Measuring CO\textsubscript{2} and CH\textsubscript{4} Emissions from Indianapolis: Preliminary Results from an Urban Atmospheric Inversion System

Kenneth J. Davis\textsuperscript{1}, Thomas Lauvaux\textsuperscript{1}, Maria Cambaliza\textsuperscript{2}, Michael Hardesty\textsuperscript{3}, Laura T. Iraci\textsuperscript{4}, Kevin R. Gurney\textsuperscript{5}, Patrick W. Hillyard\textsuperscript{4}, Anna Karion\textsuperscript{3}, Laura E. McGowan\textsuperscript{1}, Natasha L. Miles\textsuperscript{1}, James R. Podolske\textsuperscript{4}, Kuldeep Prasad\textsuperscript{7}, Igor Razlivanov\textsuperscript{5}, Scott J. Richardson\textsuperscript{1}, Daniel P. Sarmiento\textsuperscript{1}, Paul B. Shepson\textsuperscript{2}, Colm Sweeney\textsuperscript{2}, Jocelyn Turnbull\textsuperscript{3,6}, James Whetstone\textsuperscript{7}

\textsuperscript{1}The Pennsylvania State University, \textsuperscript{2}Purdue University, \textsuperscript{3}NOAA ESRL/U. Colorado, \textsuperscript{4}NASA Ames, \textsuperscript{5}Arizona State University, \textsuperscript{6}GNS Science, \textsuperscript{7}NIST

NOAA ESRL GMD annual conference, 21 May, 2013
Outline

• Motivation, objectives
• Experimental design
• Observations
  – Aircraft observations / Whole-city flux estimates
  – Tower-based observations
• “Forward” simulations
  – Detectability experiment
  – Comparison to observations
• Atmospheric inversions
  – System design experiment
  – (Real data inversions)
• (Synthesis – e.g. inventory-inversion comparisons)
Motivation, background, objectives
motivation

• Anthropogenic greenhouse gas (GHG) emissions are increasingly uncertain, even at global, annual scales (~10% uncertainty)
• Anthropogenic GHG emissions are much more uncertain at local / regional scales (% uncertainty = ?)
• Emissions mitigation will happen at local and regional scales.
• Validation of emissions mitigation will(?) require independent measurements
• Atmospheric GHG measurements have the potential to provide such independent emissions estimates.
Regional measurement campaigns

Midcontinent intensive, 2007-2009

N. American tower CO2 network circa 2008

INFLUX, 2010-201?

Gulf coast intensive, 2013-201?

Legend: Sampling Platform
- Surface-layer tower
- Mixed-layer (tall) tower
- Complex terrain
- Aircraft Profile

Colors Denote Operator
- Blue: NOAA ESRL
- Green: Canadian Carbon Program
- Red: Other (PSU, ORST, Harvard, NCAR)
- Yellow: MCI Ring of Towers 2 (PSU)
Large differences in seasonal drawdown, despite nearness of stations.


Miles et al, 2012, JGR-B
Atmospheric inversions and agricultural inventory agree!
Inversions and inventory have similar uncertainty bounds!

Schuh et al, 2013, GCB
INFLUX objectives

• Develop improved methods for determination of urban area-wide, and spatially and temporally-resolved (e.g. monthly, 1 km\(^2\) resolution) fluxes of greenhouse gases, specifically, CO\(_2\) and CH\(_4\).

• Determine and minimize the uncertainty in the emissions estimate methods.
INFLUX approach

Simultaneous application of multiple methods, e.g. aircraft mass balance, mesoscale atmospheric inversions, plume inversions, tracer methods, and emissions modeling.

• Aircraft-based, whole-city flux estimates. (Cambaliza talk)
• Aircraft and automobile plume measurements for determining emissions from strong point sources (power plants, landfills, gas leaks)
• Inventory estimates of sector-by-sector emissions (residential, commercial, industrial, traffic, power plant) at high spatial resolution. (Hestia)
• Trace gases measurements, especially $^{14}$C, to distinguish fossil from biogenic CO2. (Sweeney poster)
• Mesoscale atmospheric inversions to determine spatially and temporally resolve GHG emissions estimates. (my focus)
Future applications

• Apply methods developed for Indianapolis to other cities, including ‘megacity’ efforts.
Observational system

- 12 surface towers measuring CO$_2$ mixing ratios, 5 with CH$_4$, and 5 with CO. (Penn State)
- 4 eddy-flux towers from natural to dense urban landscapes. (Penn State)
- 5 automated flask samplers. (NOAA/CU)
- Periodic aircraft flights (~monthly) with CO2, CH4, and flask samples. (Purdue / NOAA)
- Periodic automobile surveys of CO2 and CH4. (Purdue)
- Doppler lidar. (NOAA/CU)
- TCCON-FTS for 4 months (Sept-Dec 2012). (NASA Ames)
Challenges for INFLUX

• Evaluate the urban boundary layer and land surface simulated by WRF-Chem with meteorological observations
  – surface flux data,
  – Doppler lidar,
  – airborne meteorology,
  – surface meteorological network.

• Use CO/CO$_2$/$^{14}$CO$_2$ to disaggregate fossil and biogenic CO$_2$.

• Quantify strong point sources (landfill, powerplant).
INFLUX observational results to date:
Whole-city mass-balance emissions estimates
Aircraft mass balance method

\[ F_c = \int_0^{z_i} \int_{-x}^{+x} \left( [C]_{ij} - \overline{[C]}_b \right) \ast U_{ij} \, dx \, dz \]
June 1, 2011 Flight path

Purdue Airport

NW winds, 284°
5.9 ms⁻¹

SouthPort WWTP
Harding Power Plant
Indianapolis Intl airport
Covanta Energy
SouthSide Landfill
Belmont WWTP
Eagle Valley Power Plant
Twin Bridges Landfill
Tower sites

June 1, 2011 Flight Experiment

Cambaliza et al, in prep
Vertical structure of the atmospheric boundary layer (ABL)

Vertical Profiles of Potential Temperature and H$_2$O (~ 1:00 to 1:30 p.m. EDT)

6 June, 2012
June 1, 2011 Results

Cambaliza et al, in prep
Cambaliza et al, in prep

Total CO₂ Flux (mol m⁻¹ s⁻¹)

2008/2009 Flight Experiments

2011 Flight Experiments
INFLUX tower-based observational results to date
INFLUX ground-based instrumentation

Picarro, CRDS sensors; NOAA automated flask samplers; Communications towers ~100m AGL
Spatial gradients in [CO2] across INFLUX sites

- [CO2] averaged between 1300 and 1700 LST at 9 sites, with 21-day smoothing
- Seasonal and synoptic cycles are evident
- Site 03 (downtown) is generally higher than the other sites
- Site 09 (background site to the east of the city) often measures the lowest average [CO2]

* Note: Tower heights range from 40 m AGL to 136 m AGL
Observed: Dependence of CO2 spatial gradient on wind speed

- 15 Nov 2012 at 3 pm local
- Winds: calm

Light winds: 15 ppm difference midday
Observed: Dependence of CO2 spatial gradient on wind speed

- 12 Nov 2012 at 3 pm local
- Winds: 9 m/s from the west

Strong winds: < 2 ppm difference midday
Cross city mole fraction enhancement is an inverse function of wind speed (and ABL depth).
INFLUX ground-based instrumentation

Picarro, CRDS sensors; NOAA automated flask samplers; Communications towers ~100m AGL
CO2 Enhancement (Site 02 – Site 01) as a Function of Wind Direction
April – November 2011 (Afternoon hours only)

Each point is an hour.
Red line is the median.

Note the LARGE day to day variability!
Weather!
Median urban enhancement (Site 02 – Site 01): 100+ m AGL tower: CO2

- Blue arrows point to the sources of enhanced CO2 measured at Site 02, compared to Site 01
- Primarily from the west (urban center)
- Maximum median enhancements: ~ 5 ppm CO2
Median urban enhancement (Site 02 – Site 01): 100+ m AGL tower: CO

- Red arrows point to the sources of enhanced CO measured at Site 02, compared to Site 01
- Primarily from the west (urban center)
- Maximum median enhancements: ~ 20 ppb CO
- Tracer of combustion
CH4 Enhancement (Site 02 – Site 01) as a Function of Wind Direction
April – November 2011 (Afternoon hours only)

Each point is an hour. Red line is the median.

Note the LARGE day to day variability! Weather!
Median urban enhancement (Site 02 – Site 01): 100+ m AGL tower: CH4

- Green arrows point to the sources of enhanced CH4 measured at Site 02, compared to Site 01
- Large source to the southeast of Site 02, as well as to the west (urban center)
- Maximum median enhancements: ~ 10 ppb CH4
INFLUX ground-based instrumentation

- Picarro, CRDS sensors
- NOAA automated flask samplers
- Communications towers ~100m AGL
Contributions to CO$_2$ enhancement

\[ \Delta CO_2 = \Delta CO_2^{bg} + \Delta CO_2^{ff} + \Delta CO_2^{bio} + \Delta CO_2^{ocean} \]

\[ \Delta CO_2 = \Delta CO_2^{ff} + \Delta CO_2^{bio} \]

\( \Delta CO_2 \) in winter can be entirely explained by \( CO_2^{ff} \) addition.

No apparent biosphere (respiration/photosynthesis) contribution

<table>
<thead>
<tr>
<th>Date</th>
<th>Slope (ppm/ppm)</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Towers Winter</td>
<td>1.1±0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>29 Apr 2011</td>
<td>1.1±0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>1 Jun 2011</td>
<td>0.9±0.1</td>
<td>0.9</td>
</tr>
<tr>
<td>12 Jul 2011</td>
<td>1.2±0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>18 Aug 2011</td>
<td>N/A</td>
<td>0.0</td>
</tr>
</tbody>
</table>
In winter, all $\Delta CO_2$ is due to $CO_2ff$
In summer, not so much
Holds for both towers and aircraft

(Same as previous – just add summer to the towers plot.)
Aircraft: strong CO:CO2ff correlation for general urban flights, weak/no correlation in power plant plume
Towers: CO:CO2ff correlation poor in summer, better in winter, but still not as strong a correlation as we’ve seen at other sites

CO as a fossil fuel CO2 tracer?
Observational summary

• Cross-city mole fraction differences clearly detected (given considerable averaging to see through the weather)
• Differences vary greatly with weather conditions
• Elevated sampling necessary to avoid strong surface gradients
• Winter, CO2 = CO2ff, and CO is a decent CO2ff tracer. Summer, not so.
INFLUX numerical modeling and data analysis system
Inventory
Vulcan and Hestia Emission Inventories / Models

Vulcan – hourly, 10km resolution for USA

• See: Kevin Gurney/
• http://hestia.project.asu.edu/

Hestia: high resolution emission data for the residential, commercial and industrial sectors, in addition to the transportation and electricity production sectors.
Forward model results
Status of modeling system

- WRF-Chem running with:
  - 3 nested domains (9/3/1 km resolution), inner domain 1km\(^2\) resolution, 87x87 km\(^2\) domain
  - Meteorological data assimilation
  - Hestia anthropogenic fluxes for the inner domain
  - Vulcan anthropogenic fluxes for the outer domains
  - Carbon Tracker posterior biogenic fluxes
  - Carbon Tracker boundary conditions
  - CO2 tagged by source
Simulated anthropogenic CO2 in the outer 2 domains: Ten day time series

Anthropogenic CO2: boundary conditions only. Note similarity to weather observed in site 1-2 differences.
Can we detect anthropogenic emissions?

Or do biogenic fluxes and lateral boundary conditions dominate?
Monthly mean along-wind CO$_2$: Anthropogenic CO$_2$ emissions within the domain

Winter Along Wind

Summer Along Wind

6 ppm accumulation

2 ppm accumulation

Deeper summer atmospheric boundary layer
CO2 range as a function of wind speed

**Model:** Difference along domain-averaged wind direction

**Observations:** CO2 range amongst INFLUX sites

Cross city mole fraction enhancement is an inverse function of wind speed (and ABL depth).
Monthly mean cross-wind CO$_2$: Anthropogenic CO$_2$ emissions within the domain

Winter Across Wind

Summer Across Wind

4-5 ppm “dome”

~1 ppm “dome”

Deeper summer atmospheric boundary layer
Monthly mean along-wind CO$_2$:
Anthropogenic CO$_2$ emissions within the domain

Winter Along Wind

Summer Along Wind

6 ppm accumulation

2 ppm accumulation

Deeper summer atmospheric boundary layer
Monthly mean along-wind CO$_2$: Biological CO$_2$ fluxes within the domain

Winter Along Wind

![Graph showing CO$_2$ concentration increasing from 0.1 ppm to 0.24 ppm over a distance of 40 km.]

Summer Along Wind

![Graph showing CO$_2$ concentration decreasing from 0 ppm to -10 ppm over a distance of 40 km, indicating a 6 ppm depletion.]

Large biological fluxes in the summer
Monthly mean along-wind CO₂: Total CO₂ boundary conditions

**Winter Along Wind**

1.2 ppm

**Summer Along Wind**

6 ppm accumulation
Forward simulation conclusions

- Within-domain, anthropogenic fluxes easily detected in the winter.
- Summer anthropogenic signal must be deconvoluted from large biological signals.
  - Both within-domain, and lateral boundaries
- Weather signal reminiscent of observations.
  - Both boundary conditions and within domain
- Mean gradients similar in magnitude to tower observations
Inversion experiment: Network test
Tower-based atmospheric inversion system

Atmospheric transport model: (WRF-chem, 1 km)

Boundary and initial conditions (GHGs/met):
(Carbon Tracker, NOAA aircraft profiles, NCEP meteorology)

Prior flux estimate:
(Hestia and Vulcan, EDGAR and EPA, CT posterior and/or VPRM)

Network of tower-based GHG sensors:
(12 sites with CO₂, CH₄, CO and ¹⁴CO₂)

Lauvaux et al, 2012, ACP
Inversion system, continued

- Lagragian Particle Dispersion Model (LPDM, Uliasz).
  - Determines “influence function” – the areas that contribute to GHG concentrations at measurement points.

Lauvaux et al, 2012, ACP
Preliminary inversion system test

- 6 tower system tested, hourly daytime data
- Prior errors proportional to fluxes
- Prior error correlations 3km, isotropic, correlated with land cover
- Noise added with same spatial statistics, 80% of flux magnitude
- 7 day Bayesian matrix inversion, November
- No biogenic fluxes, no boundary conditions
Sample of influence functions for 6 towers

Particle touchdown for July 12, 2011 after 72 hours. Touchdown is considered within 50m of surface. The background values are EPA 4km CO.
Gain – relative improvement prior vs. posterior

Very good system performance within the tower array.

Very idealized case, but encouraging nonetheless.

1 = perfect correction to prior fluxes
Data for atmospheric transport evaluation
Local surface met stations
Lidar wind profiling and ABL depth – one day plot
June 6, 2012 Flight Path

6.4 m/s, 54 deg
3D distribution of Potential Temperature
3D distribution of CH$_4$
3D distribution of CO$_2$ (black dot is Harding St. Power Plant)
3D distribution of $\text{H}_2\text{O}$
Conclusions

- Whole city flux estimates obtained. ~30-40% uncertainty? Aircraft.
- Tower observations detect a clear urban signal in both CO2 and CH4 (buried amid lots of synoptic “noise”).
- Simulations and measurements suggest that light winds and winter are best for urban signal detection. Strong winds and summer are the toughest conditions.
- Inversion system with 6 towers performs very well under idealized conditions.
- “Real data” inversions in progress.