The INdianapolis Flux Experiment (INFLUX): Toward Improved Capabilities in Urban-Area Scale Greenhouse Gas Flux Measurements

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Project Goals

“The uncertainty in area/regional greenhouse gas (i.e. CO₂ and CH₄) flux measurements can be 20% or better, and this uncertainty can be constrained and defined through improved measurement techniques, comparison to inventory data, and use of carbon isotope ratio data.”
Approach

Multiple simultaneous approaches to measure CO$_2$ and CH$_4$ fluxes. Focus on **Indianapolis**, due to existing measurement and Vulcan data, and regional and topographical characteristics.

1. **Aircraft-based flux measurements** for both CO$_2$ and CH$_4$. Good snapshot for comparisons, and for hunting the “missing” CH$_4$, not good for integrated averages.
2. **Tower-based fluxes**. Good for averages
3. **$^{14}$C measurements, both towers and aircraft.** Great complement to direct methods; enables determine of CO$_{2ff}$.
4. **Regional modeling/inverse analysis**—WRF-CHEM-aircraft and towers.
5. **Vulcan/Hestia modeling.**
   A bottom line. How to leverage these measurements to enable development of a better model/data fusion product.

Field measurement period is Fall 2010 – Summer 2012
Aircraft Approach

Use of ALAR

Mass Balance Approach

\[ F = \frac{\int_0^z \int_{-x}^x \left( \frac{[C]_{ij} - [C]_b}{1 \times 10^a} \right) \times n_{dij} \times U_{ij} \, dx \, dz}{A_{city}} \]

\[ [C]_b = \frac{\sum [G_{ij}]_{edge}}{n} \]

\[ n_{dij} = \frac{P_{ij}V}{RT_{ij}} \]
Results - Kriging

See Mays et al., 2009

Department of Earth & Atmospheric Sciences
Tower measurements

- We will have 11 towers in place in 2011, conducting measurements of CO$_2$, CH$_4$, and CO (some).
- Two towers currently operational.
- Tower overflights, roughly biweekly, with vertical profiles.
- Integrated sampling: Collect air over two week sampling period, only when met conditions meet certain criteria. Vary sampling rate with wind speed and/or pbl height. CO$_2$, CH$_4$, CO, $\Delta^{14}$CO$_2$, $\delta^{13}$CO$_2$, SF$_6$, N$_2$O, H$_2$.
- ?N “Grab” sample flasks: CO$_2$, CH$_4$, CO, $\Delta^{14}$CO$_2$, $\delta^{13}$CO$_2$, SF$_6$, N$_2$O, H$_2$, and a suite of halocarbons and hydrocarbons.
- We do not currently have met data defined; likely to have 2D sonics at some towers.
INFLUX Tower Experimental Design

- Multiple methods to calculate flux from the measurements
  - Simple mass balance approach
    - But mixing state in BL is unknown
    - integrated mass balance approach from aircraft
  - Inversions with WRF-CHEM
**$^{14}$CO$_2$ Measurements**

\[
CO_{2,ff} = \frac{CO_{2,obs}(\Delta_{obs} - \Delta_{bg})}{\Delta_{ff} - \Delta_{bg}} - \frac{CO_{2,r}(\Delta_{r} - \Delta_{bg})}{\Delta_{ff} - \Delta_{bg}}
\]

- We will do integrated (~biweekly) sampling at the towers, for specified wind directions/conditions. $^{14}$CO$_2$ measurements are expensive, and there is limited capacity. Aircraft samples will also be analyzed for $^{14}$CO$_2$. Analysis to be done by AMS.
- Integrated samples reduce the number of measurements, but still allow us to average over longer time periods (can average out some of the biases)
- We will also measure CO and obtain CO$_2$ff using known CO/CO$_2$ emission ratios.
Atmospheric Inversion

Inversion adjusts fluxes to minimize this difference.

In principle transport is also uncertain and could be adjusted as part of the minimization, but this is not done at present.
Comparing to/informing the Vulcan Emission Inventory/Model

Vulcan is producing high resolution emission data for the residential, commercial and industrial sectors, in addition to the transportation and electricity production sectors.

Vulcan - hourly resolution for USA

• See: Kevin Gurney/
  • http://www.purdue.edu/eas/carbon/vulcan/index.php
What we don’t have, but need

• Support for more Flask/$^{14}$CO$_2$ samples, CO instruments.

• Winds and boundary layer information
  
  - We have 3D winds and BL profiling on the aircraft, but of course this is sporadic
  
  - Need acoustic and RADAR profilers/LIDAR or the equivalent/better

• We do not yet have CO (except flasks) on the aircraft.

• We would like a partnership with NASA on this project.

• DIAL CO$_2$?
Please join the INFLUX Team!

Thank you!

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Update on Aircraft Measurements

Obie Cambaliza and Paul Shepson
Purdue University
INFLUX Meeting
To date . . .

• Three flights:
  – Oct 27, Nov 22, 2010, and last Saturday, Jan 29, 2011 (testing of the Picarro analyzer)

• Focus on initial results from our Nov. 22nd flight
  – Scientific approach
  – Scientific challenges
  – What’s interesting
Airborne Laboratory for Atmospheric Research (ALAR)

http://www.chem.purdue.edu/shepson/alar.html
Airplane installation 01.27.2011

- Tank 1
- Tank 2
- PFP

This is where Tank 3 will go

PCP
Airplane installation 01.27.2011

- Calibration system
- CRDS
- Winds computer
Flight Path on Nov 22, 2010

Wind coming from SW
CH$_4$ time series
CH$_4$ time series
CH$_4$ time series
CH$_4$ distribution (ppmv)
Kriged CH$_4$ Distribution (ppmv)
CO₂ Distribution (ppmv)
What next? Comments and Thoughts

• Aircraft measurements
  – Provide an independent estimate of area-wide emissions from Indianapolis
  – Provide important data for the inverse modeling approach
  – Will continue comparison to Hestia-Vulcan estimates with spatial resolution.

• What about the calculation of footprints to identify location of CH₄ sources?
  – Use of aircraft measurements as input to inverse modeling
  – Use of instrumented vehicle to identify specific sources and source types (landfills, waste waster treatment plants, incinerators, natural gas distribution system) and then to conduct flask sampling for δ¹³CH₄.
INFLUX FLASK MEASUREMENTS

Jocelyn Turnbull
Colm Sweeney
NOAA/ESRL Carbon Cycle Group
INSTAAR Stable Isotope and Radiocarbon Labs

Related poster:
Thursday 11 am

I-203: Measurement of fossil fuel derived carbon dioxide and other anthropogenic trace gases above Sacramento, California in Spring 2009 (Jocelyn Turnbull, Anna Karion, Marc Fischer, Ian Faloona, Tom Guilderson, Scott Lehman, Benjamin Miller, John Miller, Steven A. Montzka, Tom Sherwood, Suman Saripalli, Colm Sweeney, Pieter P. Tans)
Measure multiple species:

- $\text{CO}_2$
- $\text{CO}$
- $\text{CH}_4$
- $\text{N}_2\text{O}$
- $\text{SF}_6$
- $\text{H}_2$
- $\delta^{13}\text{CO}_2$
- $\delta^{18}\text{O}^{16}\text{O}$
- $\delta^{13}\text{CH}_4$
- $\Delta^{14}\text{CO}_2$
- halocarbons
- hydrocarbons

Quantify fossil fuel $\text{CO}_2$ additions over Indy using $\Delta^{14}\text{CO}_2$

Correlate species – calculate emission ratios – compare to inventories

Use flask $\text{CO}/\text{CO}_2$ff ratio to obtain high resolution $\text{CO}_2$ff from in situ CO measurements

Quantify $\text{CO}_2$ff emissions from Indianapolis – with uncertainties
Sample collected over 1 hour
Large mixing volume
Vary flow rate during filling to obtain close to linear mixture
Collect air into PFP flask
INFLUX tower 2 flask vs insitu CO$_2$

Hourly average in situ CO$_2$ (ppm)

Flask CO$_2$ (ppm)

slope 1.0483 +/- 0.0354
intercept -19.2280
$R^2$ 0.99
chisq 0.4
q 0.0000
F 2581.1907
F dist 0.0000
number of points 18
Offsets may be due to difference between in situ and flask averaging times
Flask sampling strategy

- Only collect when wind is coming from west or southwest
- Sample in afternoon when boundary layer is well-mixed
Flask measurements

\( \text{CO}_2 \) mixing ratios

\( \text{CO}_2 \) is enhanced at Tower 2 relative to Tower 1
Flask measurements
CO mixing ratios

- Tower 1
- Tower 2 (pm)
- Tower 2 (am)
Mixing ratios at Tower 2 vary inversely with wind speed
Wind speed from edas 40 km
Tower 2 CO:CO$_2$ ratio is similar to those seen for other US urban areas (e.g. Sacramento)
CO:CO$_2$ff is likely to be much higher
Update: Continuous tower-based in-situ measurements

INFLUX meeting at NACP
1 February 2011

Penn State team
Ken Davis
Thomas Lauvaux
Natasha Miles
Scott Richardson
Tower-based Measurements

• Current: continuous measurements of CO2 at two sites

• Planned
  • Two sites measuring CO2/CO/CH4
  • Three sites measuring CO2/CO
  • Three sites measuring CO2/CH4
  • Four sites measuring CO2
  • Five sites with flasks (sites with CO)
Tower locations (current and planned)

- Site 01: CO2/CH4/CO Flasks, PROFILE, “Rural”
- Site 02: CO2/CH4/CO Flasks, PROFILE, “Urban”
- Site 03: CO2/CH4/CO (2 instruments) Flasks, PROFILE
- Site 04: CO2/CO, Flasks
- Site 05: CO2/CO, Flasks
- Site 06: CO2/CH4
- Site 07: CO2/CH4 PROFILE
- Site 08: CO2
- Site 09: CO2
- Site 10: CO2
- Site 11: CO2
CO2/CO/CH4/H2O Analyzers
CO2/CO/CH4/H2O Analyzers
Tower-based Measurements

Sampling Strategy

• Several sites will have multiple sampling levels (profile sites)
  – Currently Site1, 2, 3 and 7
• Top level as high as possible, > ~100 m
• Additional 10 m and 40 m levels
• Sample top level 40 min/hour
• Sample other levels 10 min/hour
Tower-based Measurements: Calibration Strategy

• Two NOAA-CMD calibrated tanks at each site
• Sample cal tanks every 23 hours
• Use this to correct for daily drift

• Multi-species analyzers will have multi-species cal tanks

• To get 2 ppb CO precision:
  – Requires drying (using nafion drier)
  – Requires frequent CO calibration (~5 min 2x/hour)
  – Exact calibration requirements uncertain at this time
  – Plan to be conservative to ensure high quality data
Plans

- Sites 1 and 2: Replace CO2 only with CO2/CO/CH4
  - February 2011
- Move 2 current CO2 only instruments to other sites
  - February 2011
- Install remaining 2 CO2 only instruments
  - As sites become available
- Install remaining 6 instruments at 5 sites
  - As sites become available
Inter-site differences

- Daytime (12 – 4 LST) average differences up to 8 – 10 ppm
- Gradients up to 20 – 25 ppm /100 km (Site separation distance: 40 km)
- Biological gradients observed during MCI: 3 ppm / 100 km (Miles et al., 2011)
- Affected by both local flux and advection
- Changing wind direction
Urban (Site02) - Rural (Site01) at 100+ m AGL

NOAA HYSPLIT MODEL
Backward trajectories ending at 1800 UTC 06 Nov 10
EDAS Meteorological Data
Forward modeling results (T. Lauvaux)
Urban (Site02) - Rural (Site01) at 100+ m AGL

Forward modeling results (T. Lauvaux)
• Example of Site 02 measuring urban plume
• Forward model captures general trend in the inter-site differences during these 5 days
• For more examples, see poster on Thursday (Miles et al.)
Urban site: peaks at 7:00, 9:30, 10:30 LST for levels 10, 40, and 100+ m AGL

Vertical gradient is minimized between 11:30 and 16:30 LST

Observations

- Urban site: peaks at 7:00, 9:30, 10:30 LST for levels 10, 40, and 100+ m AGL
- Vertical gradient is minimized between 11:30 and 16:30 LST
  - Vertical mixing ?
  - Horizontal transport ?
Diurnal cycle: DOY 312, 8 Nov 2010, $\Delta > 10$ ppm

**Observations**

- Urban site: peaks at 7:00, 9:30, 10:30 LST for levels 10, 40, and 100+ m AGL
- Vertical gradient is minimized between 11:30 and 16:30 LST
  - Vertical mixing ?
  - Horizontal transport ?

**Forward model results (T. Lauvaux)**

- Differences in [CO2] absolute value
- Variability in time is well-captured
Diurnal cycle: DOY 310, 6 Nov 2010, $\Delta < 1$ ppm

**Observations**

- Differences in [CO2] absolute value
- Delay in model mixing (horizontal transport)

**Forward model results (T. Lauvaux)**

- Again, differences in [CO2] absolute value
- Delay in model mixing (horizontal transport)
Fossil Fuel CO$_2$ data product within the INFLUX experiment

Kevin Gurney$^1$, Yuyu Zhou$^2$, Igor Razlivanov$^1$, Bedrich Benes$^3$

$^1$Arizona State University
$^2$DOE PNL
$^3$Purdue University

INFLUX team: Shepson, Cambaliza, Davis, Miles, Richardon, Lavaux, Sweeney, Turnbull

Support from: NASA, Knauf insulation, Showalter Trust, Rosen Center, PCCRC

INFLUX: NIST
Proposed Research

“We propose to improve the Hestia urban-level inventory beyond its current pilot phase to best match the atmospheric observing strategy”

What is Hestia?

How will it be improved?

How will improvements best match atmos obs?

All of this in the context of “develop and test techniques/approaches…” for measuring/estimating fluxes
The Vulcan Project
Total Emissions of Fossil Fuel Carbon Dioxide, 2002

www.purdue.edu/eas/carbon/vulcan

Vulcan
Version 2.0 now available

www.purdue.edu/eas/carbon/vulcan

Gurney et al., Env. Sci & Tech, 2009
Hestia

All point sources: Vulcan

All nonpoint buildings: thermo “skin” model

Transport: Vulcan with local MPO traffic and fleet

Aircraft, nonroad: Vulcan

Cement: Vulcan
Observations regarding Marion county:
• Powerplant and onroad constitute 60% of emissions
• One large powerplant – Harding St station
• Complicated traffic (commuter and commercial)
Hestia pilot ("Etna")

Thanks: Bedrich Benes
Hestia pilot ("Etna") onroad
Improvements? Best Match?

- Contemporary emissions - 2010/2011
- Time structure: industrial, airport
- CH$_4$ (pipeline leakage?) - estimate from large pipeline “joints”
- Uncertainties (underlying data, independent data, etc)
- Harding St CO$_2$ monitor - detailed CEMs vs fuel calc, uncertainty
- Transportation sector overhaul

Integration questions we think about:
1. Will our powerplant estimate serve as a check to atmos measure or vice-versa?
2. Can tower/aircraft isolate onroad? Powerplant?

PS: discussion underway on doing Hestia in LA!
Thank You!
Opportunities for collaboration

• Atmospheric remote sensing: Ground-based or airborne or space-based
  – Greenhouse gases (e.g. lidar, FTIR)
  – Atmospheric transport (radar, sodar, lidar)

• Contributions to our understanding of regional atmospheric transport
  – Urban influence on the atmospheric boundary layer
    (surface flux data, urban meteorology)
  – Simulation of deep convection

• High resolution remote sensing of the land surface to aid flux inventories and prior flux estimates

• Alternative atmospheric inversion schemes