Urban Atmospheric Observations & Fluxes of:

Methane in Boston, Massachusetts

by Kathryn McKain

&

Carbon-dioxide in the Northeast, U.S.

by Maryann Sargent

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CMS Atmospheric Validation Working Group

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With contributions from colleagues at:

Harvard, Boston University, AER, Aerodyne, and Earth Networks

Why focus on urban areas?

Cities represent large, concentrated source areas that encapsulate multiple important anthropogenic source processes and trends

-> Tracking and verification of reported regional or national trends

-> Test bed for linking atmospheric observations from different platforms, covering different scales

-> Opportunity to link observations to underlying flux processes and drivers

-> Opportunity to translate results to actionable emission mitigation strategies

Boston GHG Network Research Activities

- Atmospheric Observations
  - In-situ CO_2 & CH_4
    - 5 stations in Boston network
    - Earth Networks and NOAA stations form regional network
  - Ground-based Remote Sensing
    - Upward-looking FTS (J. Chen, T. Jones, K. Chance)
    - Lidar measurements of aerosol backscatter (P. DeCola, Y. Barrera, J. Hegarty)
- High-resolution models of anthropogenic and biosphere CO_2 fluxes (L. Hutyra, et al.)
- High-resolution WRF meteorology (T. Nehrkorn, et al.)

Methane emissions from natural gas infrastructure and use in the urban region of Boston, Massachusetts

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Motivation:

- Uncertainty in source distributions in space, time and sector
- Major recent focus on CH_4 emissions in U. S. from natural gas
  - Especially from *production*
- Scant knowledge of CH_4 emissions from *consuming regions*

Study Objectives – Determine:

- CH_4 emissions from the whole urban area for 1 year
- Fractional contribution of natural gas
- Ratio of natural gas lost to the atmosphere versus natural gas imported to the region ("loss rate")
- Investigate seasonal variations

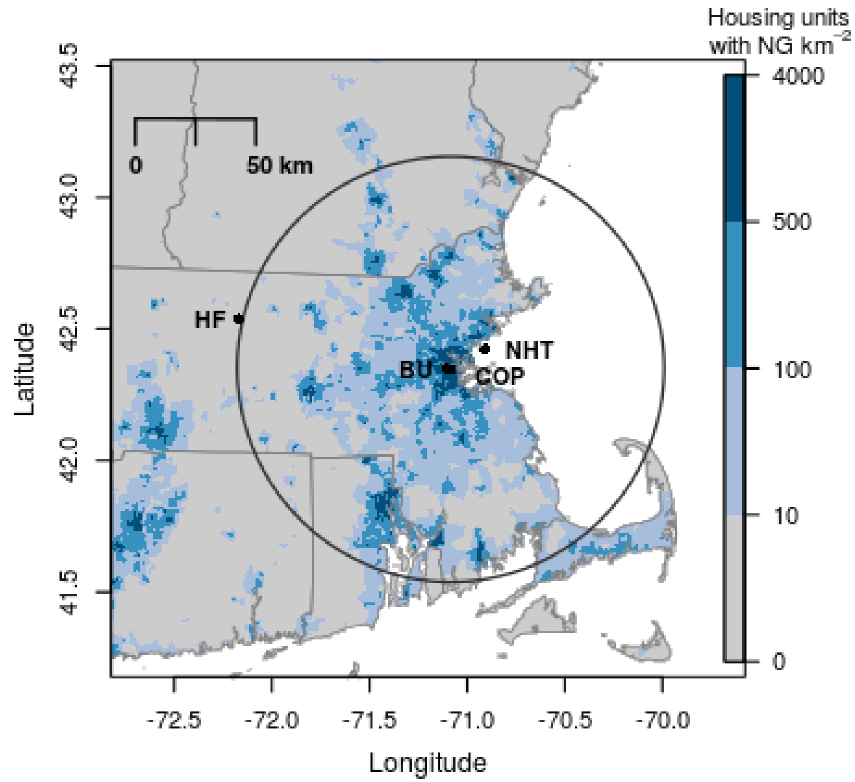
Domain:

90 km radius circle centered on Boston (18,000 km^2 land area)

Time Period:

September, 2012 – August, 2013 (1 year)

* Captures emissions from all NG activities in region: transmission, distribution, end-use, LNG importation & storage, CNG vehicles



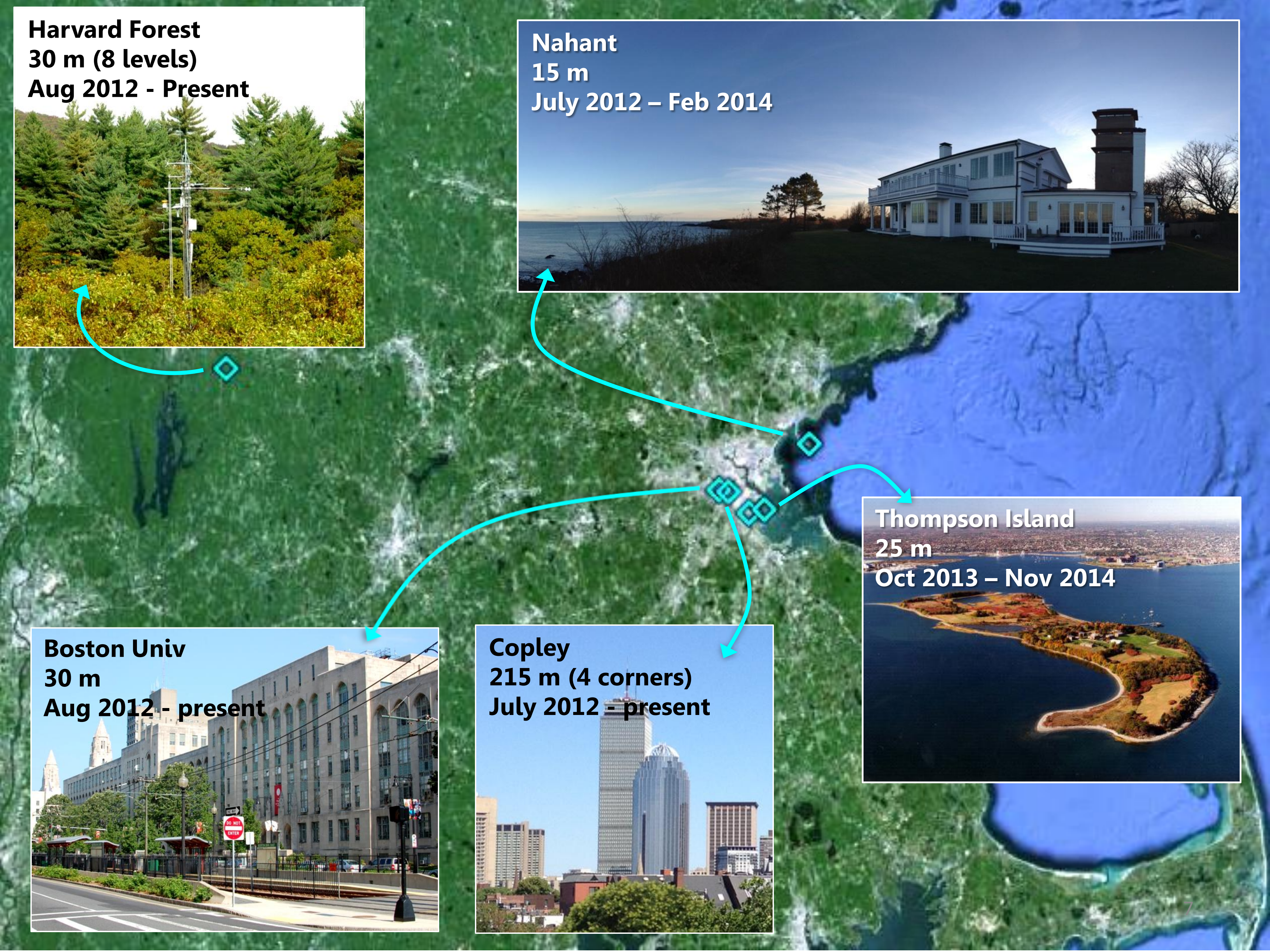
Methodological Framework

1. **Atmospheric CH_4 Measurements**
   – Continuously from inside and outside of the city
   → *Urban CH_4 enhancement (ΔCH_4) $\propto$ urban CH_4 emissions*

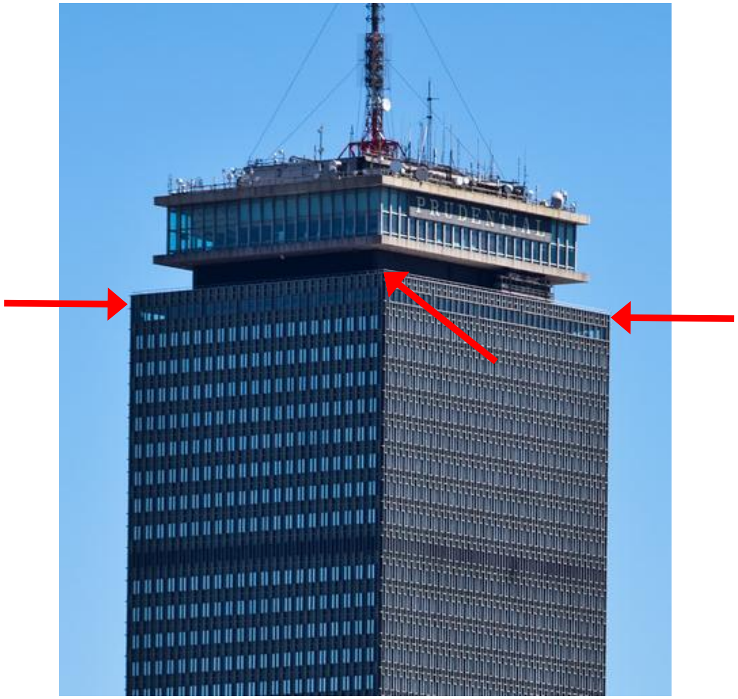
2. **Atmospheric and Pipeline Ethane (C_2H_6) Measurements (Aerodyne)**
   – C_2H_6 is a component of NG but is not co-emitted with CH_4 from biological sources
   – Compare ratio (C_2H_6:CH_4) in the atmosphere and pipeline
   → *Fraction of CH_4 emissions in the city due to NG*

3. **Atmospheric Transport Model (AER)**
   – **WRF-STILT** Lagrangian Particle Dispersion Model
   – Simulates sensitivity of obs to upwind surface fluxes (footprint, units: Δ ppb / (µmole m^{-2} s^{-1}))
   → *Emissions optimized to match observations*

4. **Natural Gas Consumption Map**
   – Spatial disaggregation of EIA monthly-state-sector totals
   → *Fraction of NG imported to the region lost to the atmosphere ("loss rate")*


Harvard Forest
30 m (8 levels)
Aug 2012 - Present
Nahant
15 m
July 2012 – Feb 2014
Thompson Island
25 m
Oct 2013 – Nov 2014
Boston Univ
30 m
Aug 2012 - present
Copley
215 m (4 corners)
July 2012 - present

Tall Building Sampling Strategy



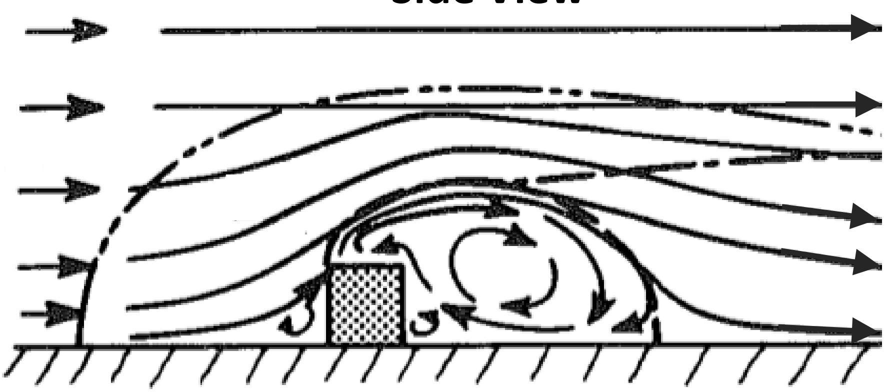
Challenges

- Building emissions
- Perturbed Air Flow

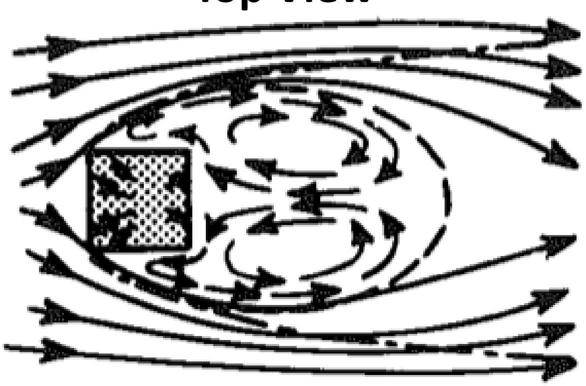
Approach

- Sample below roof from 4 corners in sequence
- Select windward corner according to observed concentrations

Side View

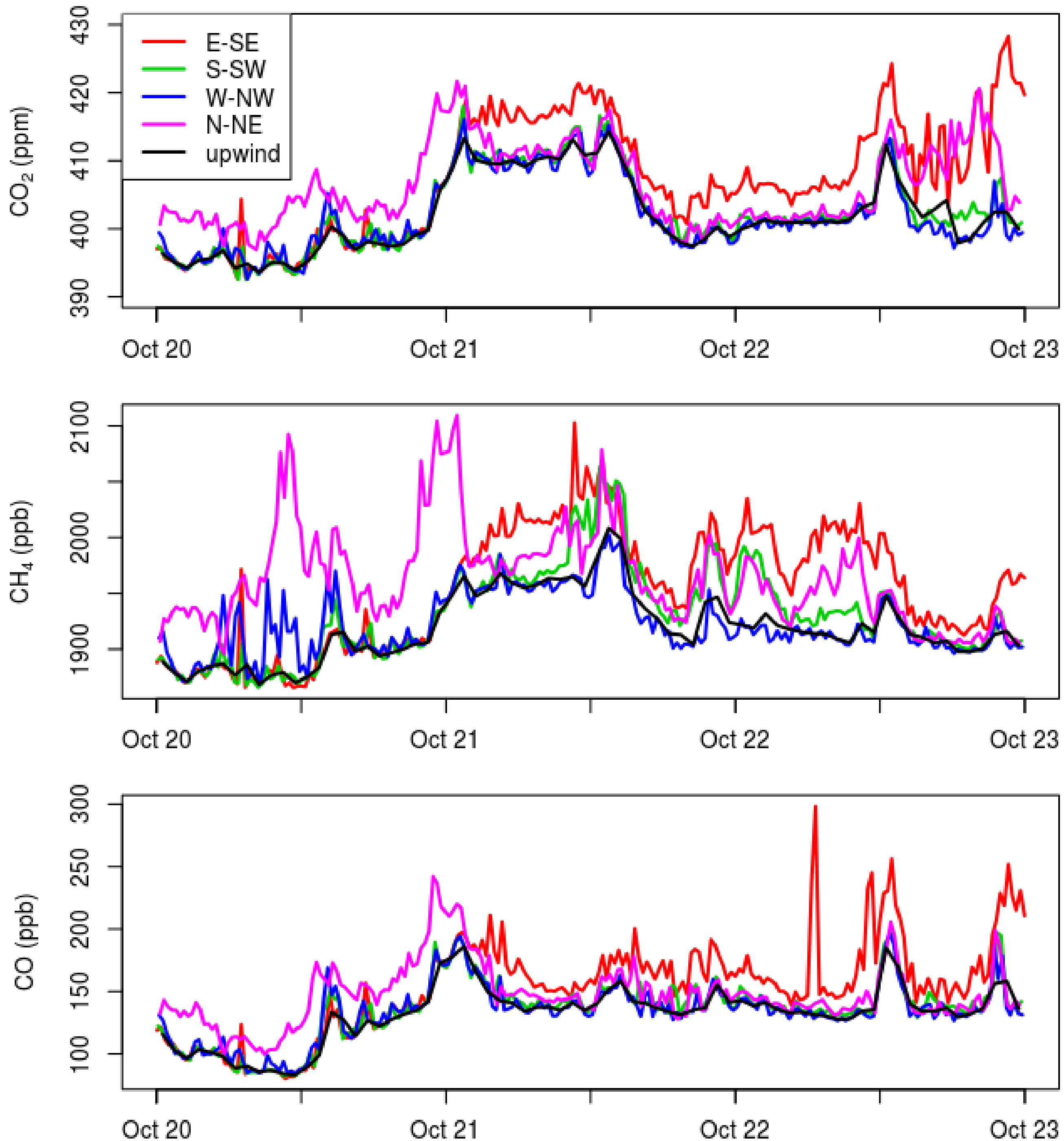


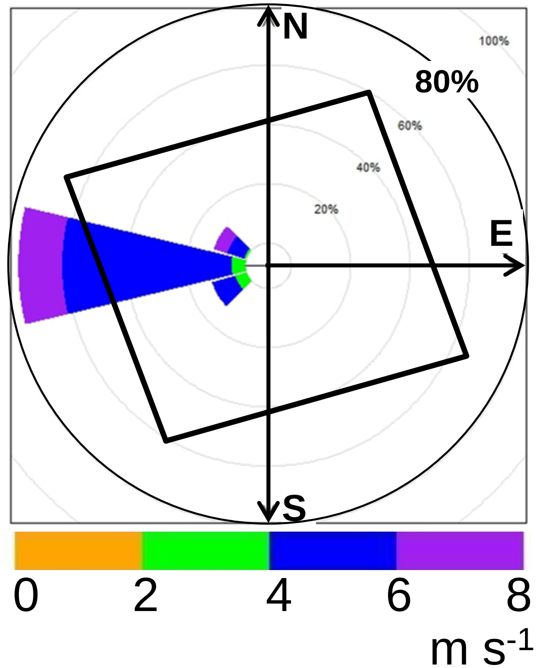
Top View



from Oke, Boundary Layer Climates

Four-corners Data Example





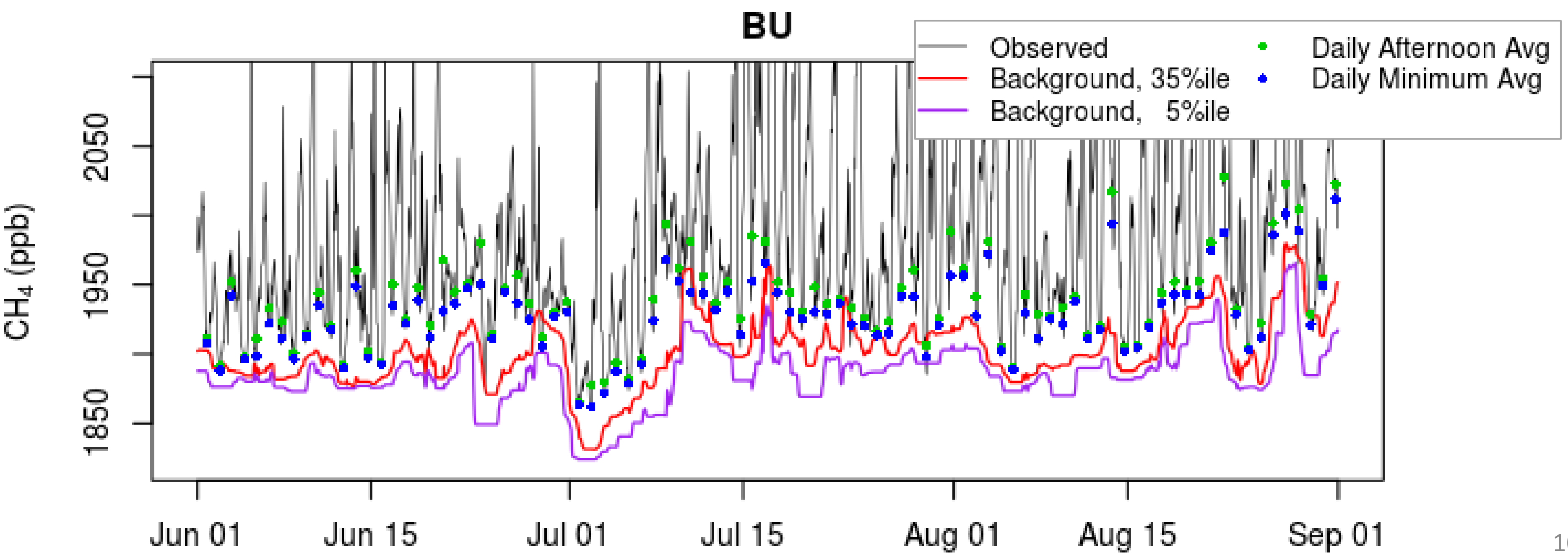
Methane Observations

Background:

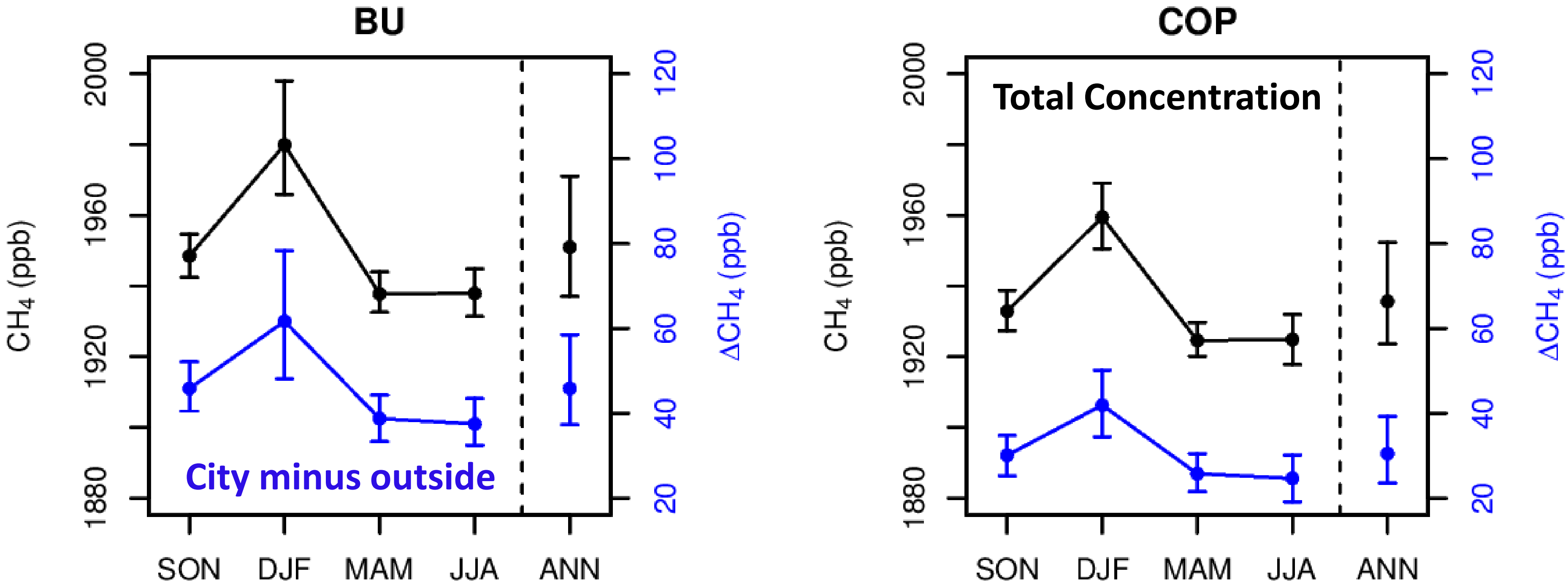
- Two upwind stations
- Station selection based on wind direction
- Distributions generated from 48-hr moving averages of lower percentiles

Methane Enhancement (ΔCH_4) =

- Urban - Background concentrations
- Daily afternoon (11-16 h EST, 16-21 h UTC) averages

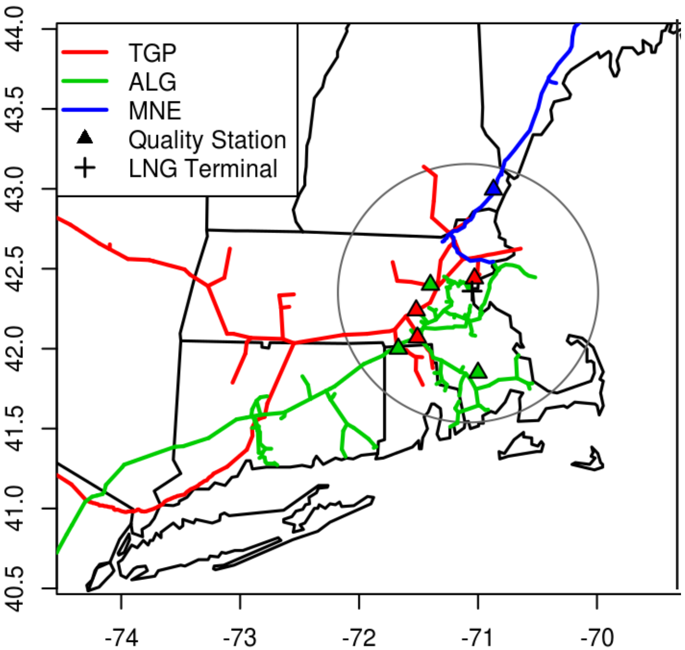


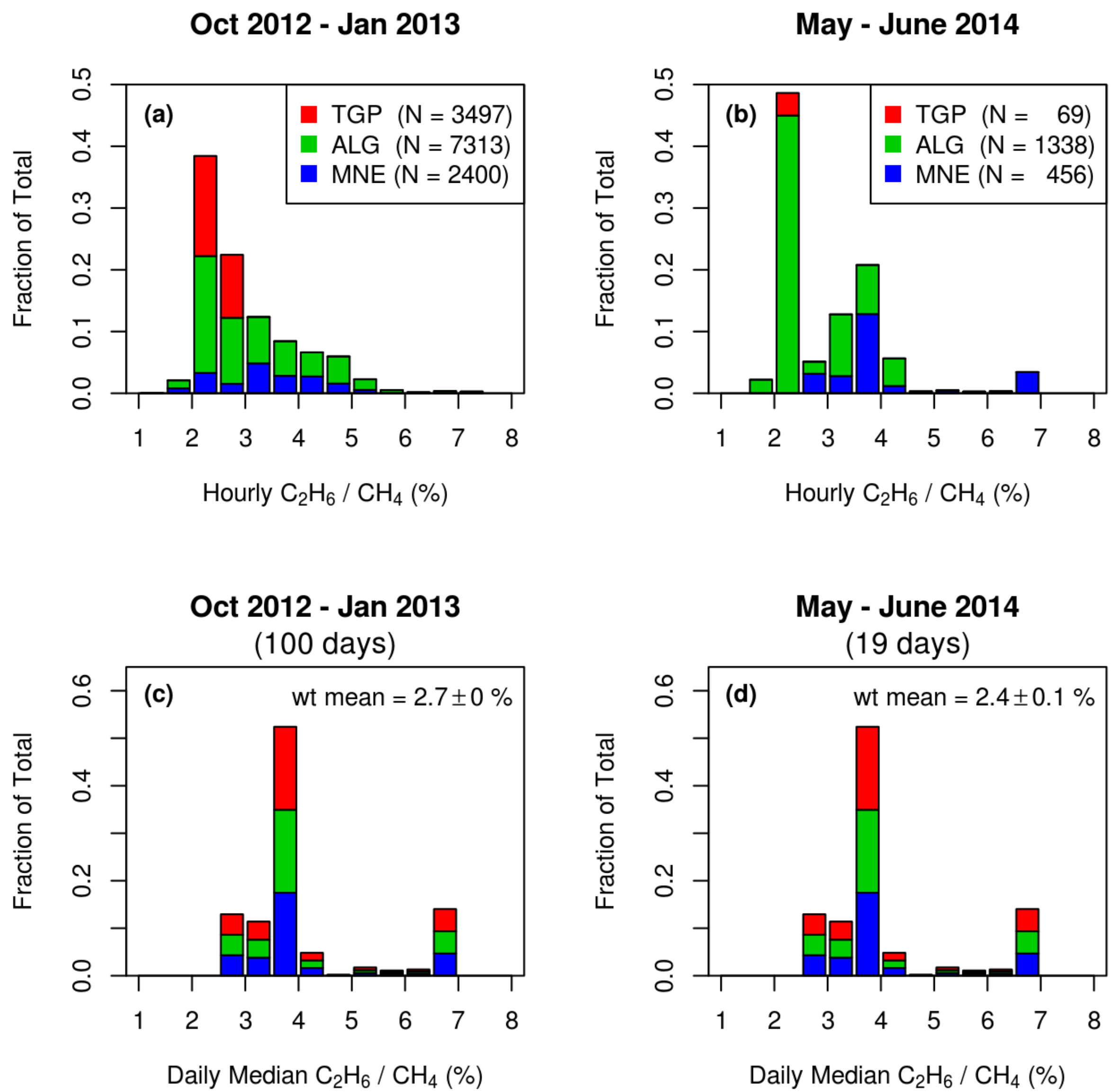
Persistent Urban Methane Enhancement



	Total CH_4 (ppb)	ΔCH_4 (ppb)
BU	1951 (1937, 1971)	46 (37, 58)
COP	1936 (1924, 1952)	31 (24, 39)

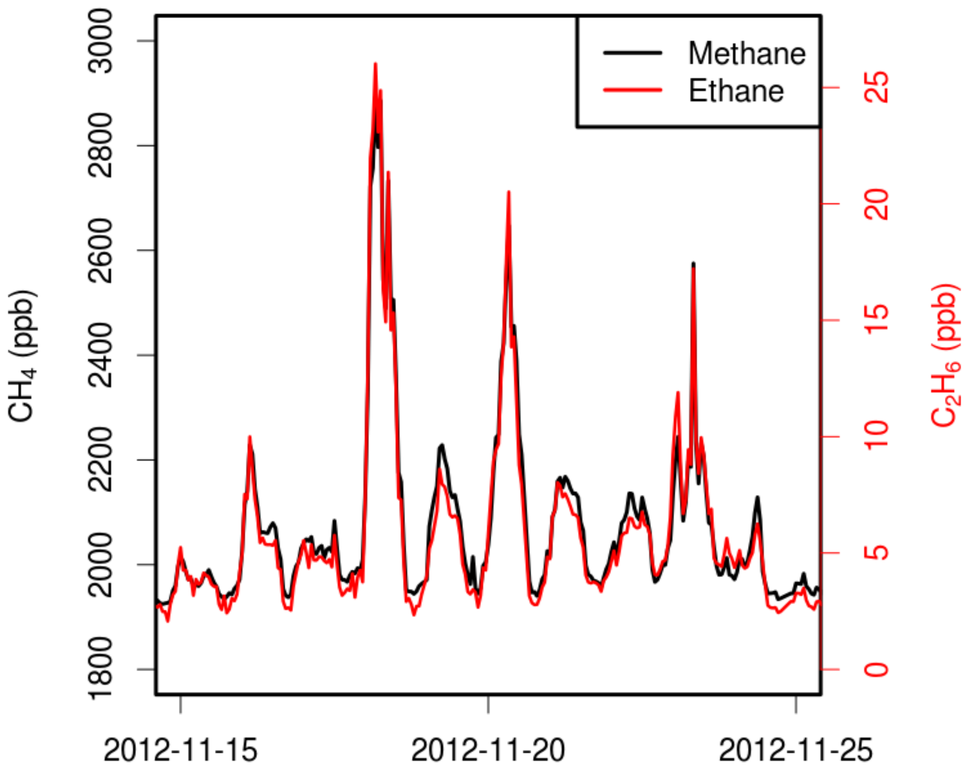
Ethane / Methane in Pipeline Gas

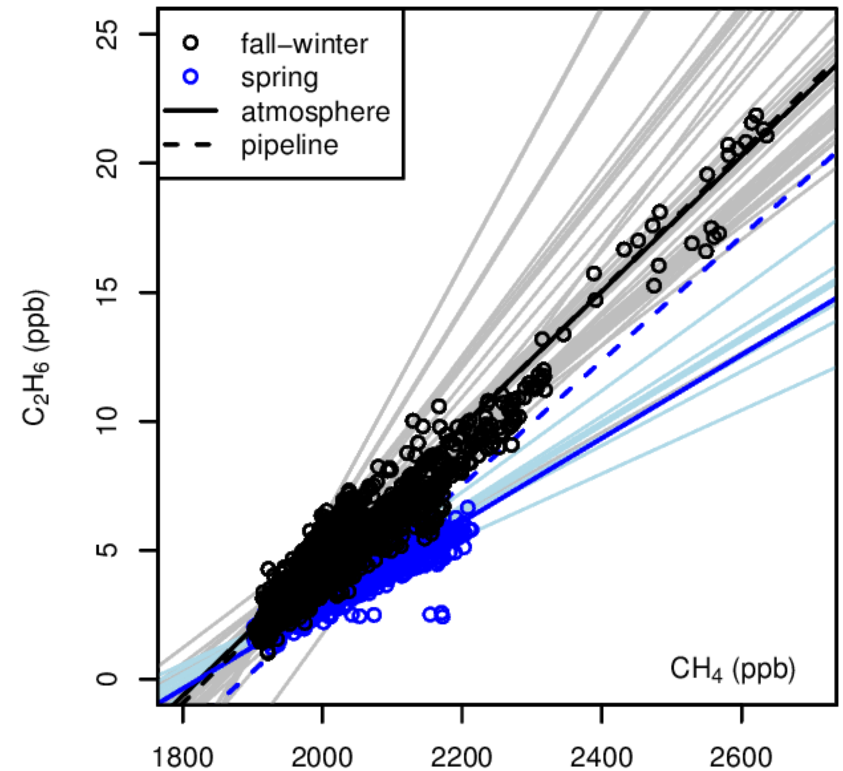




Hourly gas content data from transmission pipeline companies

Ethane / Methane in the Atmosphere vs. Pipeline

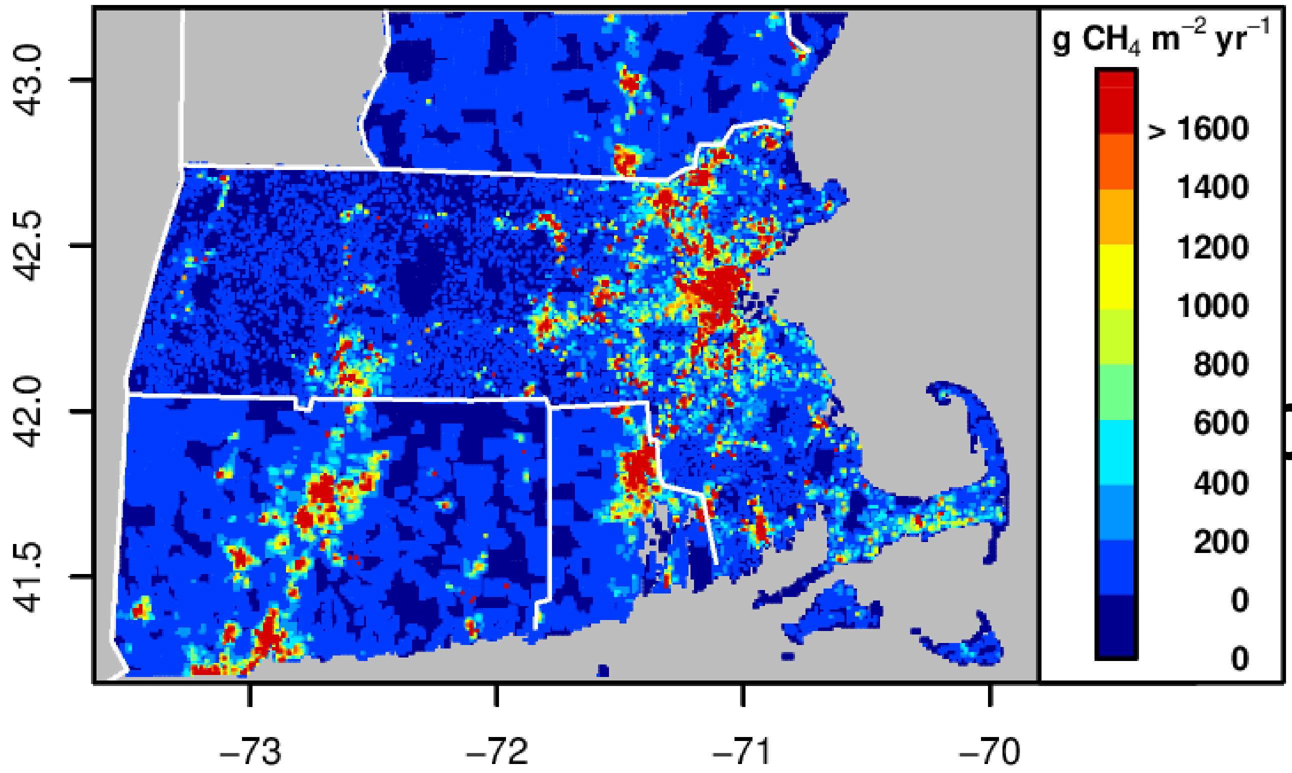




	C_2H_6 / CH_4 (95% CI)		**Natural Gas contribution to ΔCH_4**
	Atmosphere	**Pipeline**	
Cool (Oct 2012-Jan 2013)	2.6 % (2.5, 2.8)	2.7 % (2.7, 2.7)	**98 %** (92, 105)
Warm (May-June 2014)	1.6 % (1.4, 1.7)	2.4 % (2.3, 2.5)	**67 %** (59, 72)

Natural Gas Consumption

Reconstructed Geographical Distribution



Base data: EIA monthly-state-sectoral consumption

- Includes all sectors – Electric power, Residential, Commercial, Industrial, Vehicle fuel, Pipeline & distribution use

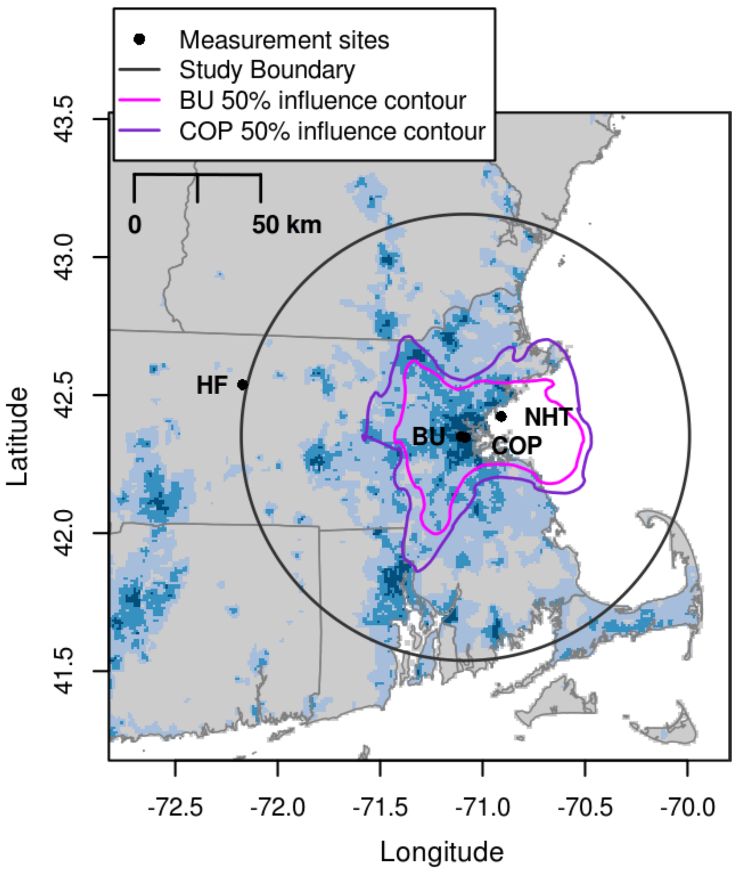
Spatially disaggregated by:

- Building square footage by fuel-type (Residential, Commercial)
- Power plant location (Electric, Industrial, Commercial)

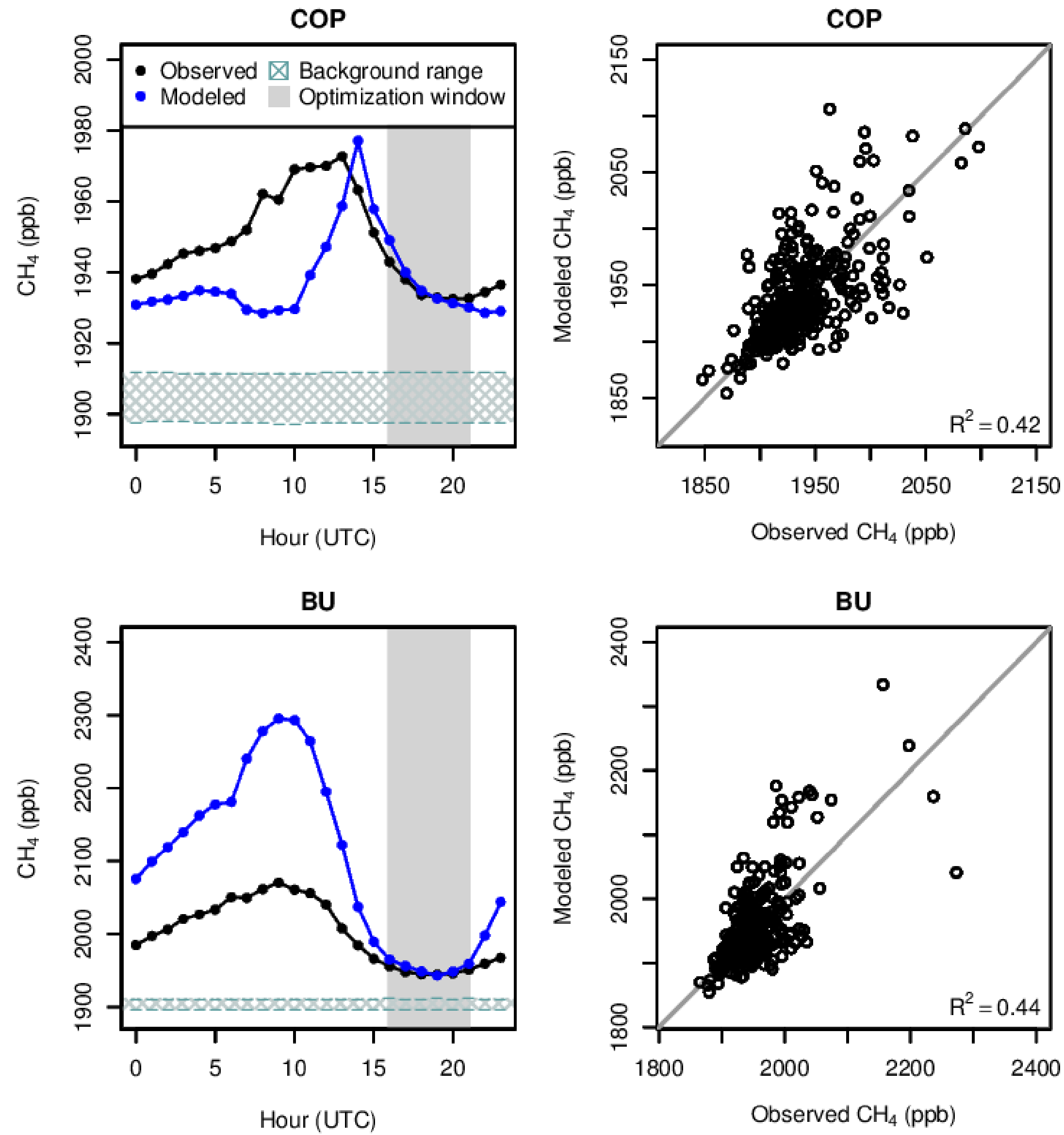
Footprints

(50% influence area)

COP footprint is larger and more diffuse.

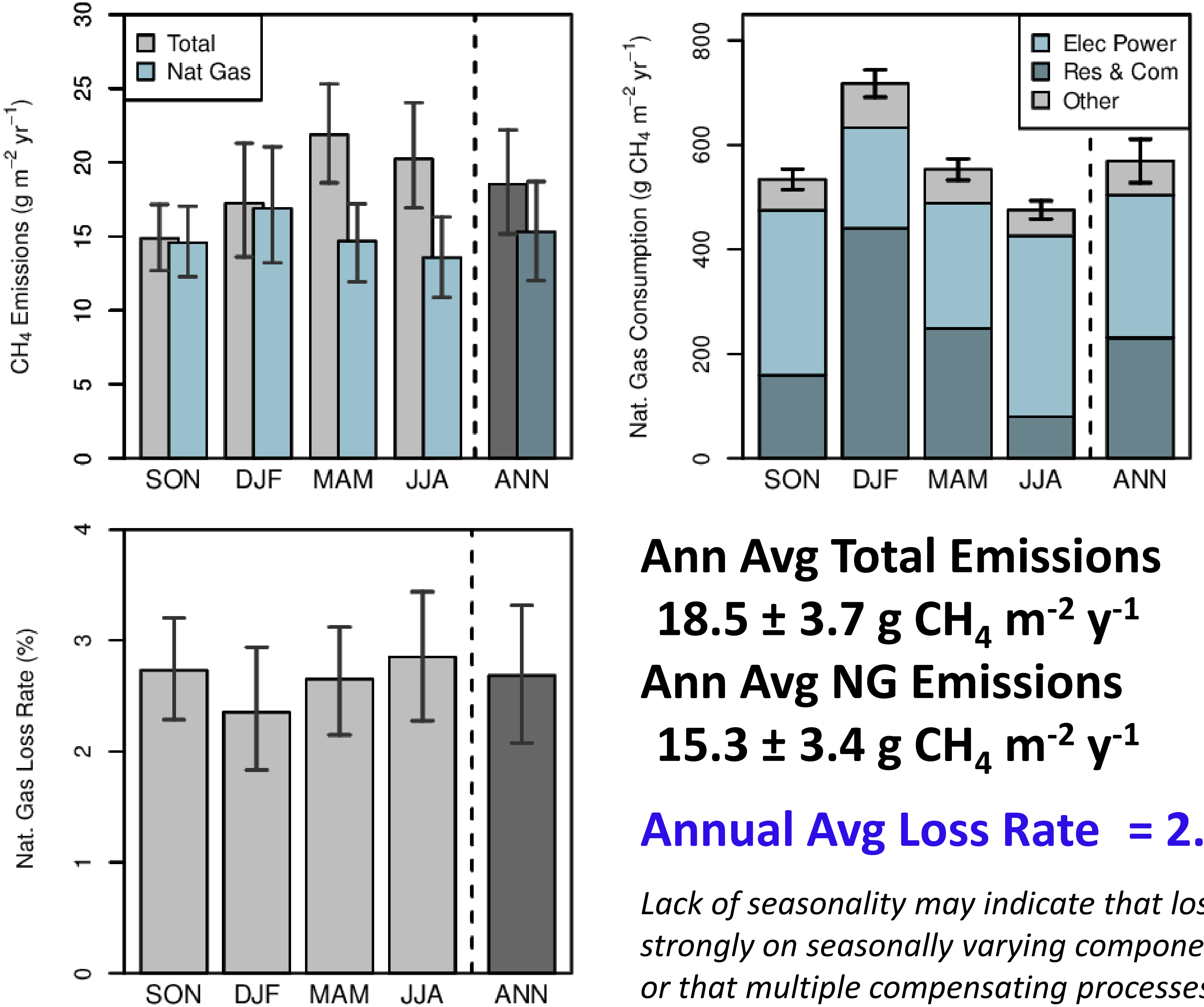


Observation-Model Comparison



Emissions scaled so afternoon seasonal mean $\Delta CH_{4,mod} = \Delta CH_{4,obs}$

Results Summary



Ann Avg Total Emissions

18.5 ± 3.7 g CH_4 m^{-2} y^{-1}

Ann Avg NG Emissions

15.3 ± 3.4 g CH_4 m^{-2} y^{-1}

Annual Avg Loss Rate = 2.7 ± 0.6 %

Lack of seasonality may indicate that losses do not depend strongly on seasonally varying component of the NG system, or that multiple compensating processes are contributing.

Comparison with Other Bottom-up Estimates

- **EPA GHG Inventory** (Dist., Trans. & Storage): **0.7%**
- **MA State GHG Inventory** (Dist., Trans. & Storage): **1.1%**
  * most valid comparison
- **GHG Reporting Programs** (EPA & MA): **0.6** (0.4-1.6) %
- **EIA-176** "Losses from leaks, damage, accidents, migrations & blow-downs": **0.4** (0.1-1.1) %
- **PHMSA LAUF**: **2.7** (0-4.6) %
  * includes leaks, metering inaccuracies and theft

Significance of Results

- Volume of Lost Gas: 15 billion scf y^{-1} , 6 scf $person^{-1}$ y^{-1}
- Value of Lost Gas: $90 million
- Mass of Emitted CH_4: 0.3 Tg y^{-1}
  ~ 8% U.S. emissions from trans, dist, storage
  ~23% of U.S. emissions distribution

Urban Atmospheric Observations & Fluxes of Carbon Dioxide in the Northeast U.S.

Maryann Sargent

CO_2 Inverse Model Goals

- What information can we add to bottom up inventories with high resolution atmospheric CO_2 measurements?
  - Impact of urban ecology, land use change on CO_2
  - How does traffic congestion impact emissions?
  - CO_2 as a proxy for NO, NO_2, which are often emitted together – better understand sources and transport
  - Refine method before applying it to other cities with larger uncertainty in bottom up inventories

Methodological Framework

1. **Atmospheric CO_2 Measurements (Harvard, ENI, NOAA)**
   – Continuously measured at 4 Harvard sites, 4+ ENI sites, 2+ NOAA sites

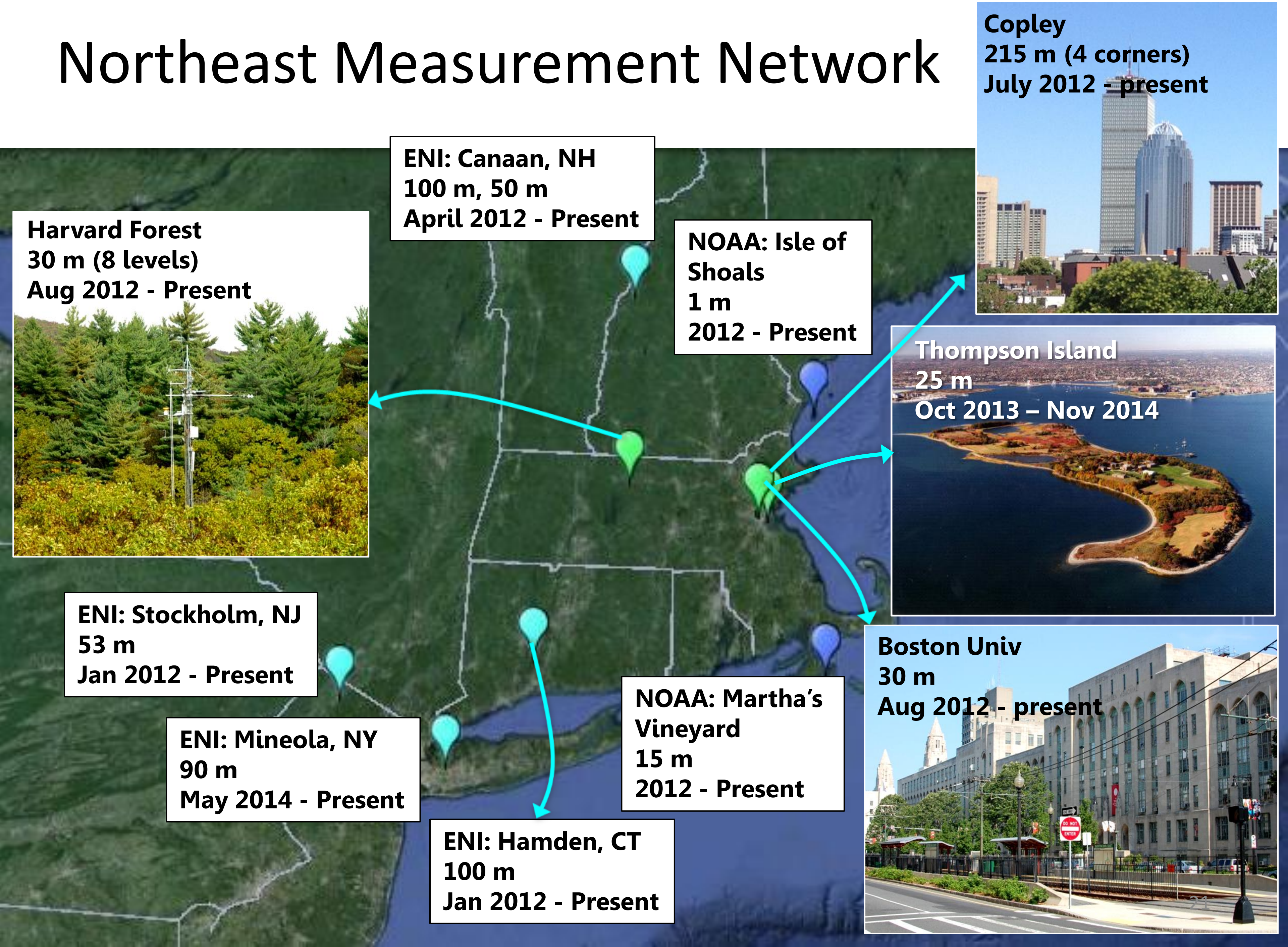
2. **Bottom-up CO_2 Emission Inventories (BU – Lucy Hutyra, Conor Gately)**
   – 1 km square grid covering northeast corridor
   – Completed sectors: onroad and offroad transportation, residential, airports, electric power generation, human respiration, industrial and commercial, oil/gas production
   – In process: biosphere fluxes

3. **Atmospheric Transport Model (AER – Thomas Nehrkorn, Marikate Mountain)**
   – **WRF-STILT** Lagrangian Particle Dispersion Model
   – Simulates sensitivity of obs to upwind surface fluxes: footprints

Urban CO_2 enhancement (ΔCO_2) ∝ urban CO_2 emissions

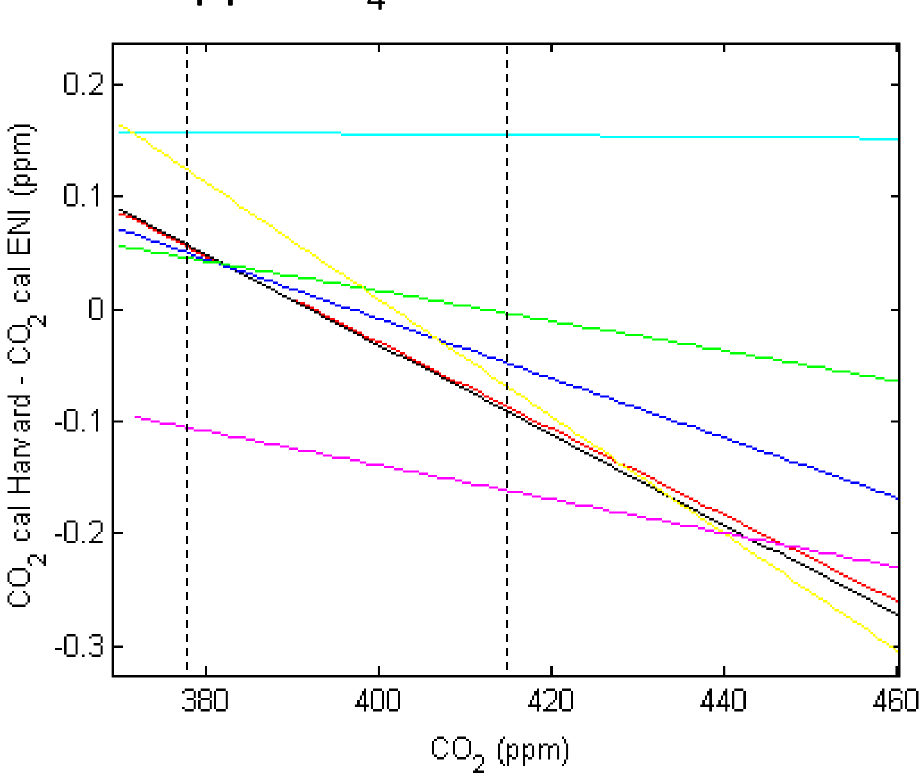
$$CO_2[\textit{urban}] - CO_2[\textit{background}] = \text{emissions } [\mu mole\ m^{-2}\ s^{-1}] * \text{footprint } [ppm/(\mu mole\ m^{-2}\ s^{-1})]$$

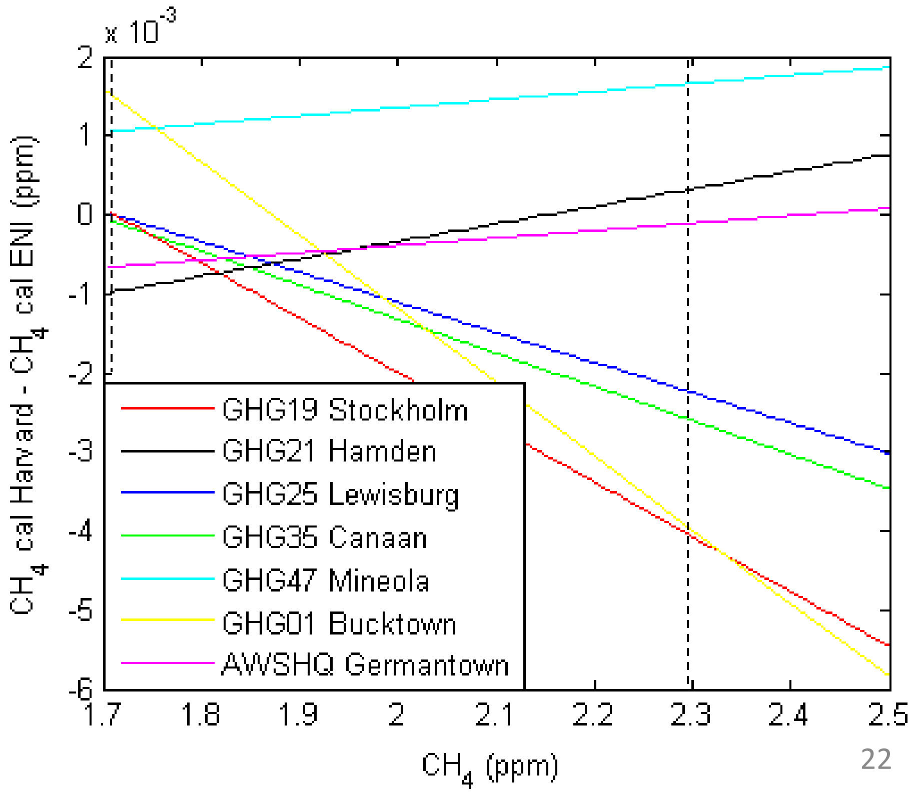
Northeast Measurement Network



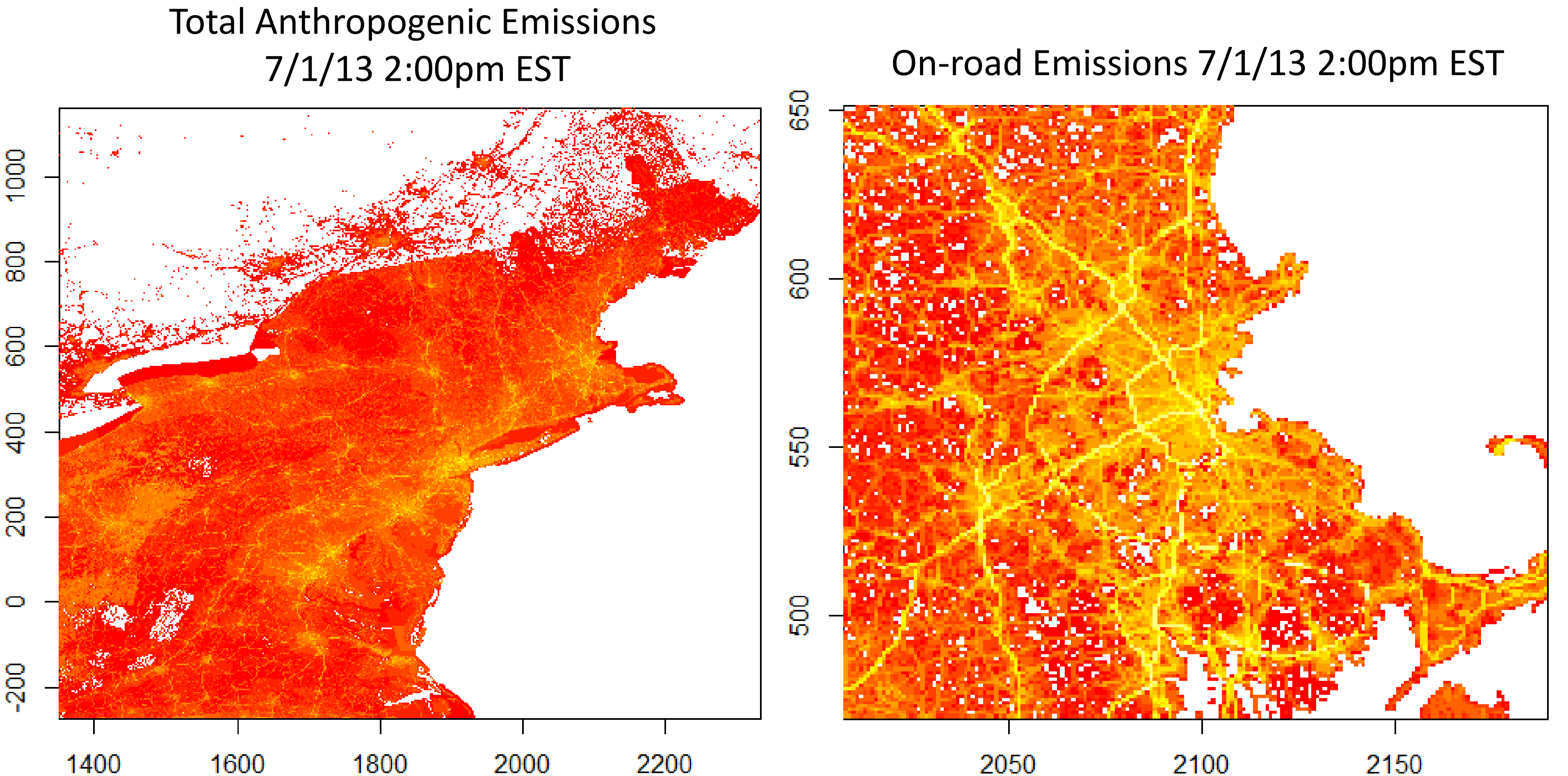
Harvard & Earth Networks Cross-Calibration

- Consistency of calibration across modeled sites critical
- All priority sites calibrated with Harvard's traveling standard tanks:
  a) 379 ppm CO_2, 1.71 ppm CH_4 b) 414 ppm CO_2, 2.30 ppm CH_4
- Earth Networks use 1-point calibration: ~395 ppm CO_2, ~1.87 ppm CH_4
- Two-point calibration necessary for desired accuracy of 0.1 ppm CO_2, 2 ppb CH_4





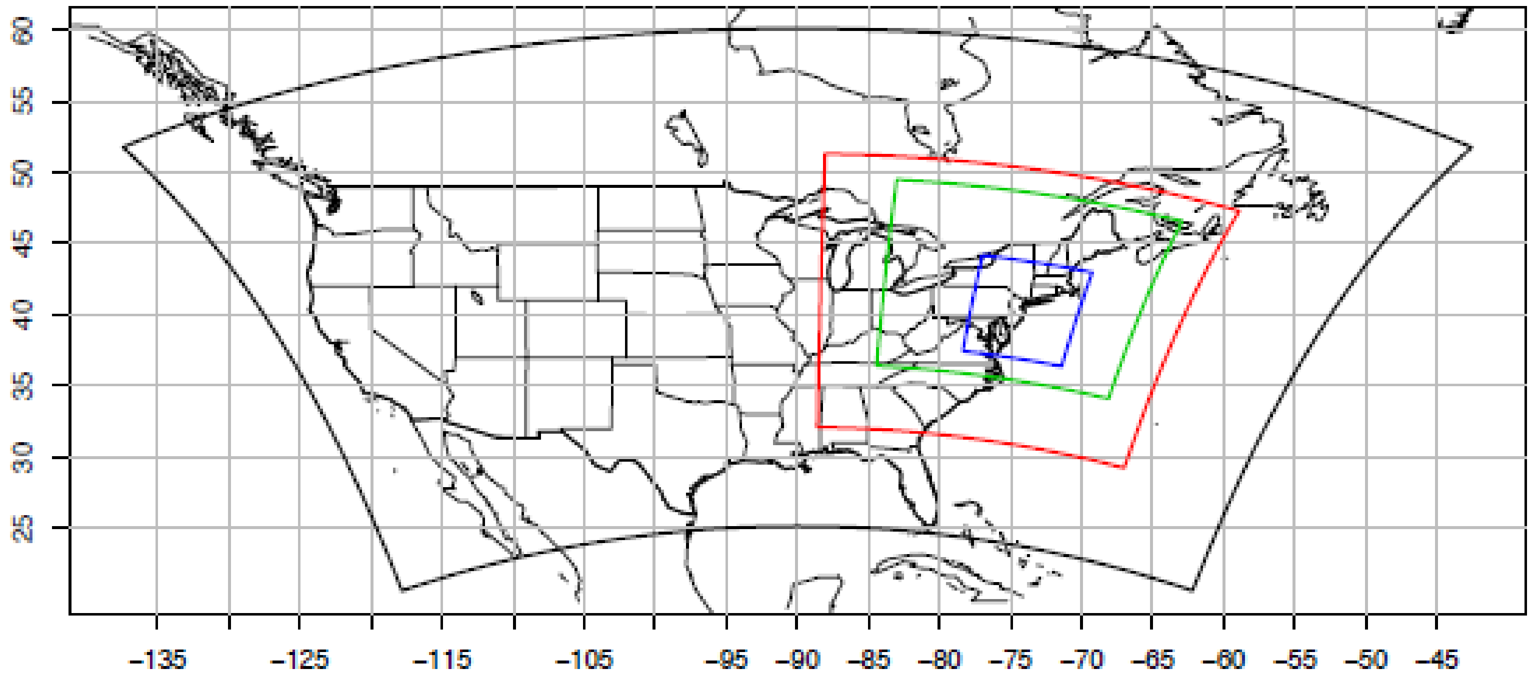
Bottom-up Emission Inventories (BU)



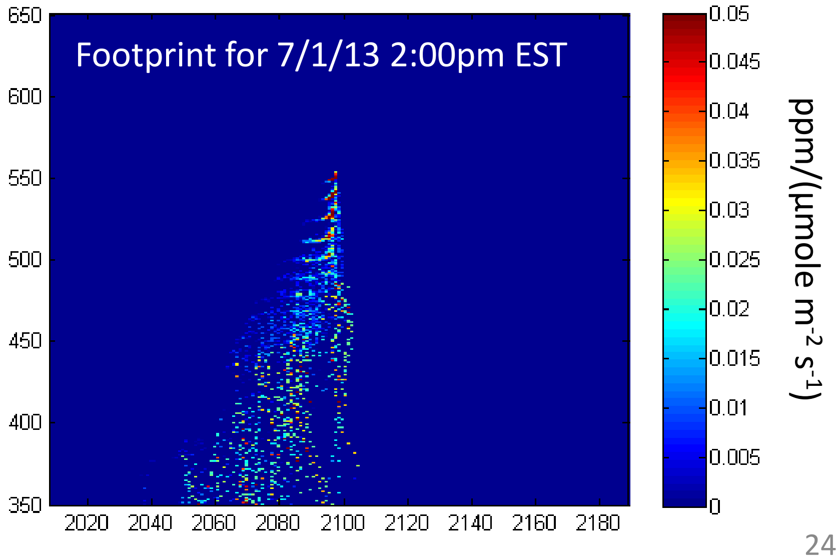
C. Gately, L. Hutyra

- Completed sectors: onroad and offroad transportation, residential, airports, electric power generation, human respiration, industrial and commercial, oil/gas production
- 1 km, 1 hr gridded emissions for January, 2013 – December, 2014

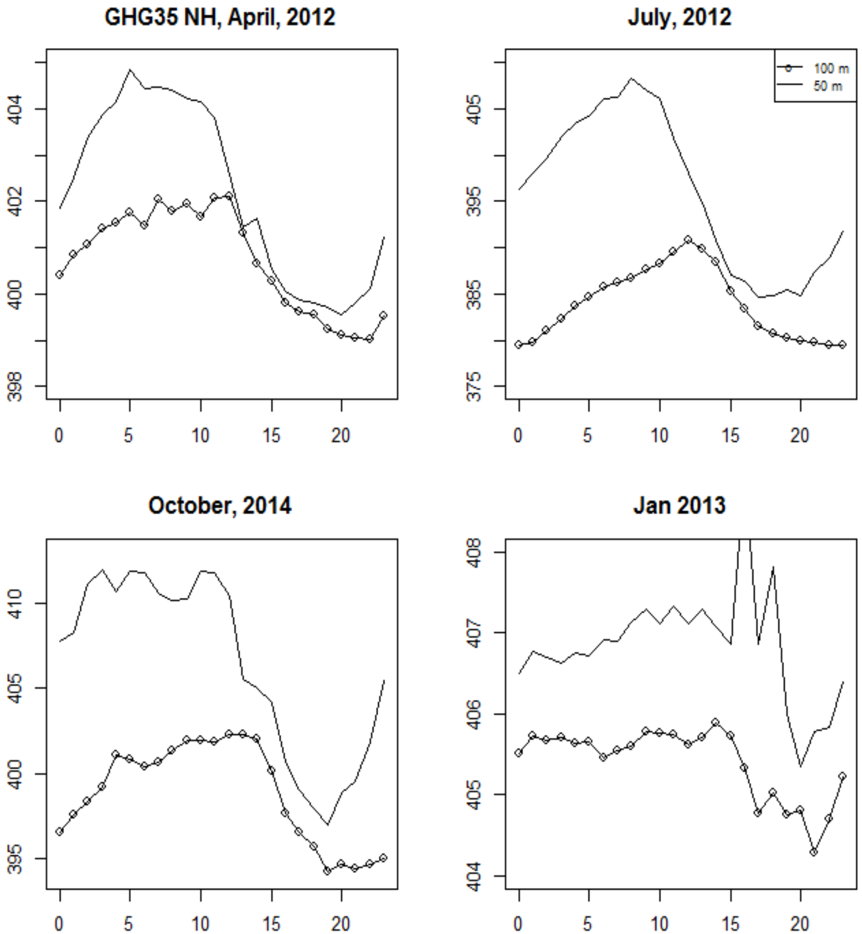
WRF-STILT Atmospheric Transport Model (AER)

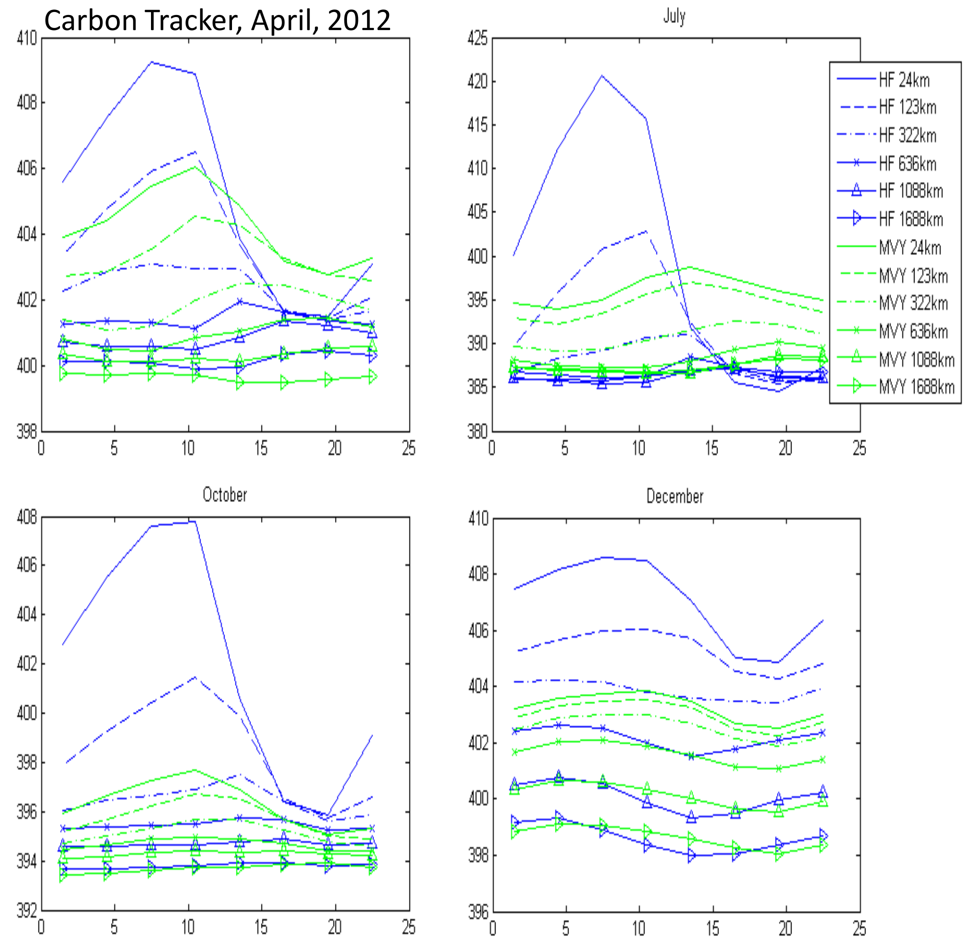


- Will incorporate increasing grid size with distance from receptor to smooth sparse footprint
- Compared impact of releasing 500 particles once per hour vs. releasing them throughout the hour
- No significant difference in ability to reproduce CH_4 obs, even during periods of shifting wind. Will continue to release particles once per hour.

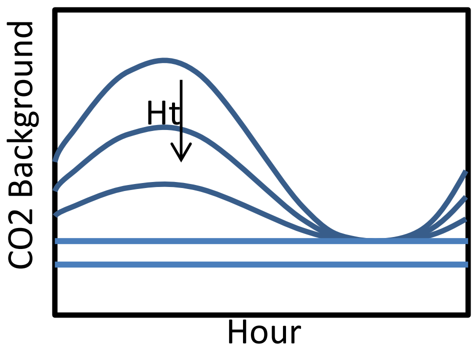


CO_2 Background Concentration





- Background CO_2 is function of altitude and angle of departure from region
- Starting from tower observations, adjust with altitude according to carbon tracker



Summary and Future Work

- Inverse model for Boston area alone:
  - Receptor sites: BU, Copley
  - Background sites: Harvard forest, Canaan NH (ENI), Martha's Vineyard (NOAA)
  - Anthropogenic bottom-up emissions completed, biosphere emissions ongoing
  - WRF runs completed for July-Dec 2013, STILT completed for July 2013; further runs ongoing
- Next step: integrated inverse model with multiple receptors for northeast corridor

Contact:

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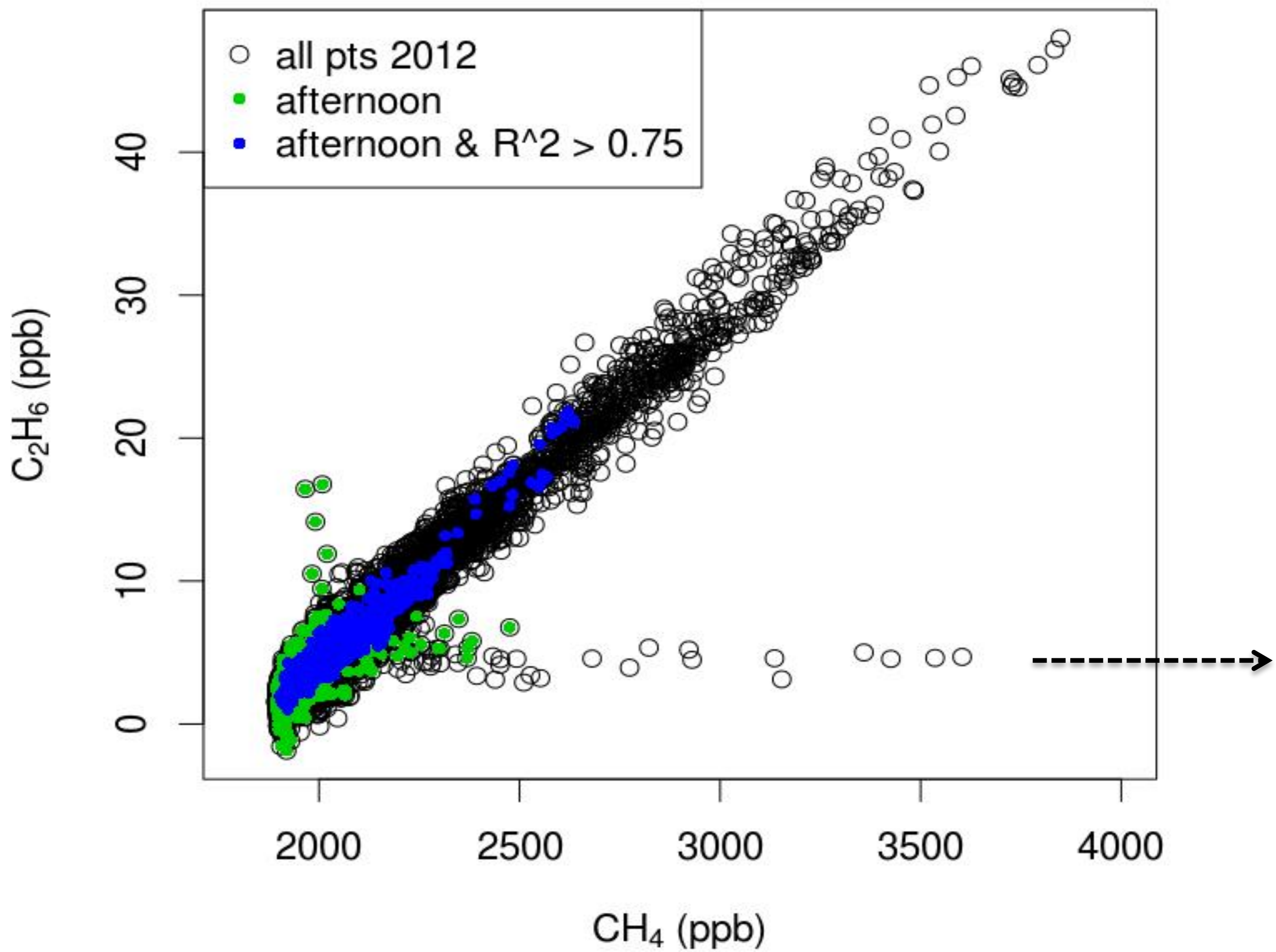
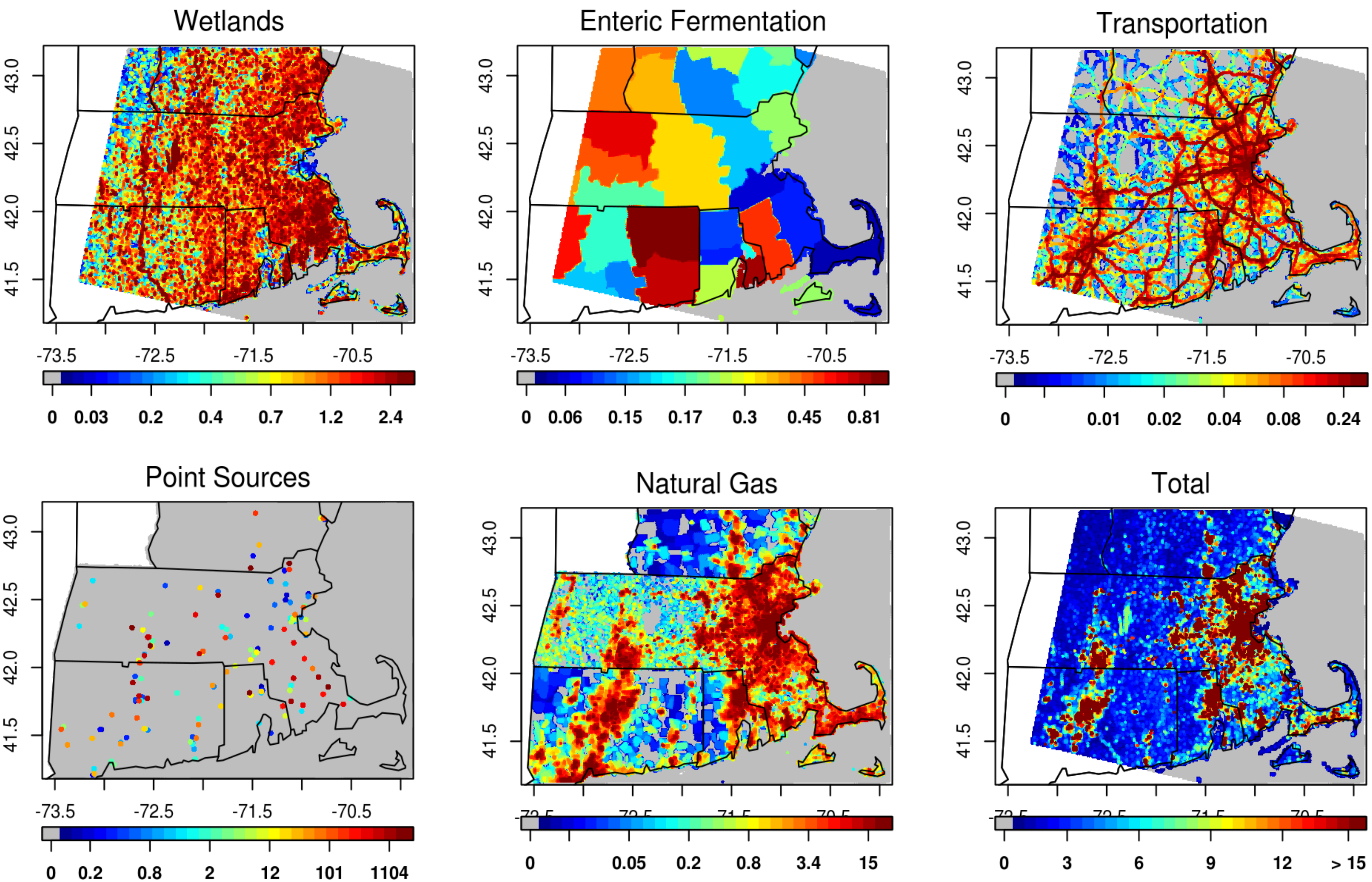
Methane Backup

Unfiltered Ethane /Methane Dataset

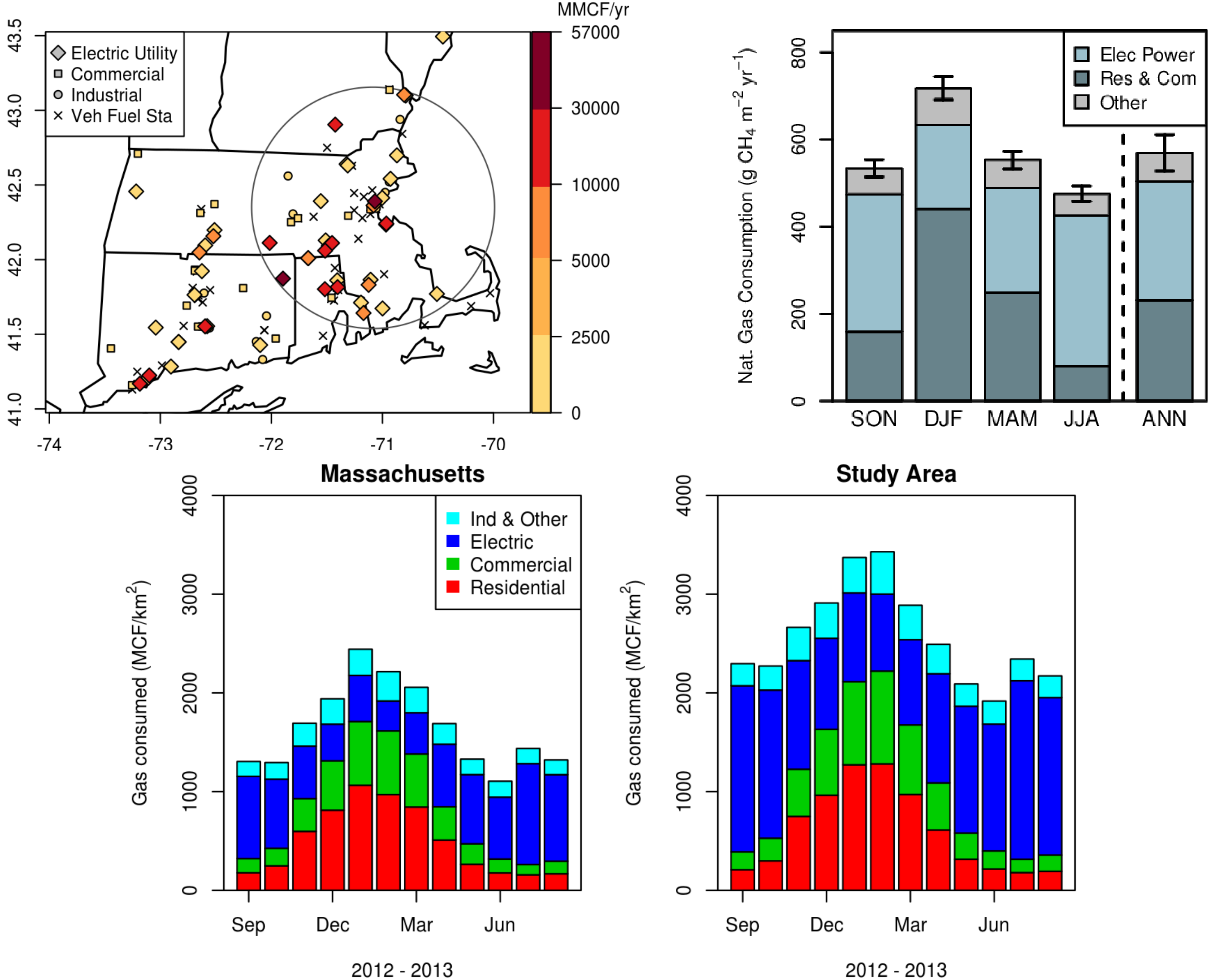


Prior Emission Fields



1 km^2 spatial resolution; static in time; major sectors only

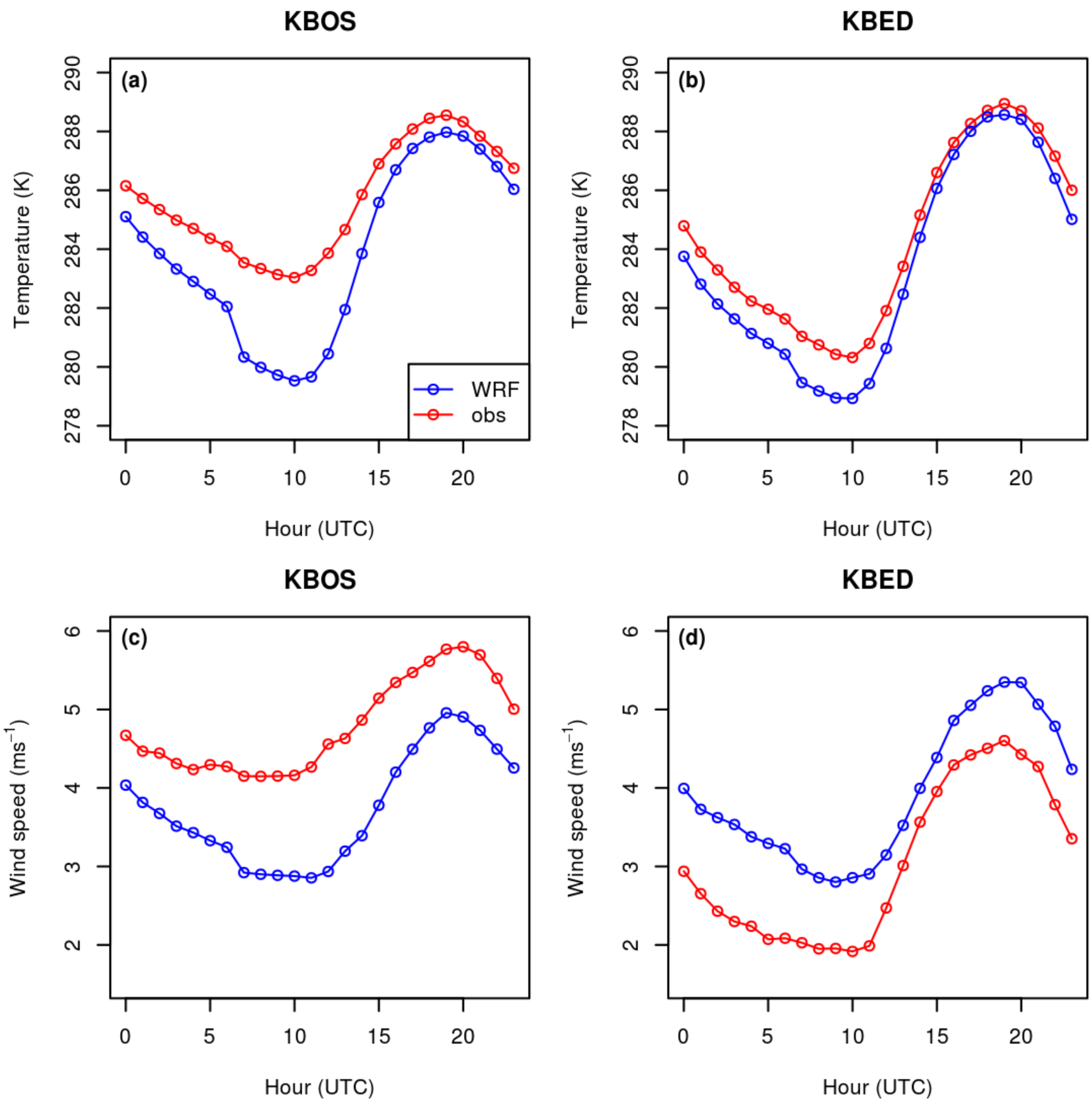
Patterns of Natural Gas Consumption



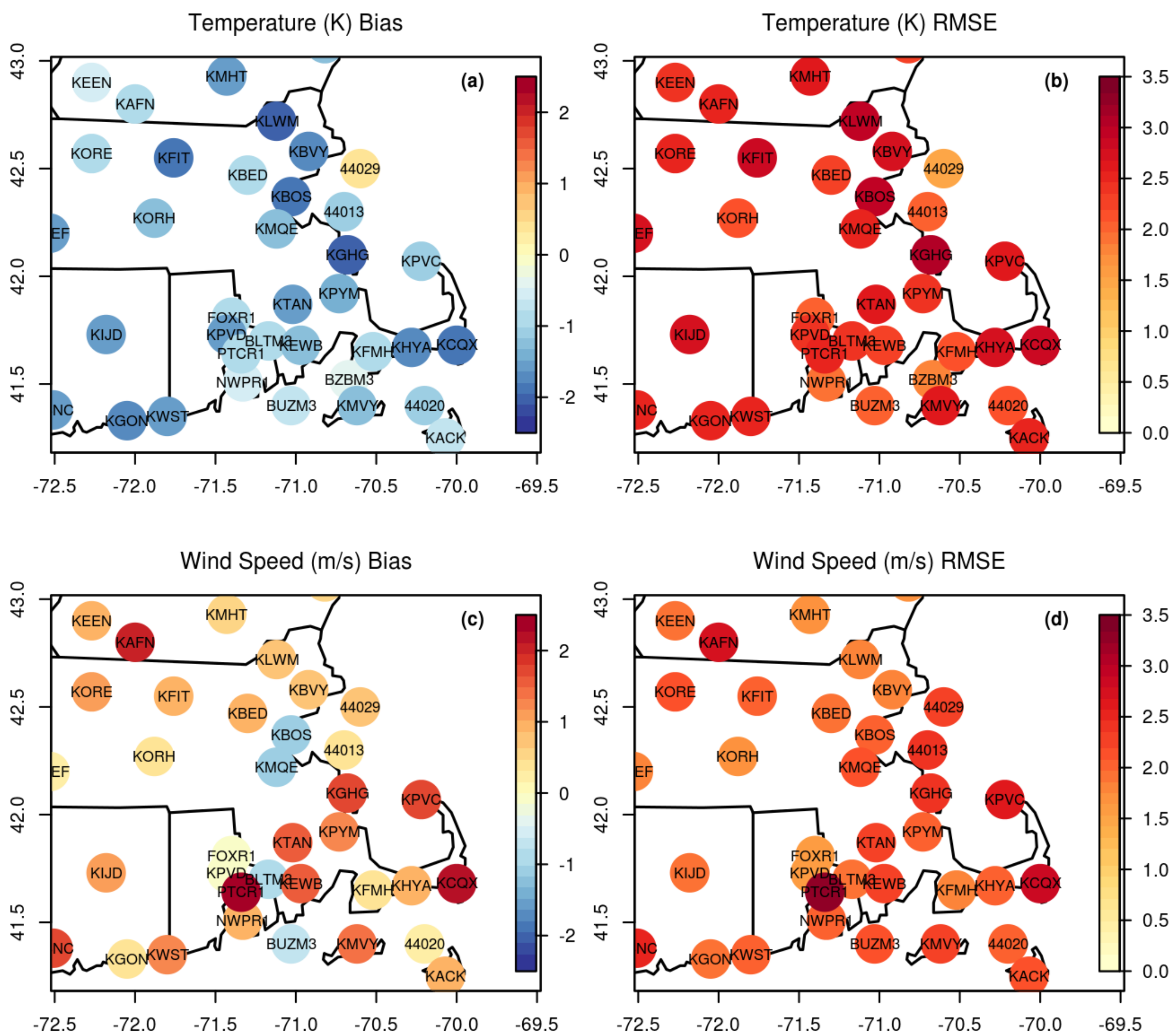
Literature Review

Ref.	Location	Measurement year	Emission Rate ($g\ CH_4\ m^{-2}\ yr^{-1}$)
43	Nagoya, Japan	1990-91	7
44	Midwest town, USA	1991	55
45	Two towns in East Germany	1992	12, 60
46	North Britain	1994	28 – 56
47	Heidelberg, Germany	1995-97	8 ± 2
48	Krakow, Poland	1996-97	20
49	St. Petersburg, Russia	1996-2000	32 ±9
50	Beijing, China	2000	50
51	Los Angeles County, CA, USA	2007-08	205 ± 6*
52	South Coast Air Basin, CA, USA	2007-08	228 ± 38*
53	Indianapolis, IN, USA	2008	71 ± 50
54	South Coast Air Basin, CA, USA	2010	167 ± 57*
55	South Coast Air Basin, CA, USA	2010	156 ± 14*
56	South Coast Air Basin, CA, USA	2010	127 ± 21*
57†	South Coast Air Basin, CA, USA	2010	160 ± 30*
57‡	South Coast Air Basin, CA, USA	2010	118 ± 30*
58	Florence, Italy	2011	58
59	London, UK	2012	66 ± 10

Evaluation of WRF



Evaluation of WRF



Error Analysis

- Emissions: End-to-end bootstrap of distributions of background, observed and modeled CH_4 at hourly, daily and seasonal time scales, and optimization factors (± 20%)
- Attribution: Bootstrapped errors of atmosphere and pipeline data (± 10%)
- Denominator: errors reported by EIA (± 7%)
- Loss Rate from all above (± 25%)
- *Does not include errors for spatial distribution of emissions and consumption*

Sensitivity Tests

1. Outliers included (-6%)
2. Alternative data aggregation (+15%)
3. EDGAR prior emissions (-10%)
4. Coarser prior emissions (+12%)
5. Prior NG emissions scaled to match attribution (-15%)
6. BU Only (-5%)
7. COP Only (+30%)
8. Transport: NAM/HYSPLIT (-25%)