Greenhouse Gas Emissions and Transport

Measurement Science to Quantify and Locate Sources of Greenhouse Gas Emission in an Urban Domain

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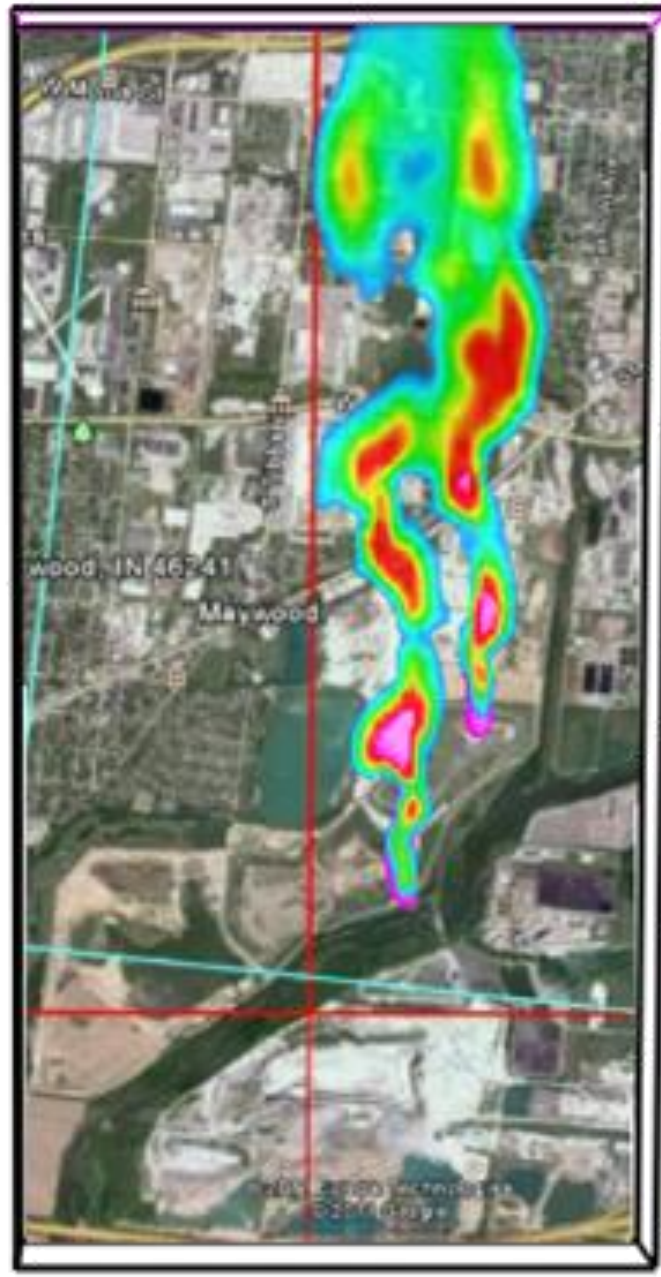
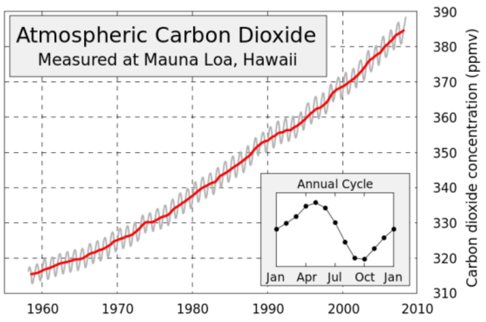
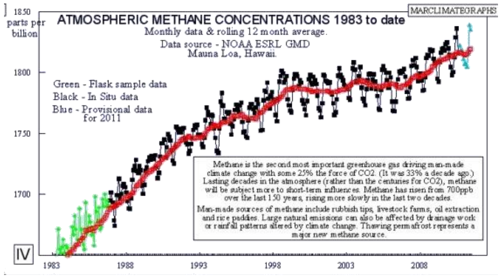
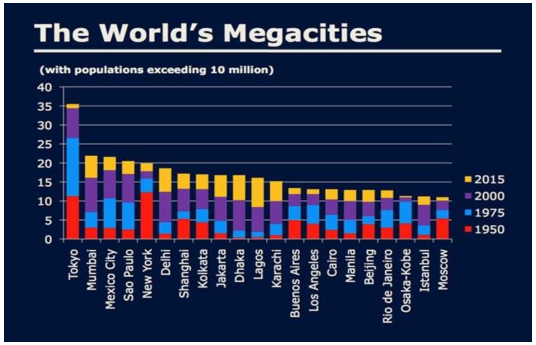


Introduction

- US anthropogenic carbon emissions - *6.7 billion tons (2007)*.
- Impact of greenhouse gases : *US Climate Action Report, US DoS 2010*.
- Leaks from natural gas extraction and pipeline transmission are the largest human-derived source of methane emissions (*EPA, 2012*).
  - 2010, San Bruno, CA natural gas pipeline explosion
- Without accurate measurement of emissions, it is difficult to measure progress in reducing emissions or to determine the effectiveness of mitigation strategies. (*Greenhouse Gas Emission Quantification and Verification Strategies Workshop 2010*).
- Ability to accurately measure, report, and verify greenhouse gas (GHG) emissions is vital to future GHG management strategies
- Megacities are the largest producers of Greenhouse Gases.
  - Large population growth in megacities. High energy demand.
  - Focus on measuring the GHG emissions for megacities.
- Questions : What tools / methods are needed to measure GHG emissions for megacities with prescribed un-certainty bounds.





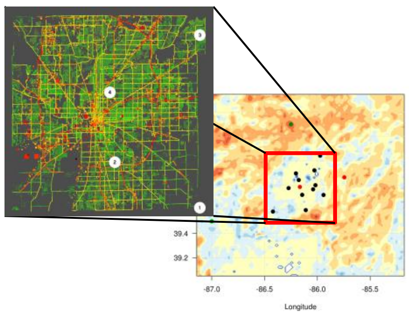


Key Outcome

- Develop and demonstrate measurement capability to accurately locate greenhouse gas sources and measure their flux to the atmosphere at urban and regional locales for:
  - Reduce uncertainty between Bottom-up and Top-Down Approaches
  - Independent verification of greenhouse gas emissions, and
  - Location of previously unidentified sources and sinks.
- Quantifiable Goals
  - Spatial resolution of 1 km^2 for location information
  - Flux measurement accuracy of 10% or better
- NIST initiated the INFLUX (Indianapolis Flux) Program in 2010 as a pilot project to investigate and demonstrate the capability :
  - Investigate the use of spatially dense, surface-based observing networks to locate GHG sources and determine their flux at the targeted levels of accuracy.
  - Reconcile Bottom-Up and Top-Down methodologies.
- Inter-disciplinary approach enabled by recent technological advances.

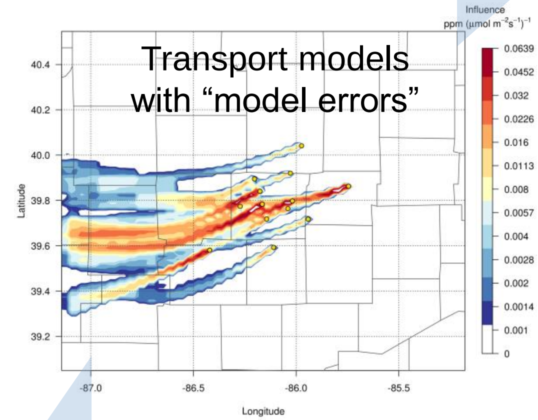
Top-Down CO_2 Inversion framework

Prior GHG fluxes
(“bottom-up” inventories)
with uncertainties

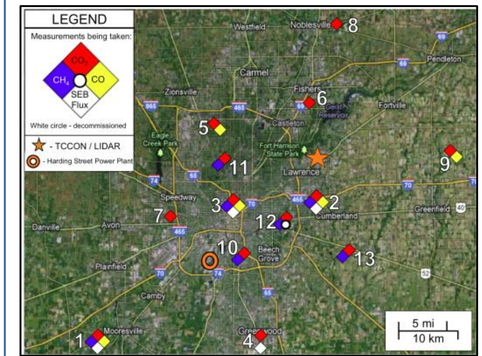


Simulation of the GHG
atmospheric transport

Transport models
with “model errors”



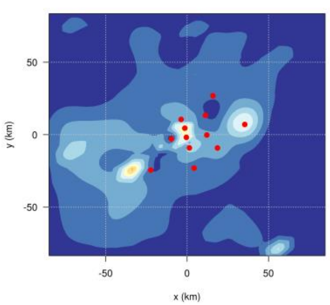
Comparison to
The measurements



GHG atmospheric
measurements with
measurement errors
(Towers, planes, flasks...)

Statistical inversion: optimal
corrections that minimize the
sum of misfits to the
measurements & prior

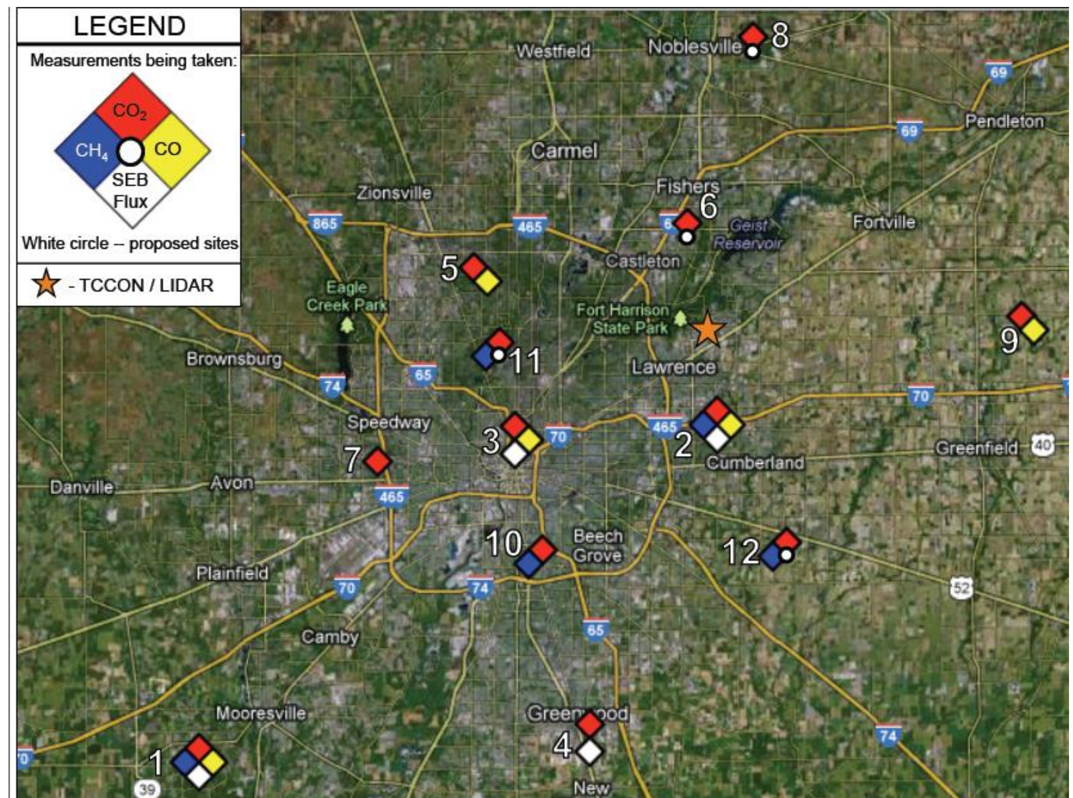
Inverted GHG fluxes
with uncertainties



While bottom-up inventories for CO2 are available, similar inventories for Methane do not exist.

Measurement system

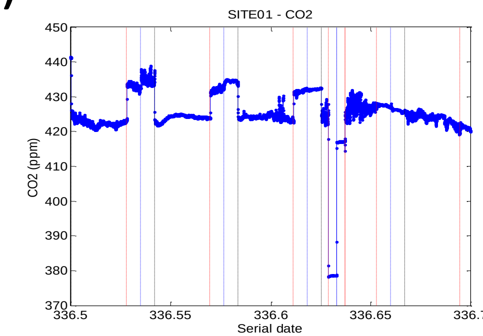
CRDS Instrument real-time observations with flask sampling



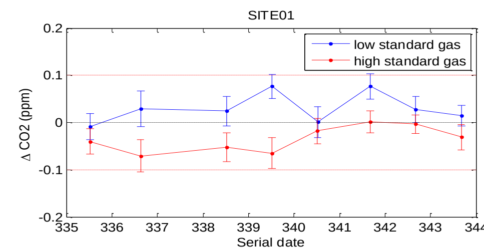
Quality Control for Greenhouse Gas Data

(Heming, Israel, Kuldeep)

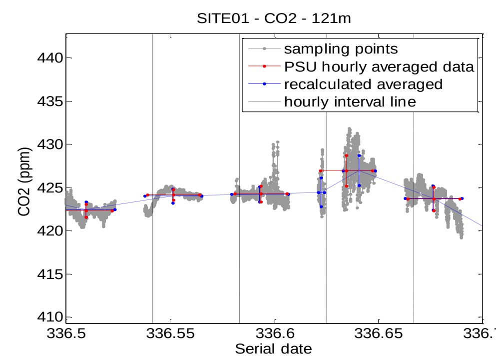
- Why?
  - QC data with highest possible standards of accuracy are needed.
  - Heterogeneous data streams (Tower, airplanes, mobile, flasks...)
  - Instrument uncertainty : <50 ppb(CO_2), <2 ppb(CO), <1 ppb(CH_4)
- Challenges?
  - Mechanical, electrical, software problems.
  - Missing data detection, error detection.
  - Large amount of real-time data, different formats
- Data calibration, uncertainty estimation.
- Standardized QC process is documented.
- QC'ed data available for inversion analysis.



Raw data



calibration

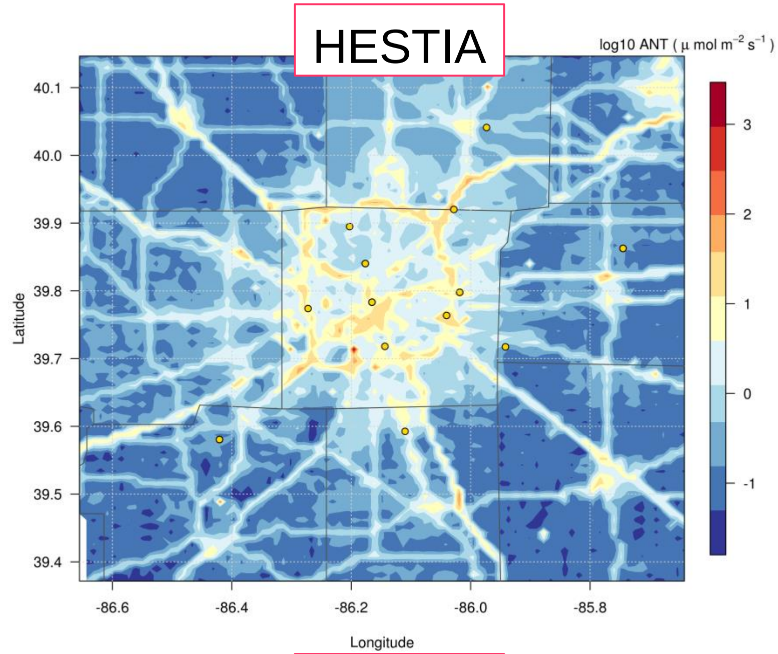


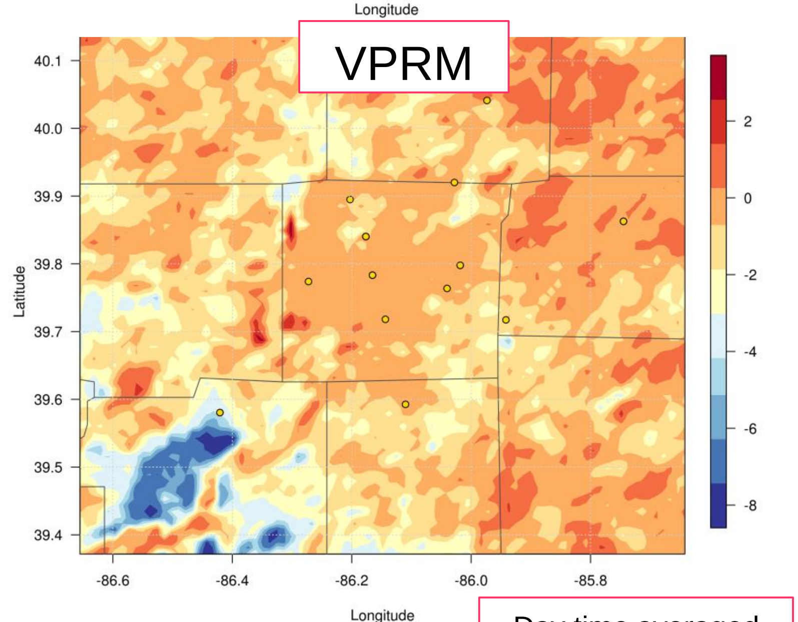
QCed data

Raw data ASCII → Indexed and flagged data → Calibrated and corrected → Hourly data

Estimating Prior CO_2 fluxes (Israel, Heming, Kuldeep)

- Why?
  - Priors for inversion
  - Measurement analysis and sectoral attribution
- What?
  - Anthropogenic: Hestia, Vulcan, Odiac
  - Biogenic fluxes: Vegetation Photosynthesis and Respiration Model (VPRM)
    - WRF-VPRM augmentation (inclusion of corn vegetation category) and parameters optimized for our specific domain (INFLUX) and period
- Impact
  - Influence of emissions on towers, planes and flasks measurements.
  - Biogenic fluxes as prior for inversion.

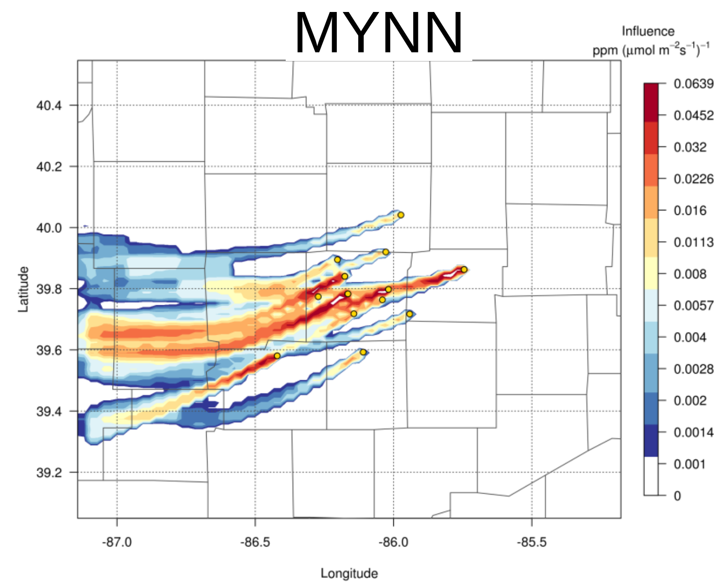


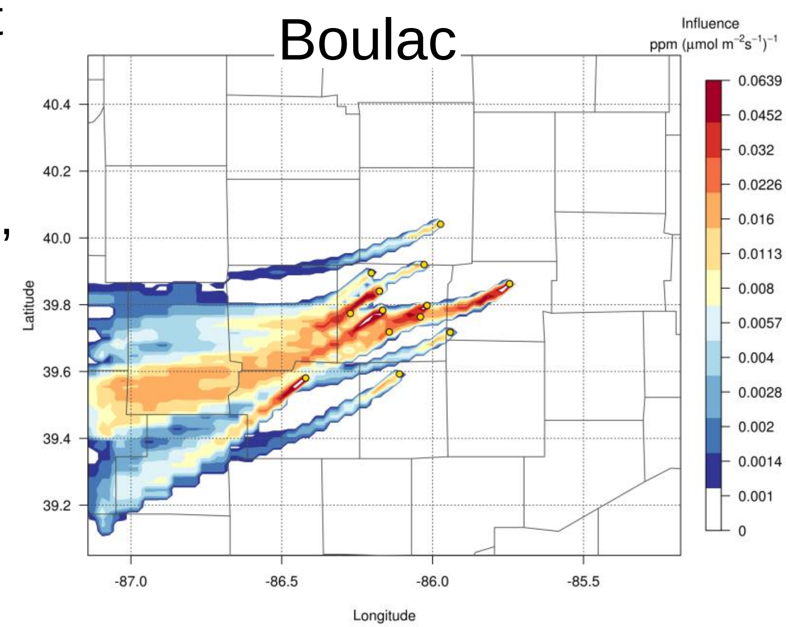


Day time averaged (12:00-16:00 PST)

Direct model-data comparison (Israel, Kuldeep)

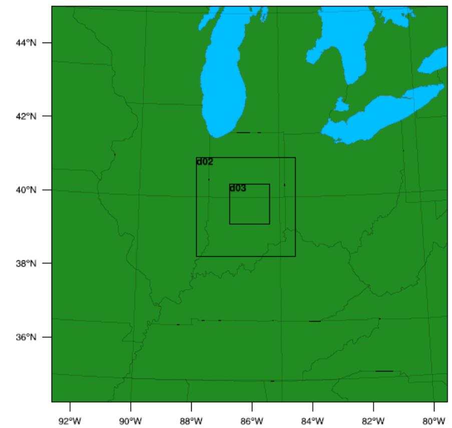
- Why?
  - Need to quantify and reduce the errors between model predictions and measurements.
  - Develop footprints for inversion
  - Sectoral attribution and background evaluation
- What?
  - Forward: WRF-CHEM
  - Backward: STILT → Footprints (adjoint approximation)
  - Meteorological data assimilation
  - Direct model-data comparison for CO2, including anthropogenic (Hestia + Vulcan) and biogenic (VPRM) fluxes
- Impact
  - Transport errors minimization.
  - Database of “model errors” error covariance matrices calculation.





WRF-FDS Coupling (<u>Kuldeep</u>, Heming, Israel)

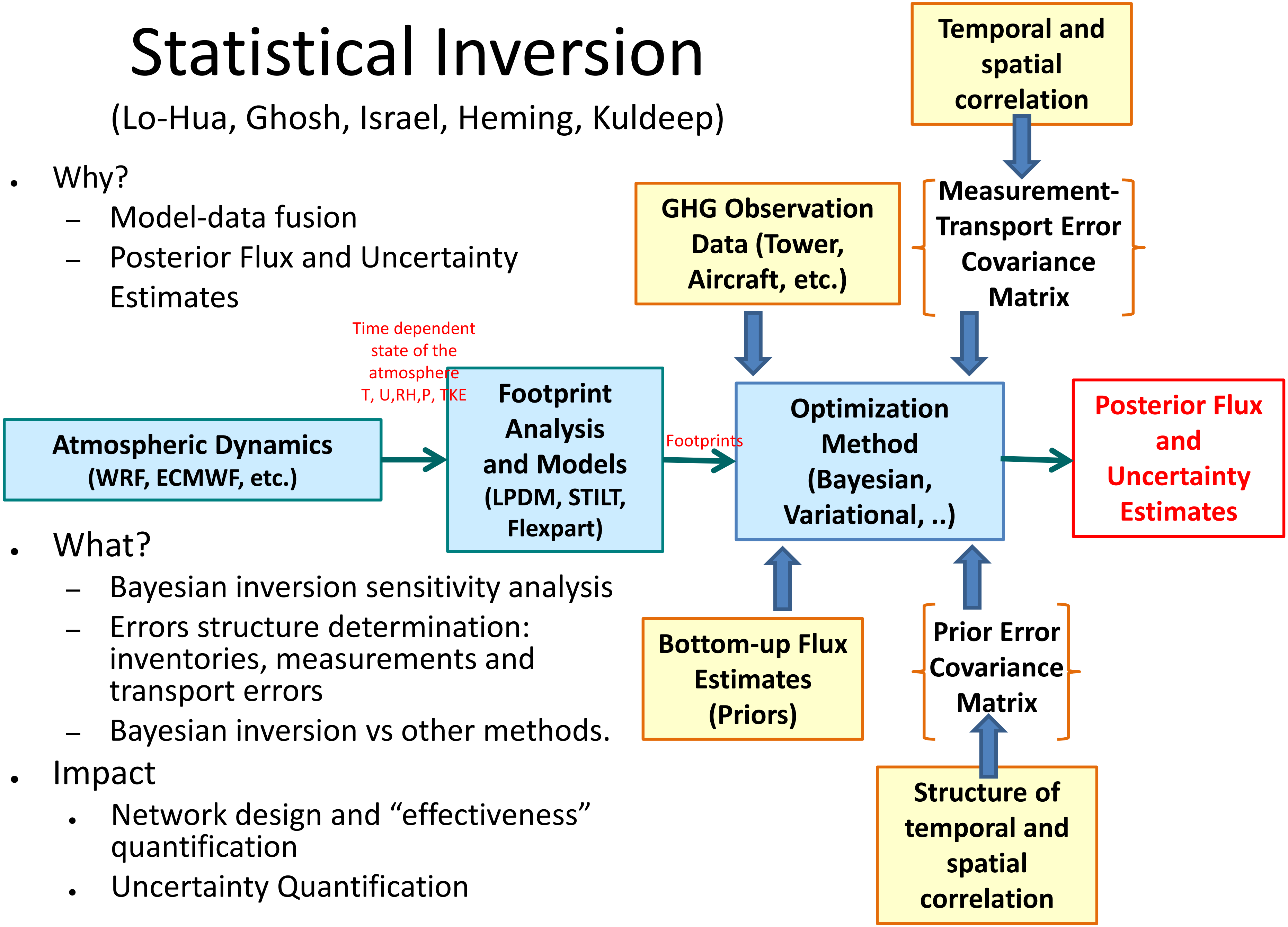
- Why?
  - WRF used to simulate atmospheric dynamics with spatial resolution of 1-2 km.
  - WRF does not resolve the fine scale dynamics (turbulence) around building and communities. Effect on footprints?
  - Significant problem for urban domains.
- What?
  - Develop a building resolved model for the city of Indianapolis with in FDS.
  - FDS is run as a sub-grid scale model coupled with WRF.
  - Wind speed, direction, radiative flux, lapse rate and turbulence parameters are obtained from WRF simulations.
  - Incorporate emission inventory from Hestia database
  - Large Eddy Simulations (LES) are used to simulate tower measurements and evaluate footprints.
- Impact
  - Model error reduction.



Statistical Inversion

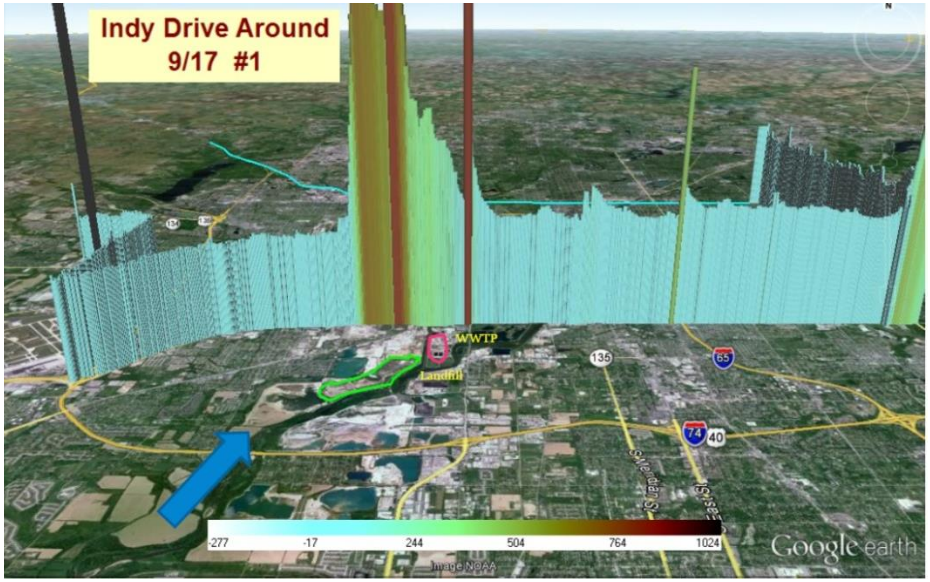
(Lo-Hua, Ghosh, Israel, Heming, Kuldeep)

- Why?
  - Model-data fusion
  - Posterior Flux and Uncertainty Estimates



- What?
  - Bayesian inversion sensitivity analysis
  - Errors structure determination: inventories, measurements and transport errors
  - Bayesian inversion vs other methods.
- Impact
  - Network design and “effectiveness” quantification
  - Uncertainty Quantification

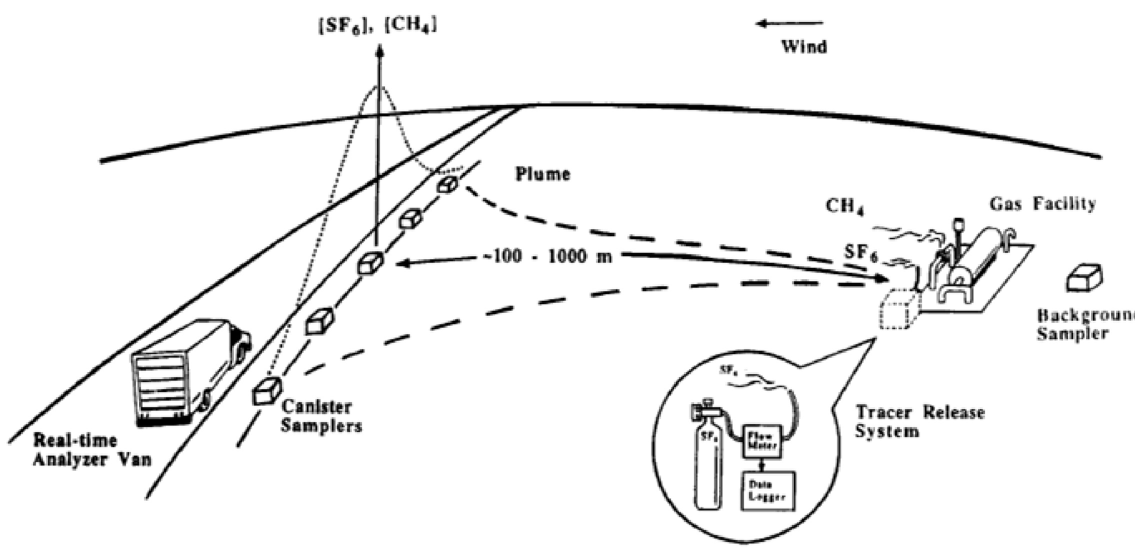
Methane Emission Inventory (Kuldeep, Heming)



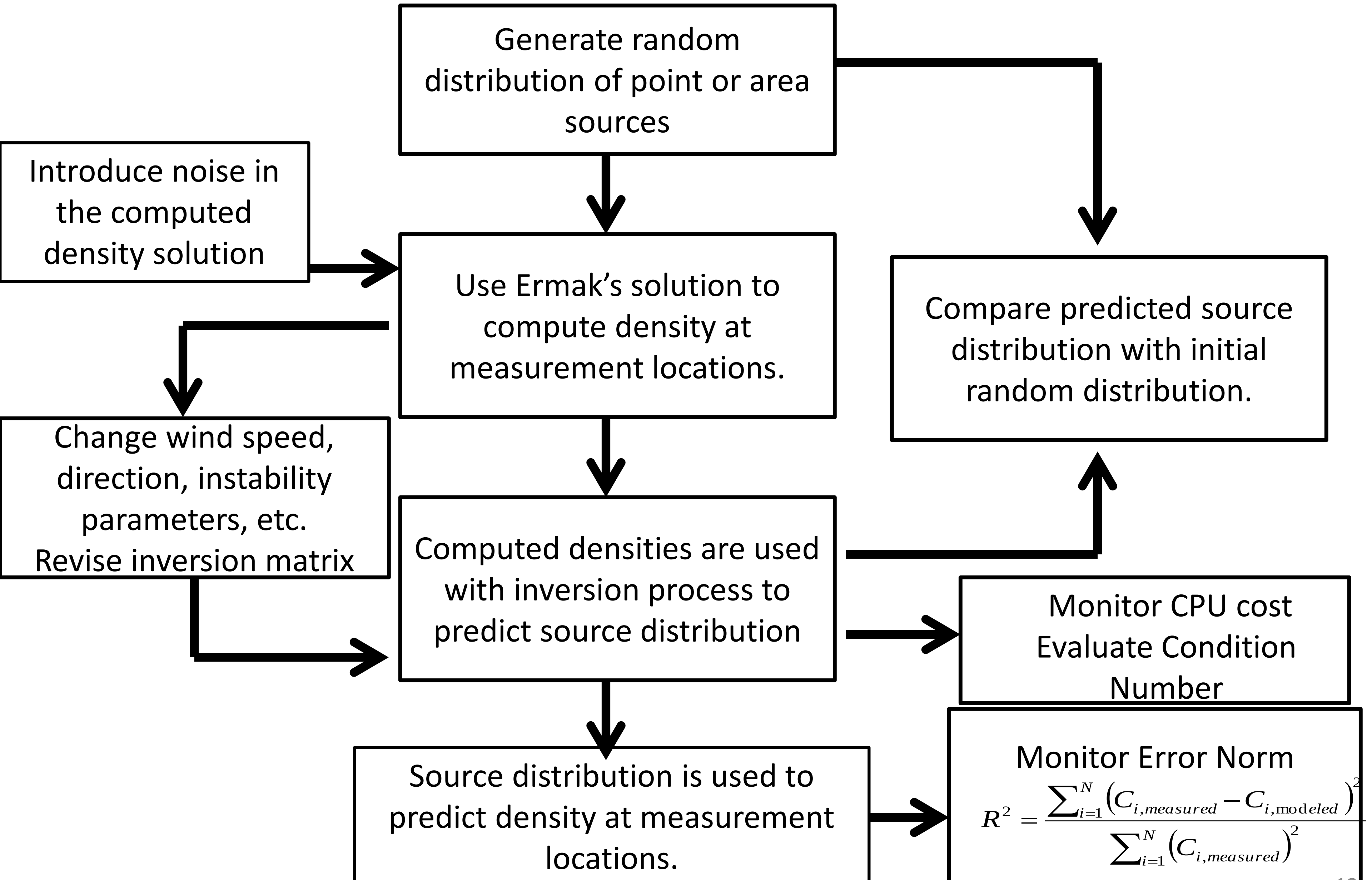
Intensive Measurement Campaign –June 2013

- Purdue University
  - Picarro, GPS, 3-D sonic instruments.
- Washington State University (WSU)
  - Picarro CRDS, GPS, 2-D Sonic Anemometers, Meteorology Package.
- Two Mapping Partner Cars (CSU)
  - Picarro CRDS , GPS
- SF6 tracer release and measurements

- Ranking of the major CH_4 sources.
- Measurement approach for reducing uncertainty.
- Detailed measurements around large methane sources.
- **Development of a Methane inventory for the city of Indianapolis**
- Comparison with EDGAR / EPA inventory and other approaches.

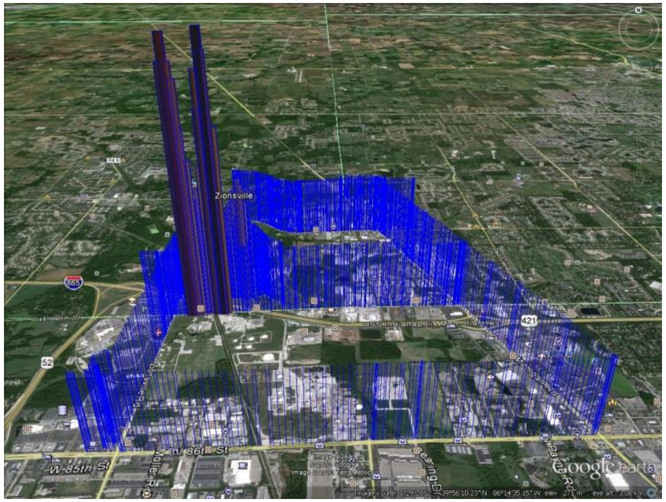


Methane Inventory : Model Verification

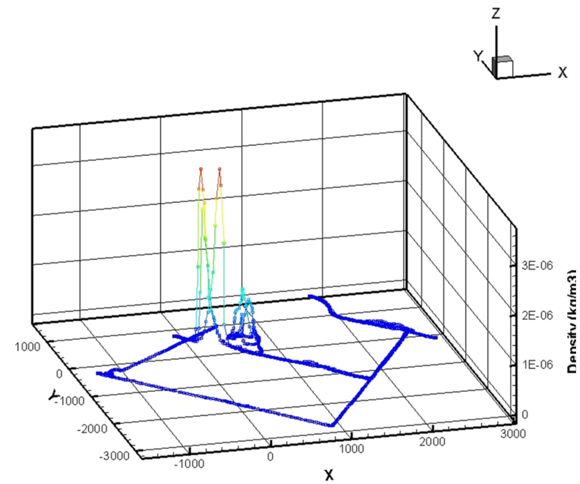


Panhandle Eastern Station : Case Study

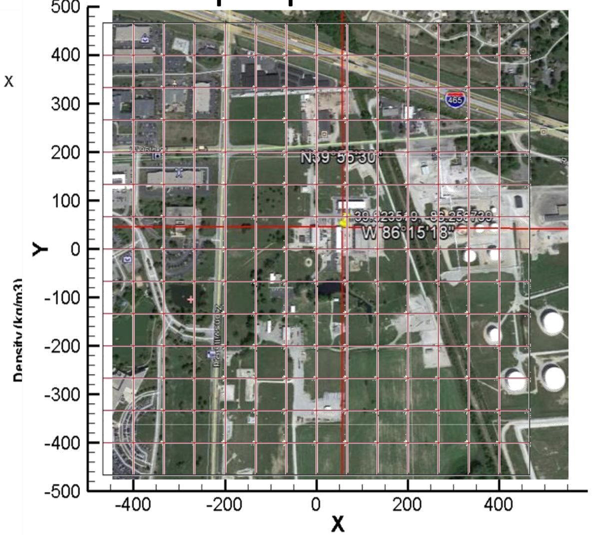
Drive Path



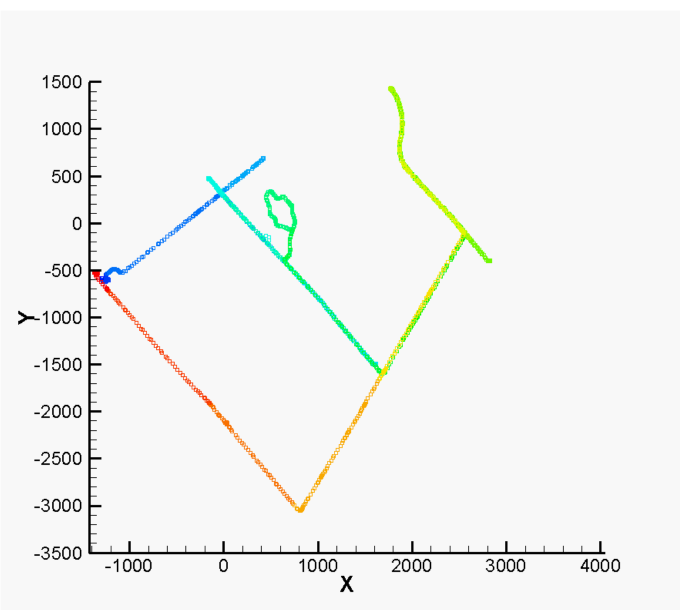
Measured Methane Profiles



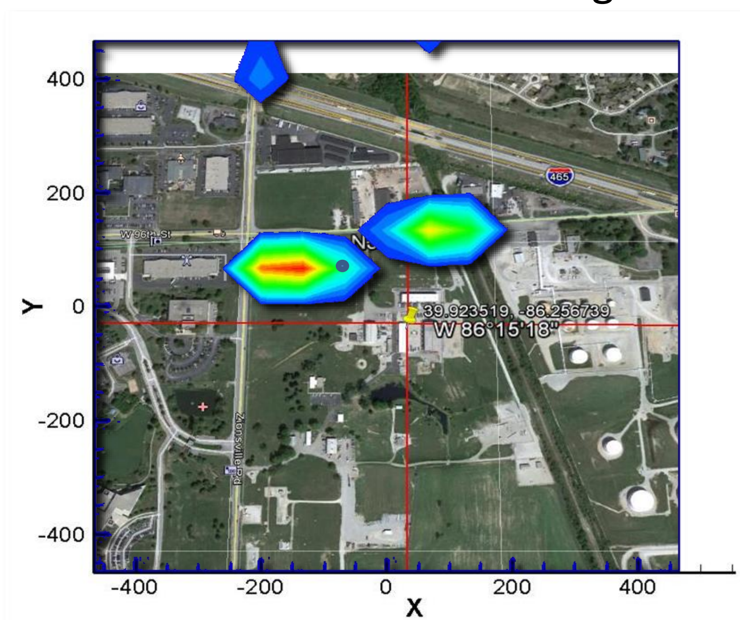
Multiple point sources



Animation of the Drive Path



Source Location and Strength



Least Squares Method
Minimize error

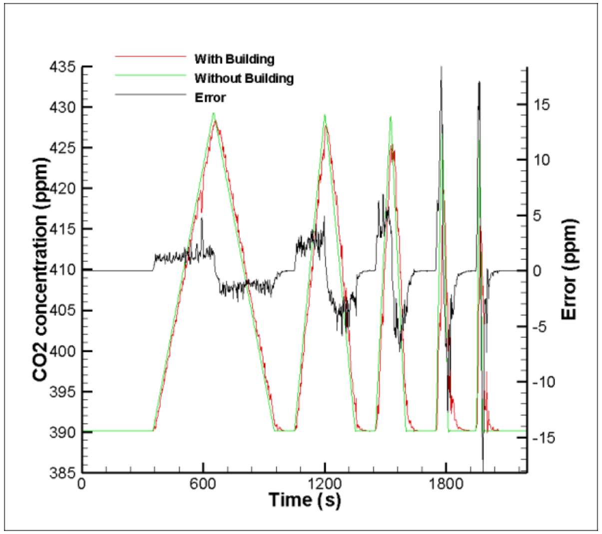
Invert a matrix of plume equations for multiple sources and multiple receptors.

Total Source Strength
1200 grams / min

Key Accomplishment to date: Indianapolis Methane Inventory

	Indianapolis Methane Inventory (grams /min)					
		Best estimate	Aircraft Mass Balance Approach	Tracer Ratio Method	High Flow Instruments	Plume Inversion Model
1	Total City Emission Rate	**129600**	129600			
2	Southside Landfill (SSLF)	**36720**	43200			30240
3	Transmission and Regulating Station TRS #2	**34.8**	21.6	33 to 72	25.2	22
4	Panhandle Eastern Pipeline	**1260**				1260
5	Leak at the Oliver Avenue Bridge	**22.2**		22.2		
6	Julietta LF/ Whispering LF					
7	Southport Waste Water Treatment Plant					ongoing analysis
8	Texas Gas Station					
9	Harding/Epler underground leak	**4.9**			4.9	
10	Underground pipeline leaks (14 measured, 115 surveyed by LDC)	**279.1**			34.0	
11	M&R stations (23 measured)	**31.4**			31.4	
12	Un-combusted methane (5% loss?)	**79613**	g/min			SCF/yr/
13	dig-ins	**3188**	total pipeline miles	9164	EF for dig-ins	1590
14	all meters	**1355**	total services (assume = meters)	269000	EF for meters	143
	Total individual sources*	**122509**				
	% of city flux	**95%**				

- Development and demonstration of measurement capability and methodology to accurately locate greenhouse gas sources and measure their flux.
- Measurement capability and methodology is adopted in other cities / countries.
- Effect of remediation techniques. Is the methodology sensitive / accurate enough?

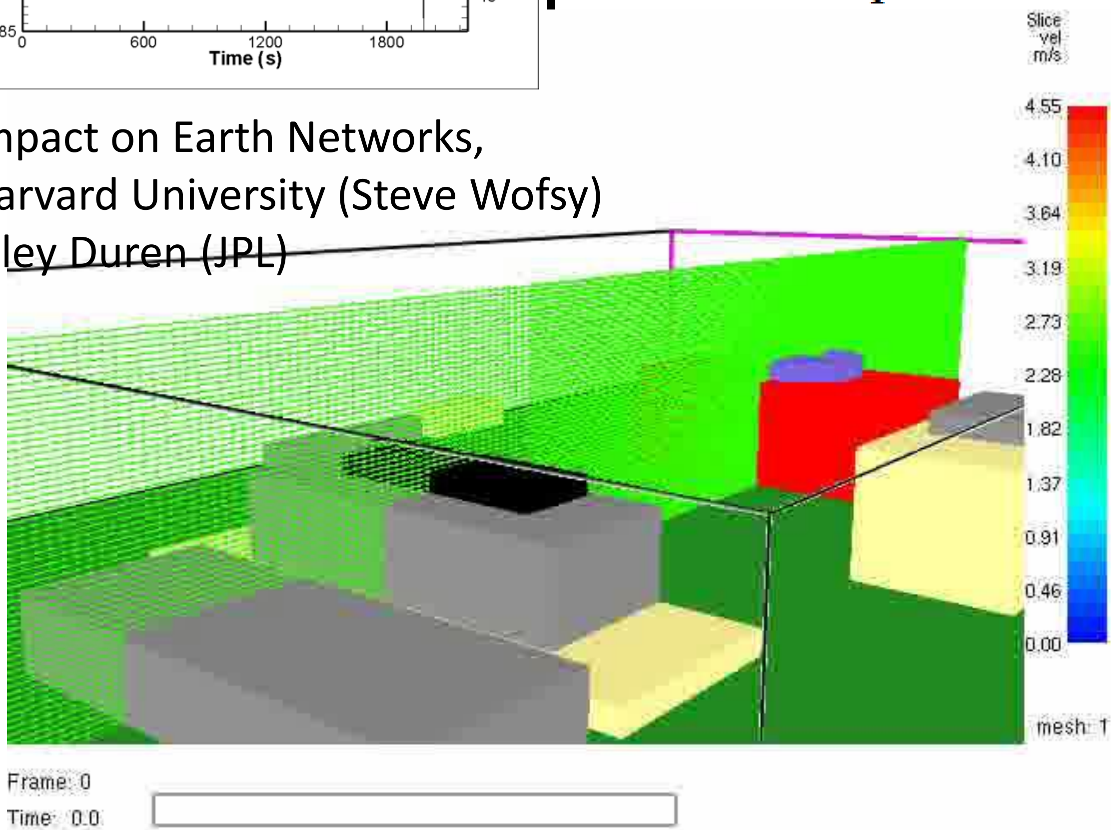


Impact on Earth Networks,
Harvard University (Steve Wofsy)
Riley Duren (JPL)

NIST Special Publication 1158

Greenhouse Gas Emissions and Dispersion

1. Optimum Placement of Gas Inlets on a Building Rooftop for the Measurement of Greenhouse Gas Concentration



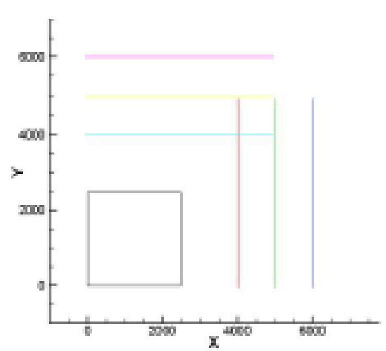
Kuldeep Prasad
Anthony Bova
James R. Whetstone
Elena Novakovskaia

http://dx.doi.org/10.6028/NIST.SP.1158

Use of bootstrap method to estimate variability in source attribution.

Report describes the scientific basis for making mobile measurements in Indianapolis.

Approach used during the June 2013 mobile campaign.



NIST Special Publication

Greenhouse Gas Emissions and Dispersion

3. Reducing Uncertainty in Estimating Source Strength and Location through Plume Inversion Models

Kuldeep Prasad
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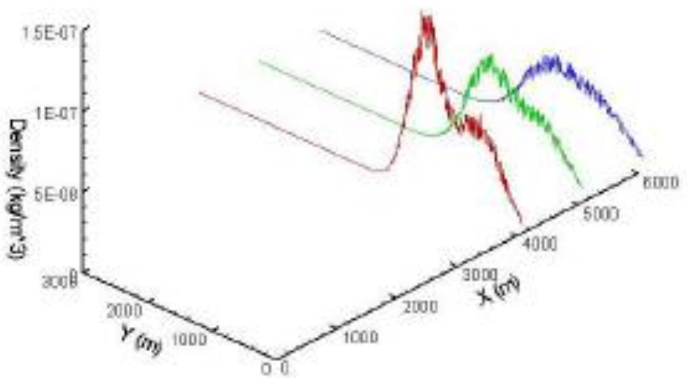
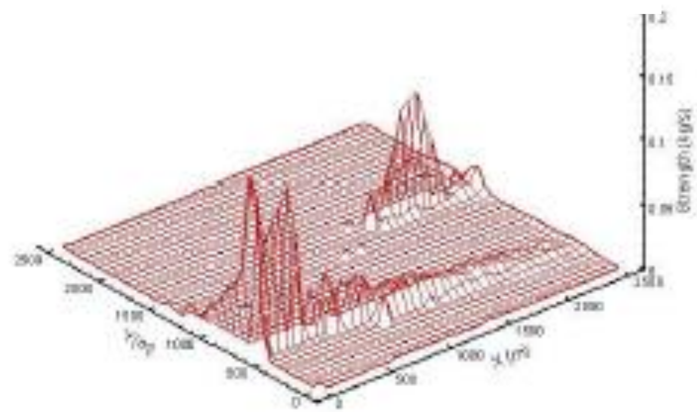
Heming Hu
Israel Lopez-Coto
Dennis Ngo
James R. Whetstone





Recent Publications and Presentations

- Greenhouse Gas Emissions and Dispersion 3. *Estimating and Reducing Uncertainty in Source Strength and Location through Plume Inversion Models*, **Kuldeep Prasad, Adam Pintar, Israel Lopez-Coto, Heming Hu, James Whetstone, NIST Special Publication, 2014.**

- Quantification and source apportionment of the methane emission flux from the city of Indianapolis, **M. Cambaliza, K. Prasad, J. Whetstone, submitted, Energetica, 2014.**

- Monitoring methane in the boundary layer using a network of instruments at tall towers in the northeastern US, Elena Novakovskaia, Kuldeep Prasad**, AMS Conference January 2013.**

- Measuring CO_2 and CH_4 emissions from Indianapolis: Preliminary results from an urban atmospheric inversion system, K. Davis, M. O. Cambaliza, K. Gurney, M. Hardesty, P. Hillyard, L. Iraci, A. Karion, T. Lauvaux, L. McGowan, N. Miles, J. Podolske, K. Prasad, I. Razlivanov, S. Richardson, D. Sarmiento, P. Shepson, C. Sweeney, J. Turnbull, J. Whetstone, **NOAA GMD Conference, May 2013**.

- Methane emission flux from Indianapolis, IN: identification and contribution of sources to the total citywide emission, Maria Obiminda Cambaliza, Paul Shepson, Brian Stirm, Dana Caulton, Chase Miller, Alyssa Hendricks, Brittany Moser, Anna Karion, Colm Sweeney, Jocelyn Turnbull, Ken Davis, Thomas Lauvaux, Scott Richardson[5] Natasha Miles, Eric Crosson, Kuldeep Prasad, James Whetstone, **NOAA GMD Conference, May 2013**.

- Quantification of Methane Emissions From Street Level Data**,** Kuldeep Prasad, Brian Lamb, Maria Obiminda Cambaliza, Tegan Lavoie, Olivia E Salmon, Paul Shepson, Thomas Lauvaux, Ken Davis, and James R. Whetstone, **International Smoke Symposium, 2013.**

- Quantification of Methane emission flux from Indianapolis, IN: identification and contribution of sources, Maria Obiminda Cambaliza, Paul Shepson, Brian Stirm, Dana Caulton, Chase Miller, Alyssa Hendricks, Brittany Moser, Anna Karion, Colm Sweeney, Jocelyn Turnbull, Ken Davis, Thomas Lauvaux, Scott Richardson[5] Natasha Miles, Eric Crosson, Kuldeep Prasad, James Whetstone, **AGU Conference 2013**.

- Greenhouse Gas Emissions and Dispersion 2. *Comparison of FDS Predictions with Gas Velocity Measurements in the Exhaust Duct of a Stationary Source*, **Kuldeep Prasad, Kevin Li, James Whetstone, NIST Special Publication, 2012**

- Greenhouse Gas Emissions and Dispersion 1. *Optimum placement of gas inlets on a building rooftop for the measurement of greenhouse gas concentration*, **Kuldeep Prasad, Anthony Bova, James Whetstone, Elena Novakovskaia, NIST Special Publication, 2012**

Collaborators and Websites

- Penn State University : Ken Davis, Thomas Lauvaux, Natasha, Scott
- Purdue University : Paul Shepson, Maria Cambaliza, Dana Carlton, Olivia
- Arizona State University : Kevin Gurney, Risa
- Washington State University : Brian Lamb
- Scripps Institution of Oceanography : Ray Weiss, Ralph Keeling
- NOAA : Mike Hardesty, Anna Karion, Colm Sweeney
- Jet Propulsion Laboratory : Riley Duren, Chip Miller
- NCAR : WRF Developers
- NIST : Antonio Possolo, Hratch Semerjian, Adam Pintar, Lo Hua, Randy McDermott
- Picarro, Inc : Eric Crosson
- Earth Networks : Christopher Sloop, William Callahan, Amanda Lon

- INFLUX - http://sites.psu.edu/influx/
- LA Megacities project : http://megacities.jpl.nasa.gov/portal/
- Hestia/Vulcan - http://hestia.project.asu.edu/
- WRF - http://www.wrf-model.org/index.php
- FDS / Smokeview - http://code.google.com/p/fds-smv/