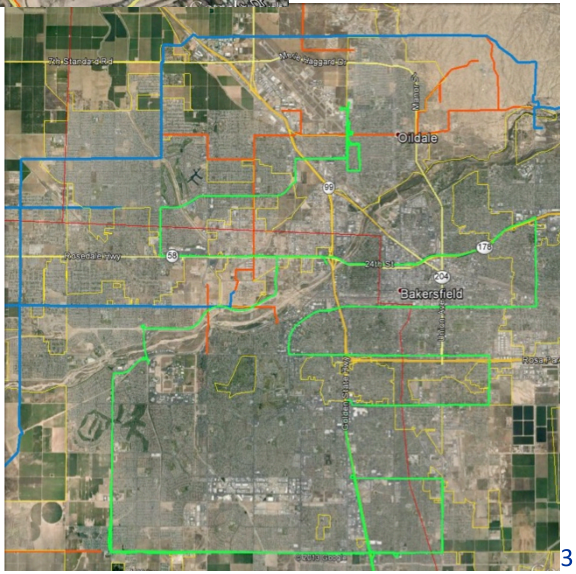


Localized Plume Measurements: Bakersfield Distribution & Consumption

- Survey 80km of Bakersfield public streets
- Detect 20 large (~ 1 ppm) leaks above background
- 40% of total emissions found within 0.5 km of large distribution pipes
- Plume integrations yield total emissions of 6.4 kg CH_4 hr^{-1}
- Scaling by area suggests total emissions ~ 90 kg CH_4 hr^{-1}
- Comparing with consumption suggests ~ 0.3% distribution leakage – similar to bottom up



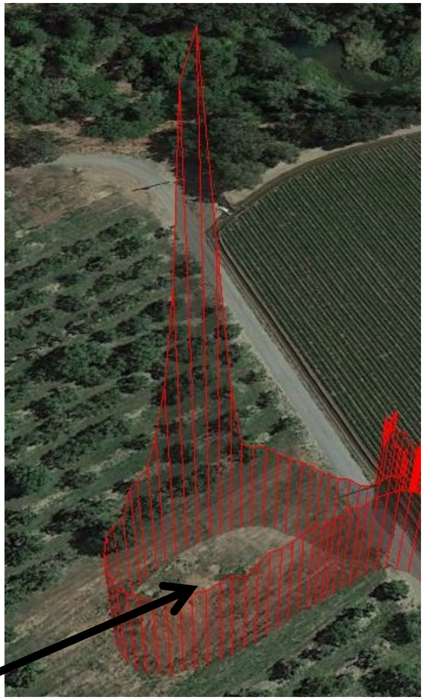
CH_4 enhancements (green), distribution (orange) and transmission (blue) pipelines



Localized Plumes: Sacramento Delta Gas Wells

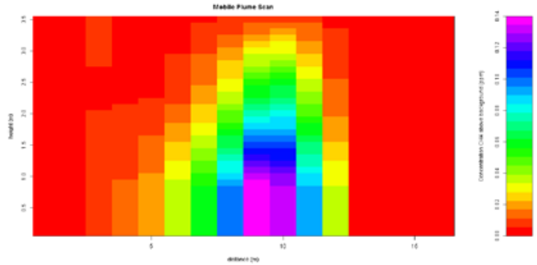
- CA Dept. Cons. well map data
- Initial inspection of 13 capped or idle wells
  - Quantify one plume 5 +/- 1.7 g CH^4 hr^{-1} (5 passes)
  - Detected three plumes 1.6-14 g CH_4 hr^{-1} (1pass each)
  - Non-detect downwind at 2 sites
  - 7 sites did not allow downwind access

Methane Plume



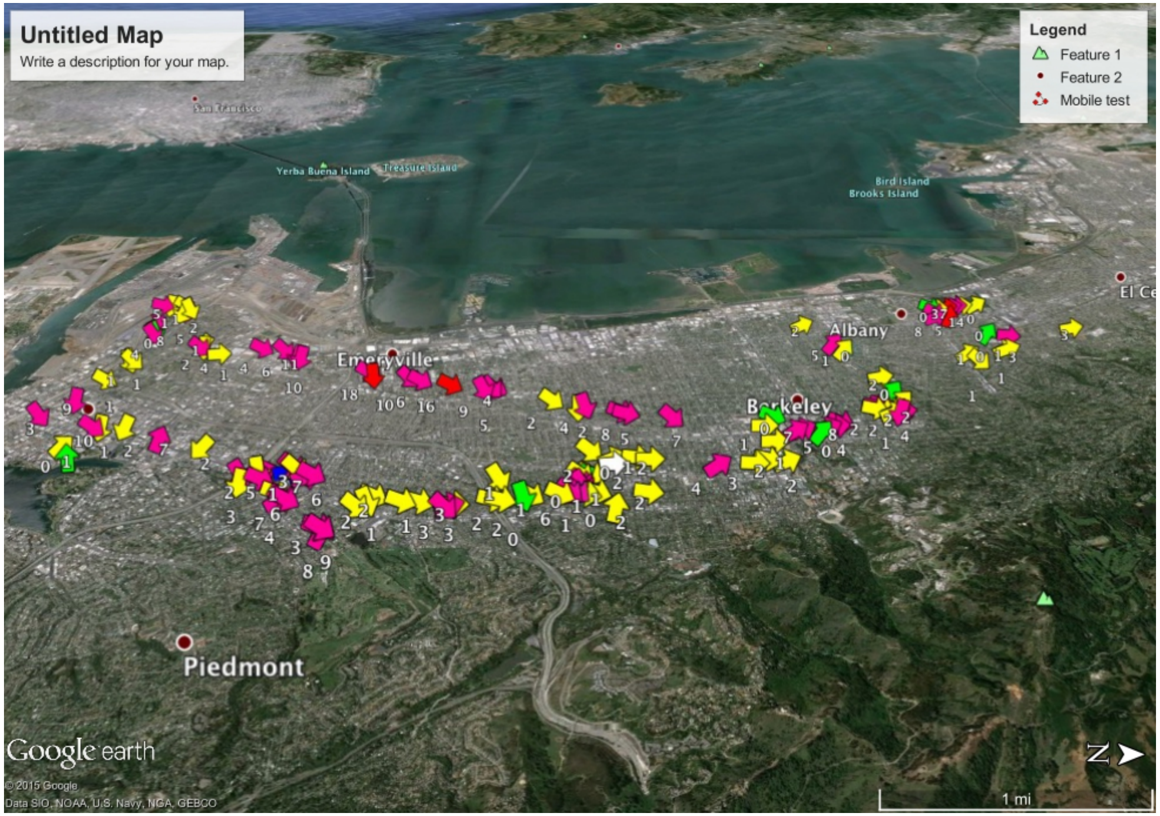
Capped well

CH_4 Enhancement in vertical plane

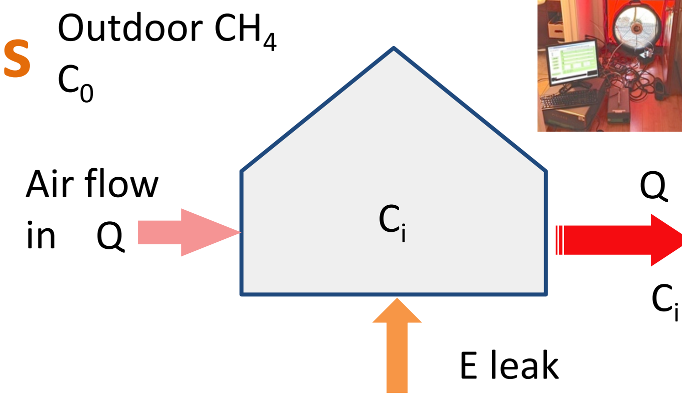


Localized Sources:
East Bay Distribution & Consumption

- Small (<< 1 ppm) CH_4 plumes observed in SF East Bay
- Individual plumes emit ~ 0.07 – 0.3 g CH_4 hr^{-1}
- Emissions largest on commercial avenues w/ food service
- Total emissions ~ 5 g CH_4 hr^{-1} over 30km route



Whole Building Measurements: Quiescent Residential Emissions

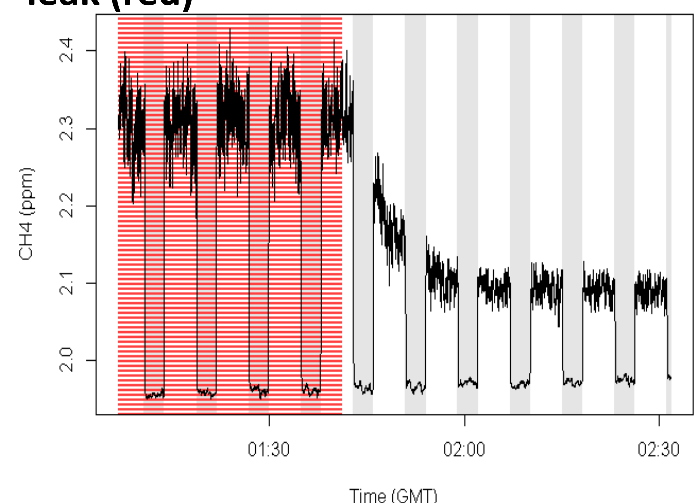


- Measurements
  - Depressurize house producing controlled inflow of outdoor air
  - Measure CH_4 enhancement relative to outdoor air
  - $^{13}CH_4/^{12}CH_4$ identifies NG vs. biological
- Results from 10 SF Bay homes
  - Median leak rate 0.2 g CH_4 hr^{-1} (0.1-0.4 g CH^4 hr^{-1} lower-upper quartiles)
  - Equivalent to ~ 0.2% of house consumption
- CEC project underway to measure 50-75 homes across CA housing stock

$$C_0Q + E = C_i Q$$

$$E = Q\,(C_i - C_0)$$

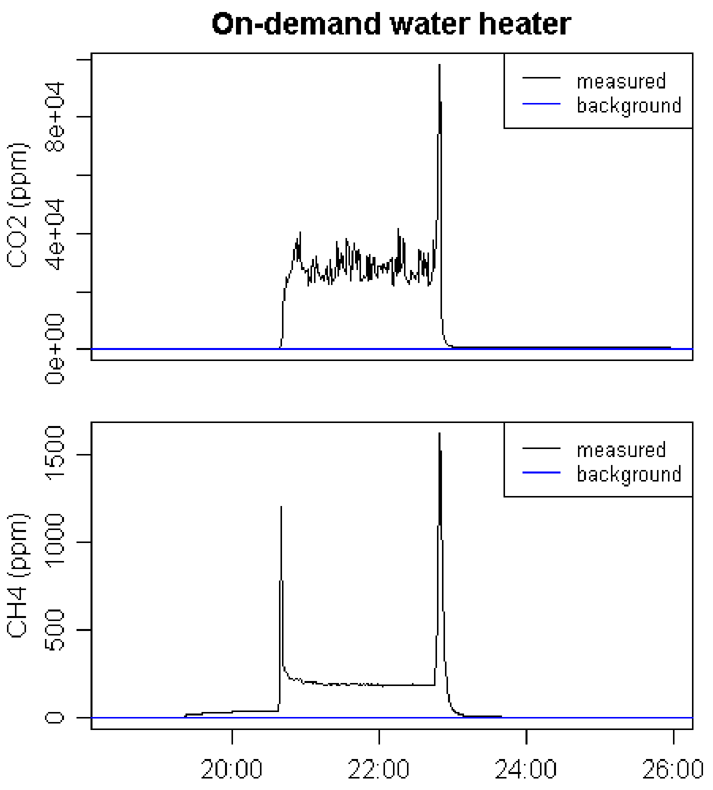
Measured indoor (white) and outdoor (grey) methane during calibrated indoor leak (red)



Combustion Appliance Emissions

- Emission Ratio Method
  - Emission = product of CH_4:CO_2 enhancements * measured NG usage
- Tank-less water heaters
  - Test of three tank-less water heaters yield emissions of 3 - 12 g CH^4 hr^{-1}

  (1 hr operation ~ equal 1 day of quiescent house leakage)
- Clothes Driers and Gas Cooktop
  - One gas range emitted ~ 2 g CH^4 hr^{-1} in continuous operation
  - Two clothes driers emitted ~ 0.4 g CH^4 hr^{-1} emissions in continuous operation



Summary

1. CH_4 emissions present across all NG subsectors from wells to burners
2. Regional inversions suggest emissions from SFBA distribution ~ 0.3-0.5% of NG consumption
3. Production field measurements (limited but) ~ consistent with bottom-up but expect variability (particularly well completion)
4. Gas storage facility emissions variable but ~ consistent with reporting
5. Petroleum refining emissions appear larger (4-25 x) than reporting
6. Localized emissions in distribution & consumption sectors measurable and appear to ~ scale with gas throughput

Recommendations

1. Daily multi-species tower measurements needed for inversion-base verification of regional integrated NG CH_4 emissions
2. Plume imaging from ground, air, and space needed to identify local emission hotspots to guide site specific quantification and mitigation
3. Mass balance flights and mobile plume integration needed for quantitative assessment of facility and localized source emissions
4. Continuous (open-path or multi-point CH_4) sensing valuable for ongoing leak detection at high volume/flow facilities
5. Energy efficiency programs would benefit from added leak detection and repair procedures and revised standards guidance for low-emission appliances