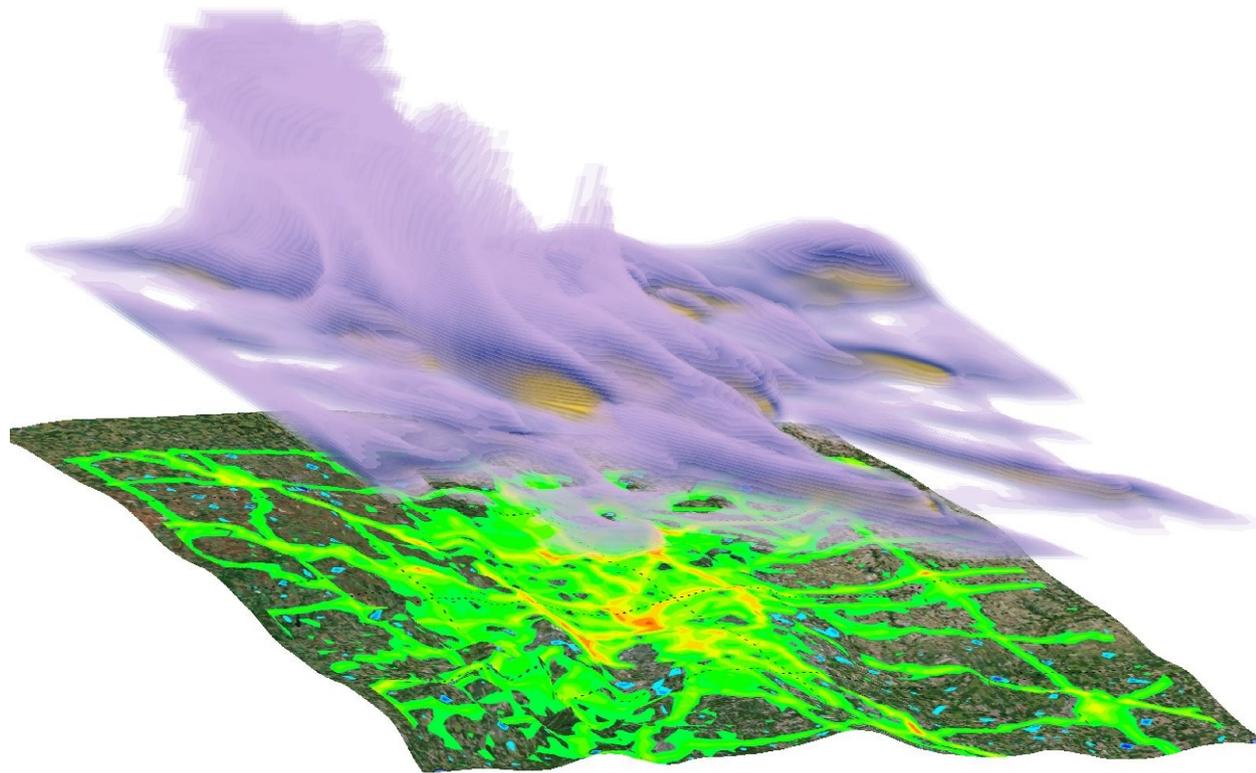


## Combining urban scale inversions and process-based information from sectors of economic activity in the Indianapolis Flux Experiment (INFLUX) to monitor CO<sub>2</sub> emissions

Thomas Lauvaux, Paul Shepson, Maria Cambaliza, Kenneth Davis, Aijun Deng, Robert Hardesty, Laura Iraci, Kevin Gurney, Anna Karion, Laura McGowan, Antonio Possolo, Igor Razlivanov, Daniel Sarmiento, Colm Sweeney, Jocelyn Turnbull, and James Whetstone



# Combining urban scale inversions and process-based information from sectors of economic activity in the Indianapolis Flux Experiment (INFLUX) to monitor CO<sub>2</sub> emissions

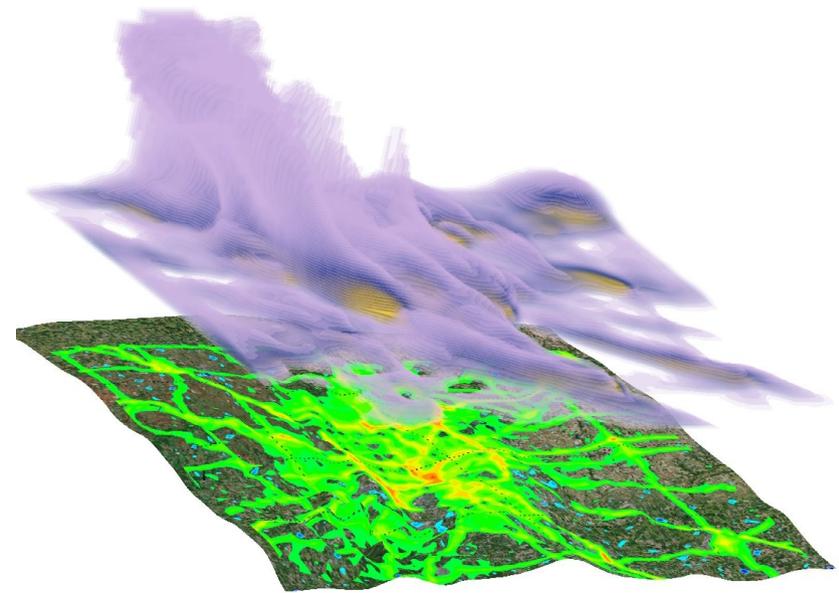
INFLUX: emission quantification over Indianapolis at 1km resolution

Emissions include large contribution from power plant: Require high resolution

Define modeling needs (i.e. transport errors) and strategy to improve the atmospheric model

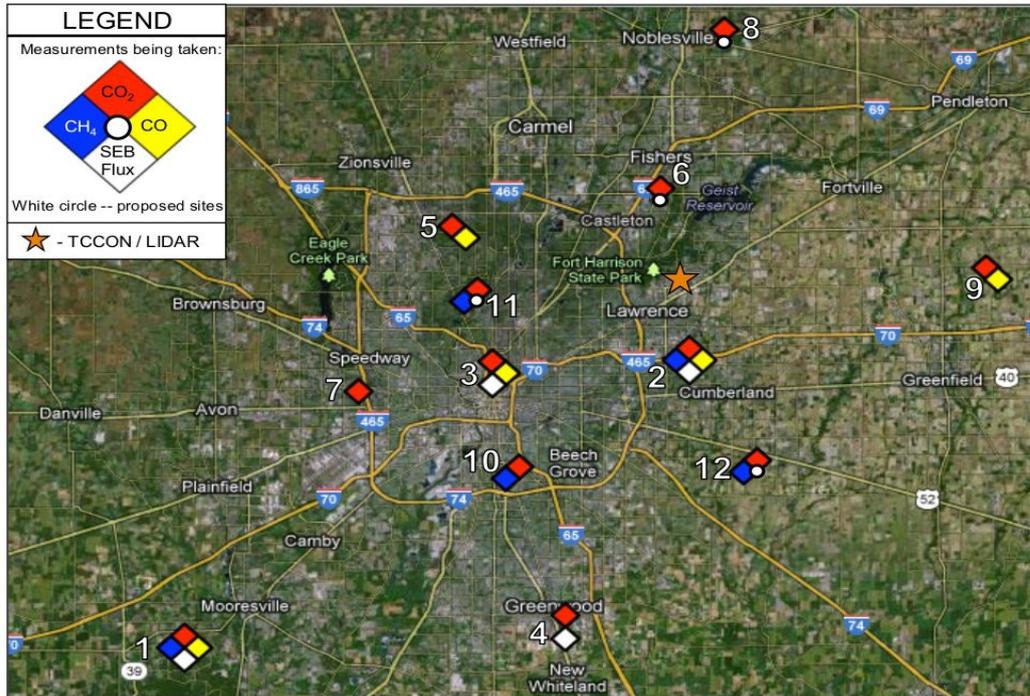
Towers and sources are co-located: vertical gradients are key components

- Current state of the network for CO<sub>2</sub> mixing ratios
- The high resolution atmospheric modeling system
- Sector emissions and first inversion



Map of road emissions from Hestia with their respective atmospheric modeled CO<sub>2</sub> concentration using the WRF-FDDA system (1km) on Oct 7<sup>th</sup>, 2011 at 5pm (LST)

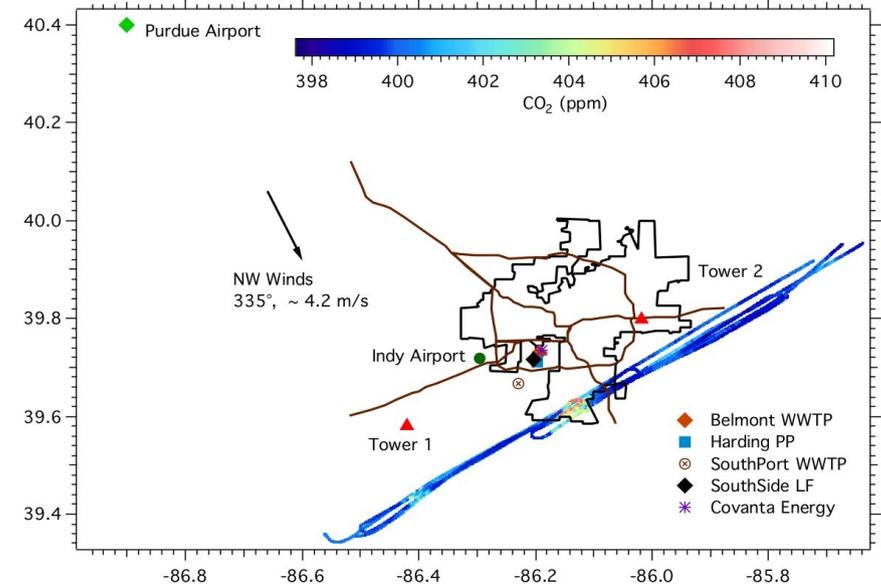
# INFLUX: the CO<sub>2</sub> and CO measurement network



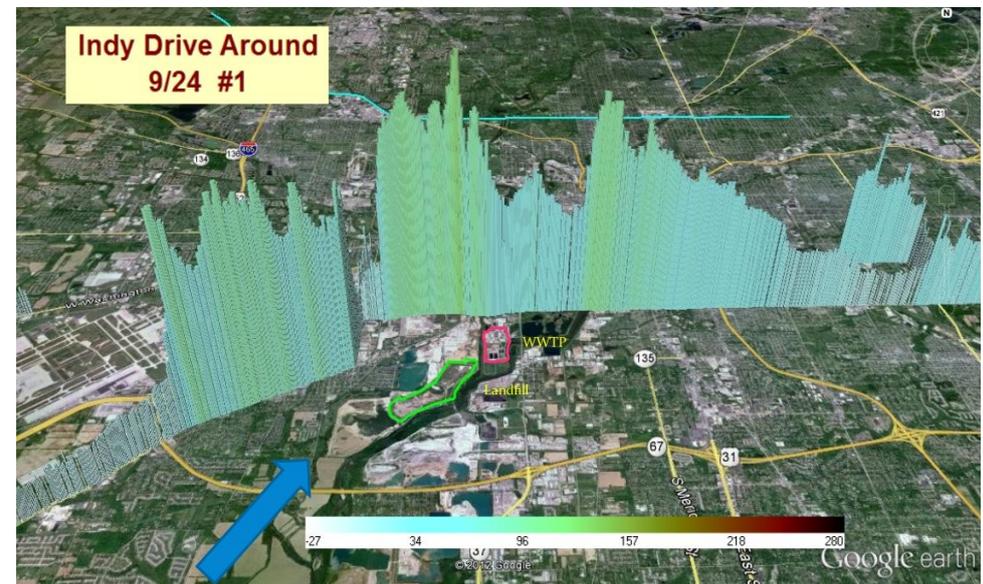
Map of the observing network over Indianapolis (Indiana) including GHG concentrations from surface towers, Eddy-flux towers, and the surface-based TCCON-FTS instrument

## Surface measurement network

- 12 surface towers measuring CO<sub>2</sub> mixing ratios, 5 with CH<sub>4</sub>, and 5 with CO,
- 4 eddy-flux towers from natural to dense urban landscapes,
- 4 automated flask samplers from NOAA,
- Frequent flights (monthly) with CO<sub>2</sub>, CH<sub>4</sub>, and flask sampler,
- Doppler Lidar,
- TCCON-FTS for 4 months (Sept-Dec 2012).

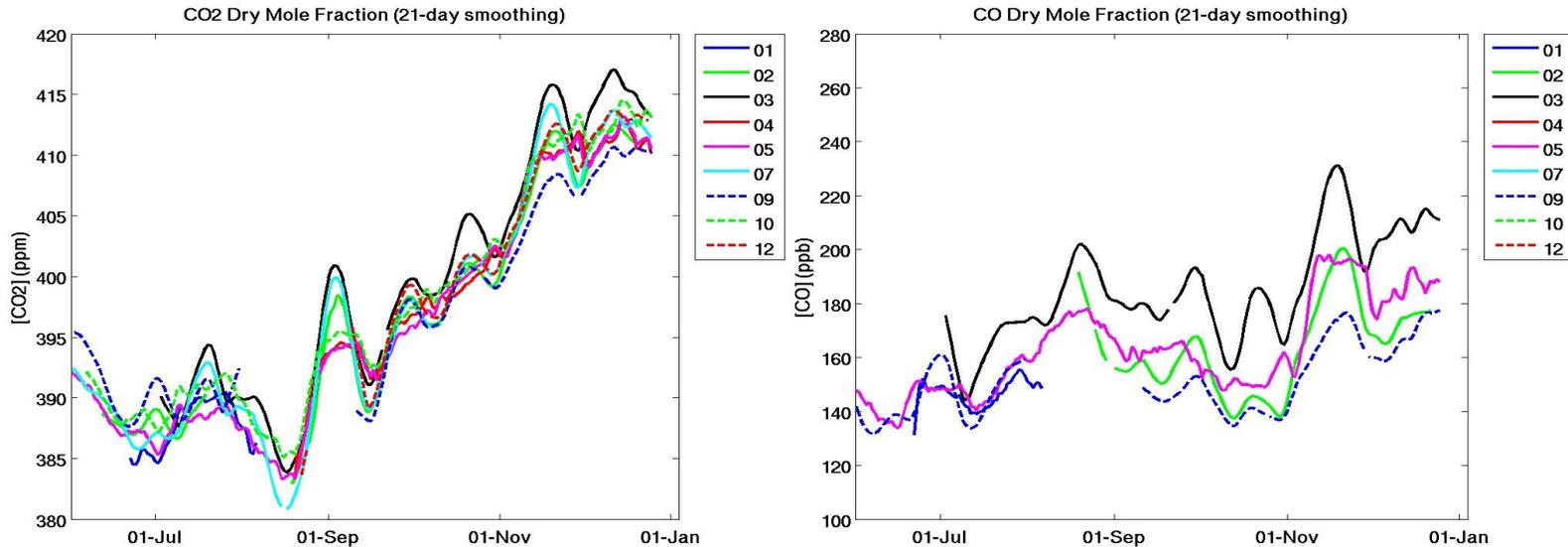


CH<sub>4</sub> concentrations observed from the aircraft (29 Apr 2011) over the Indianapolis urban area



CH<sub>4</sub> concentration enhancement observed during a drive-around campaign (24 Sept 2012) near the SouthSide Landfill

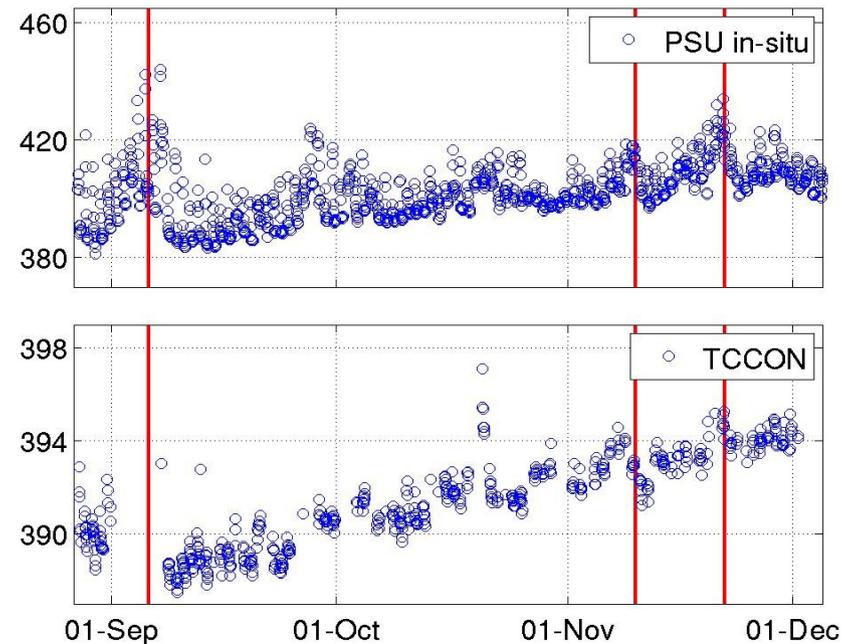
# INFLUX: the CO<sub>2</sub> and CO measurement network



Atmospheric mixing ratios at 9 surface towers for CO<sub>2</sub> (left panel) and CO (right panel) from June to December 2012.

## *Observations in and around the urban area of Indianapolis*

- Large spatial gradients over 40km related to distance to the source and residence time of the air masses
- Carbon monoxide depends on the distribution of emissions per sector, with larger gradients across the city
- Importance of vegetation in and around the city critical in summer (from flask analysis, not shown here) and reduced in winter (90% of the observed signals from anthropogenic CO<sub>2</sub>)



CO<sub>2</sub> atmospheric mixing ratios at site 2 (upper panel) and dry air mole fraction from the TCCON-FTS (8km from site 2) (lower panel) from Sept to November 2012

# WRF configurations and physics

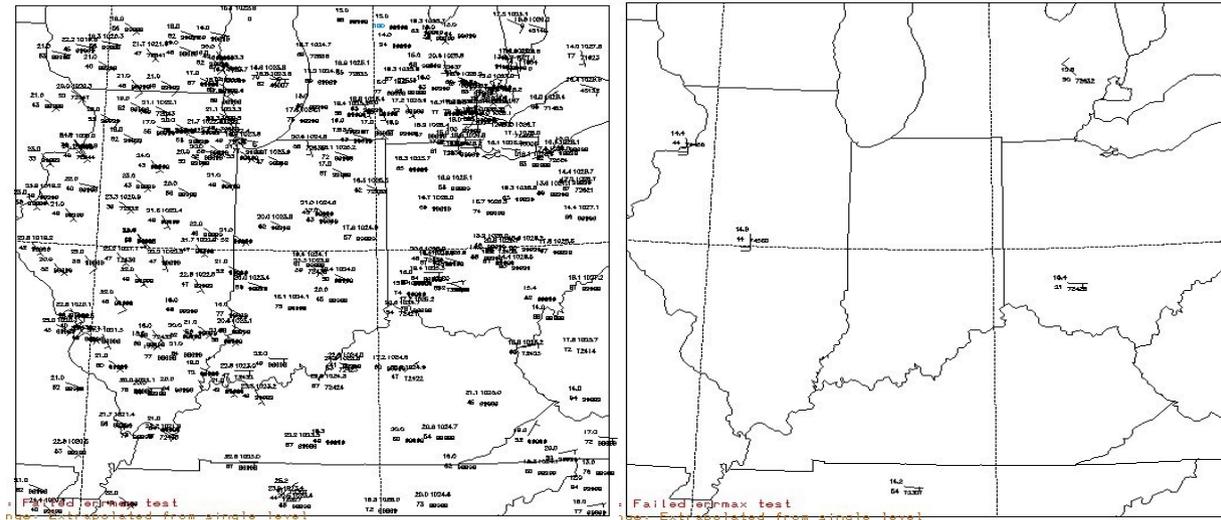
## High resolution atmospheric modeling

- Atmospheric model WRF-Chem : 9km/3km/1km (nesting mode)
- Meteorological forcing : North American Regional Reanalysis (40km resolution), 3-hourly
- Two model configurations :
  - Four Dimensional Data Assimilation (FDDA) : real-time nudging of meteorological observations (both surface and profiles)
  - Historical mode : no FDDA (classic configuration)

## Model physics

- First order : sensitivity to surface conditions
- Second order : Planetary Boundary Layer
- Two model physics :
  - Urban Land Surface Scheme (Energy and Building Models) with Mellor Yamada Jancic PBL scheme (MYJ)
  - Simple urban scheme within the NOAA Land Surface Model with the Mellor Yamada Nakanishi-Niino PBL scheme (MYNN)

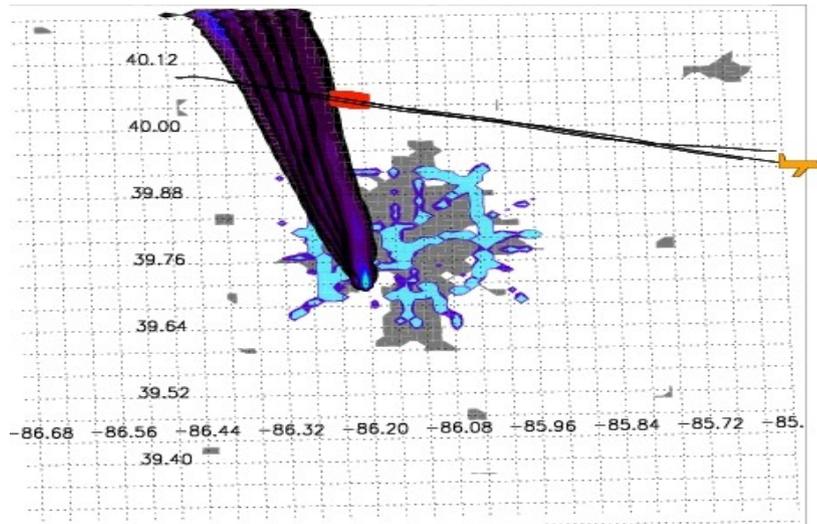
Mode	FDDA	No FDDA
PBL Physics and LSM	MYJ Urban	MYNN NOAA



Surface observations (left panel) and at 850hPa used in the Four Dimensional Data Assimilation system (data nudging) for the 9-km grid of the WRF-CO2 model

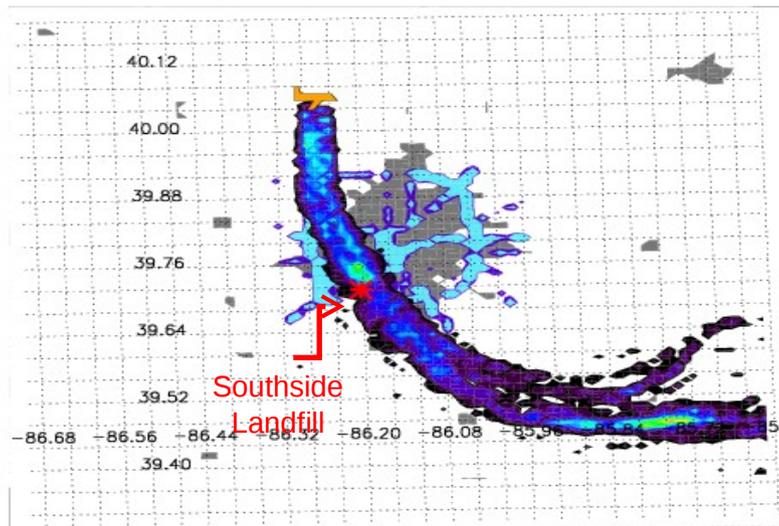
# Initial model results: evaluation using Aircraft data

## Direct model

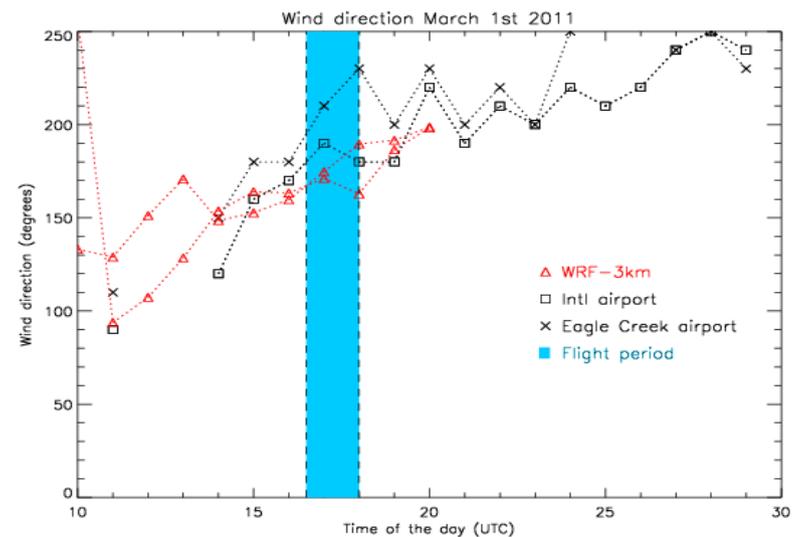
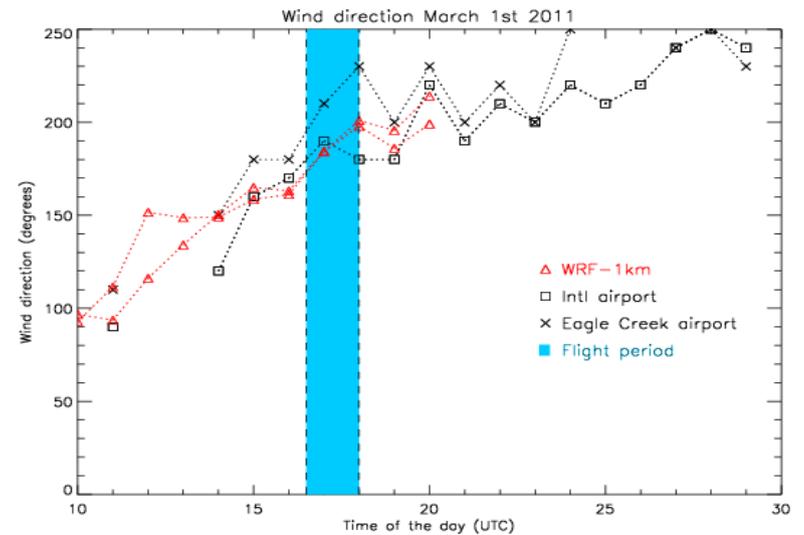


Plume of methane from the South Landfill as observed by the aircraft (maximum in red) and simulated by WRF at 1km resolution (March 1st, 2011)

## Adjoint model

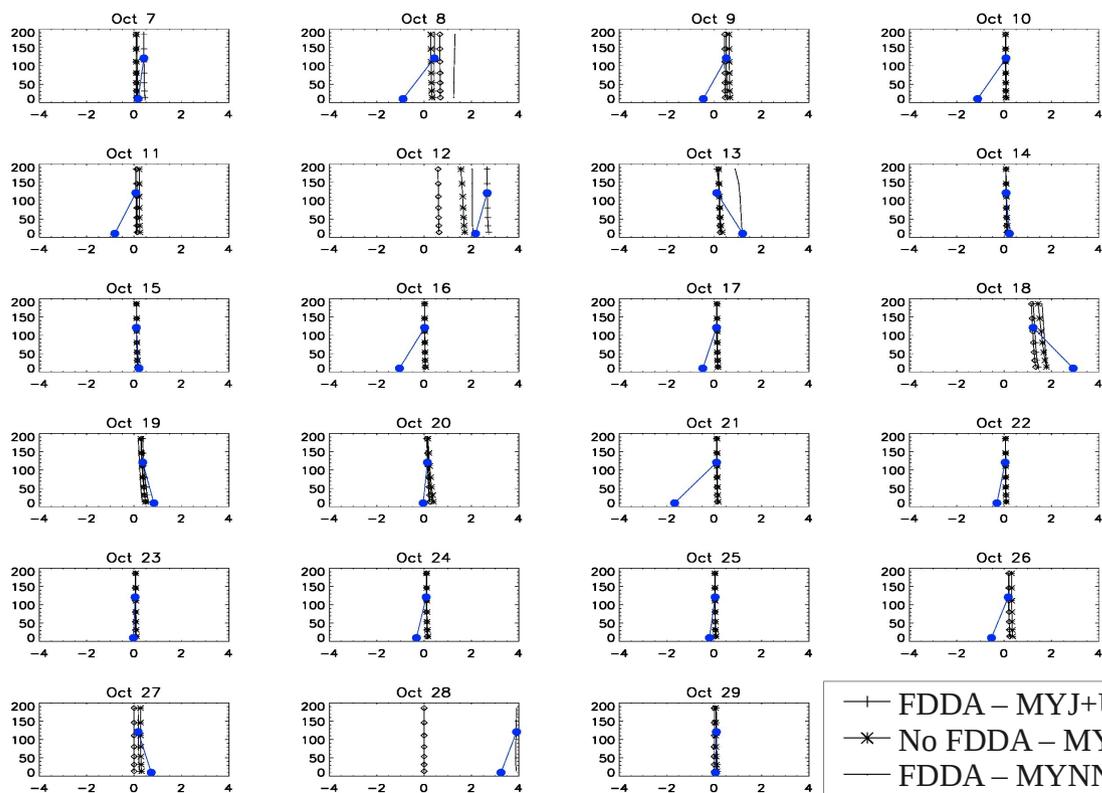


Surface footprint from the aircraft and simulated by LPDM at 1km resolution (March 1st, 2011)



Wind direction measured at the Int'l Indianapolis Airport and Eagle Creek airport (in black) and simulated by WRF (in red) at 1km resolution (upper panel) and 3km resolution (lower panel), March 1st, 2011

# Vertical gradients in near-surface CO2 mixing ratios



Modeled (in black) and observed (in blue) CO2 mixing ratios at the upwind site sampled at 10m and 121m using the FDDA system at 1km resolution, from Oct 7th to Oct 30th 2011 (3pm LST)

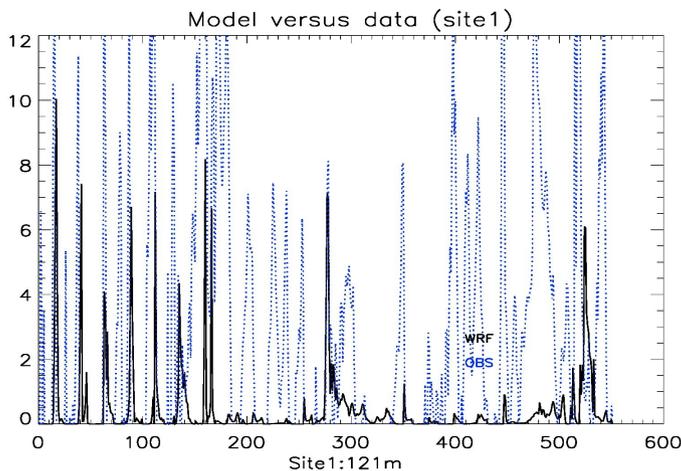
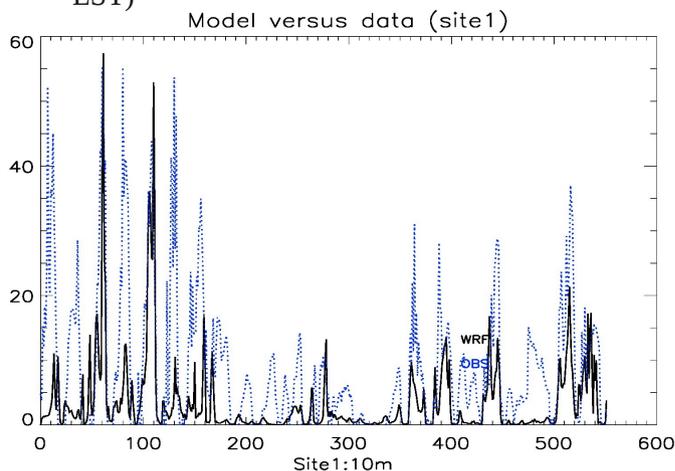


## Site 1: rural - upwind

- Site 1 located in mixed forest/agriculture landscape, low density urban area
- Low vertical gradients observed between 10m and 121m sampling heights (less than 2ppm)
- 4 different model configurations simulate low vertical gradients as well
- Differences across simulations are less than 1ppm (2ppm maximum)
- *Urban scheme provides similar surface energy fluxes*
- *No noticeable impact from physics or configurations*

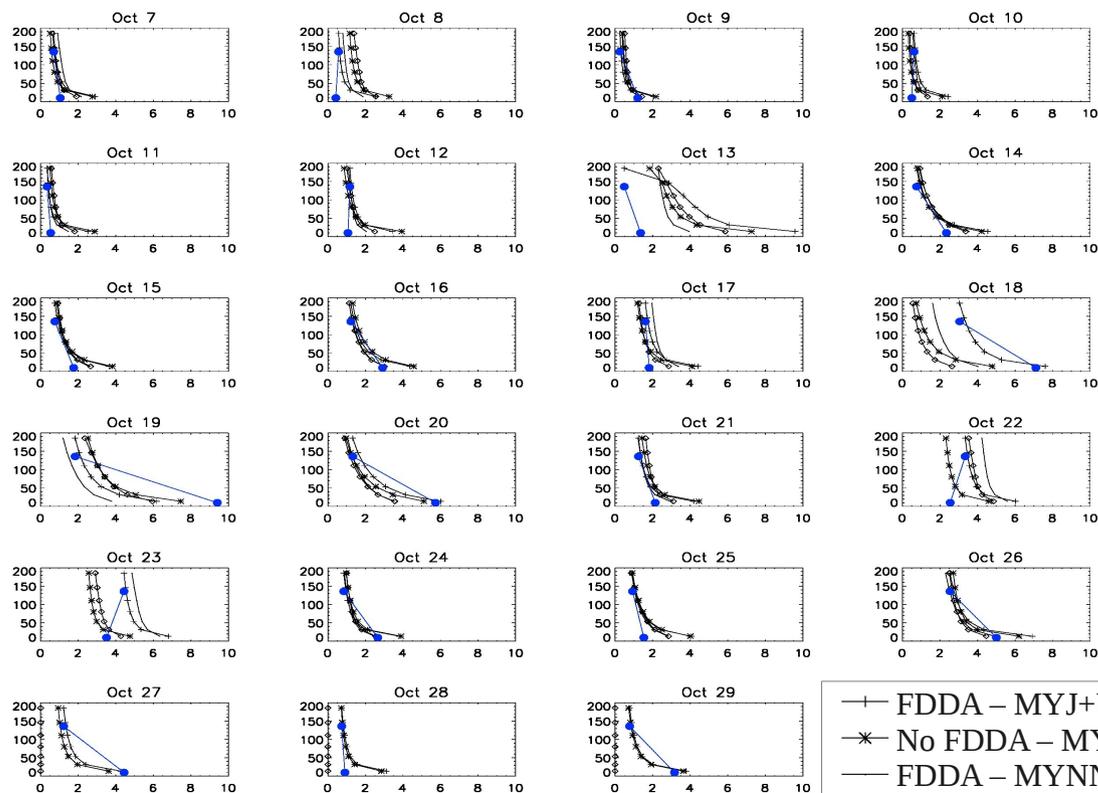
## Initial model evaluation

- Variability and amplitude consistent with measurements at 10m but not at 121m
- Frequent peaks not captured by the modeling system



Modeled (in black) and observed (in blue) CO2 mixing ratios at the upwind site sampled at 10m (left panel) and 136m (right panel) using the FDDA system at 1km resolution, from Oct 7th to Oct 30th 2011 (hourly)

# Vertical gradients in near-surface CO2 mixing ratios



Modeled (in black) and observed (in blue) CO2 mixing ratios at the upwind site sampled at 10m and 136m using the FDDA system at 1km resolution, from Oct 7th to Oct 30th 2011 (3pm LST)



## Site 2: urban - downwind

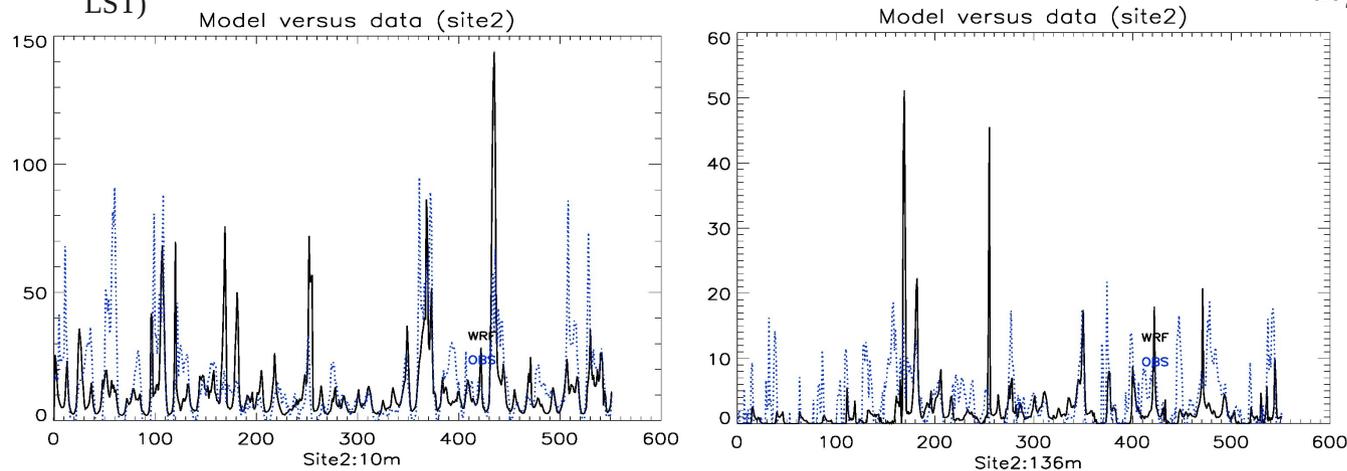
- Site 2 located in urban landscape, medium population density
- Large vertical gradients observed between 10m and 136m sampling heights (up to 10ppm)
- 4 different model configurations simulate large vertical gradients as well
- Differences low on average but large at the daily time scale (up to 6ppm)

- *Urban scheme provides similar surface energy fluxes*

- *Low impact from physics or configurations at the monthly time scale but significant on several days*

## Initial model evaluation

- Variability and amplitude consistent with measurements at 10m and at 136m
- Most peaks captured at 10m but not at 136m : vertical mixing error



Observed (in black) and modeled (in blue) CO2 mixing ratios at the downwind site sampled at 10m (left panel) and 136m (right panel) using the FDDA system at 1km resolution, from Oct 7th to Oct 30th 2011 (hourly)

# Correlation coefficients: hourly CO2 concentrations

	S1 - 10m	S2 - 10m	S1 - 121m	S2 - 136m
FDDA-MYJ	0.5	0.47	0.19	0.29
No FDDA-MYJ	0.56	0.48	0.07	0.25
FDDA No Urban-MYNN	0.41	0.44	0.17	0.36
No FDDA No Urban-MYNN	0.41	0.42	0.18	0.36

## Correlation Coefficients between modeled and observed CO2 mixing ratios for sites 1 and 2:

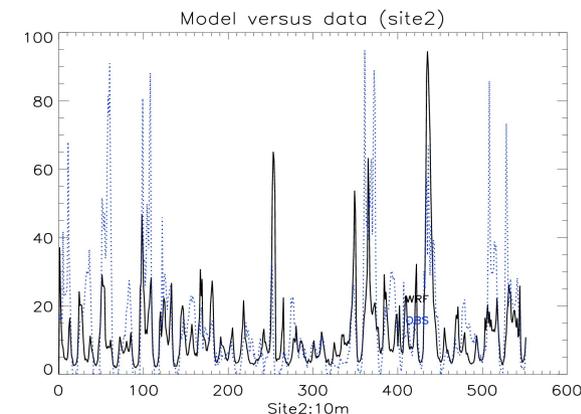
- Low impact of FDDA configuration on vertical gradients
- Absence of signals at higher sampling levels for both sites

	S1 - S2 10m	S1 - S2 121/136m
FDDA-MYJ	0.37	0.18
No FDDA-MYJ	0.37	0.12
FDDA No urban-MYNN	0.44	0.18
No FDDA No Urban-MYNN	0.38	0.2

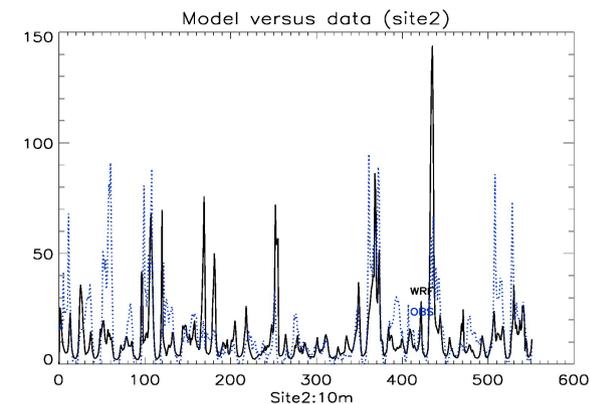
## Correlation Coefficients between modeled and observed site-to-site differences of CO2 mixing ratios:

- FDDA has positive but limited impact
- Absence of signals at higher sampling levels for both sites

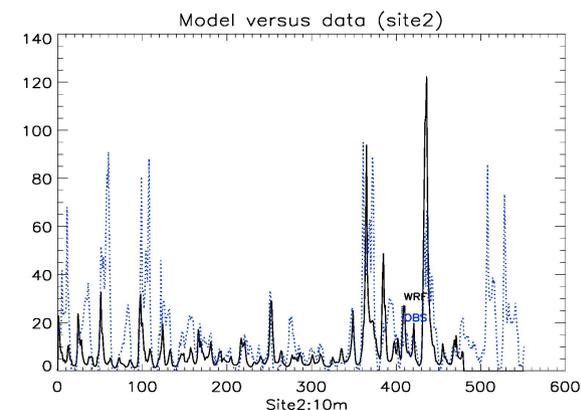
FDDA  
MYJ



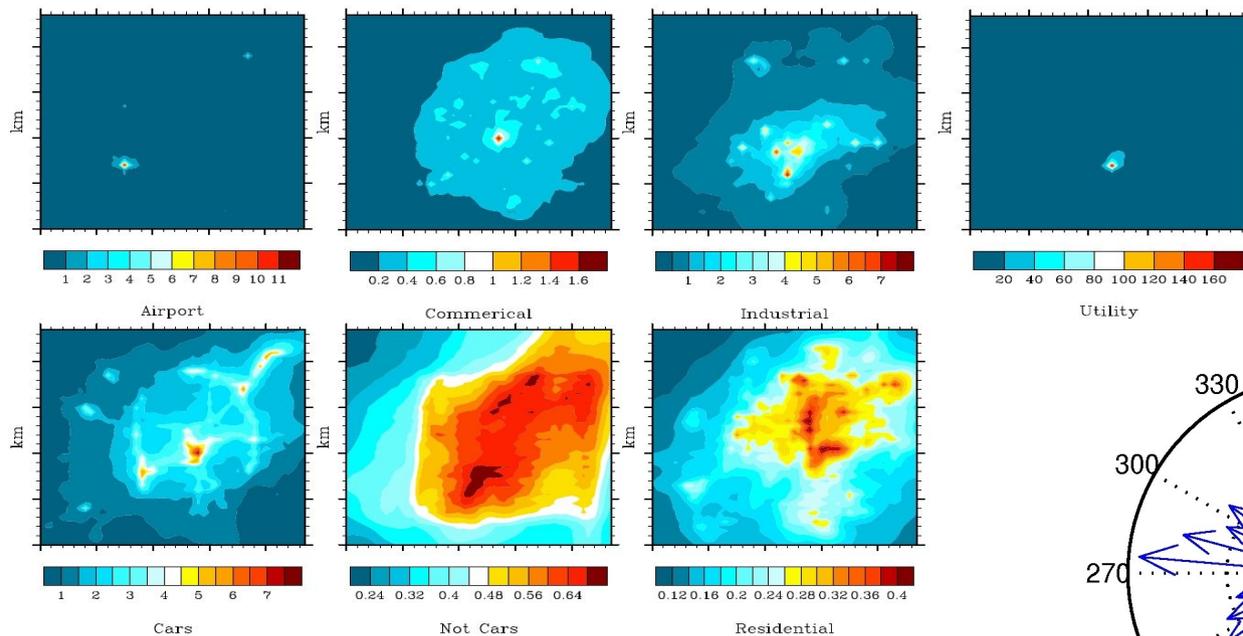
No FDDA  
MYJ



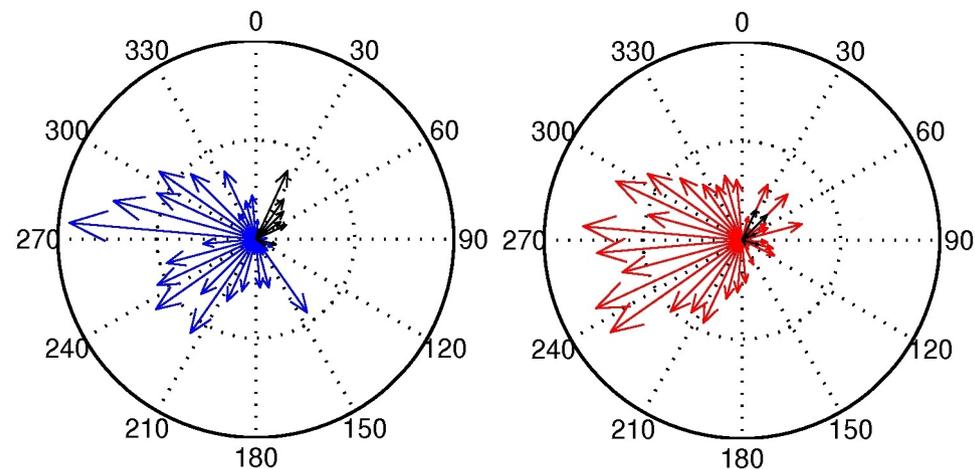
FDDA  
MYNN



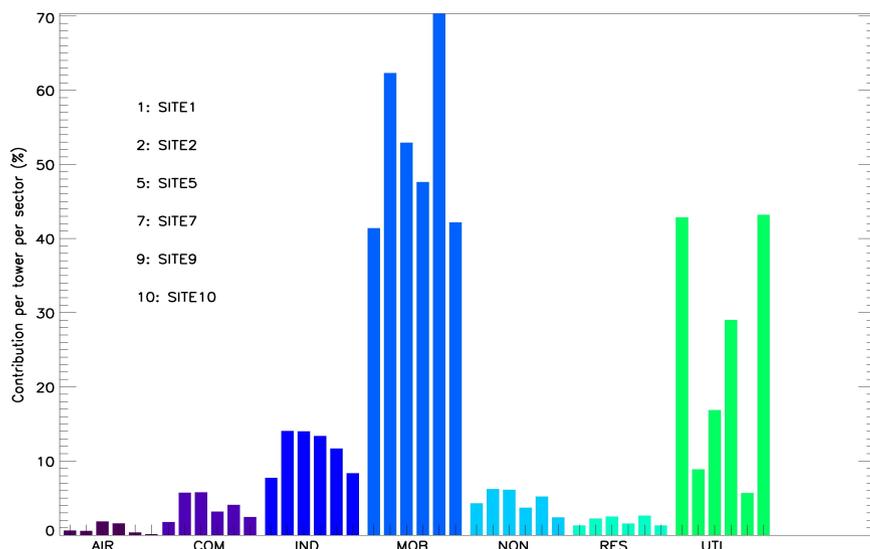
# Contribution per sector and observed CO2/CO signals



Map of averaged mixing ratios over July 2011 for each of the 7 activity sectors of Hestia, in ppm



CO2 (left panel) and CO (right panel) mixing ratio enhancement (upwind minus downwind) in ppm as a function of wind direction by 10° angle

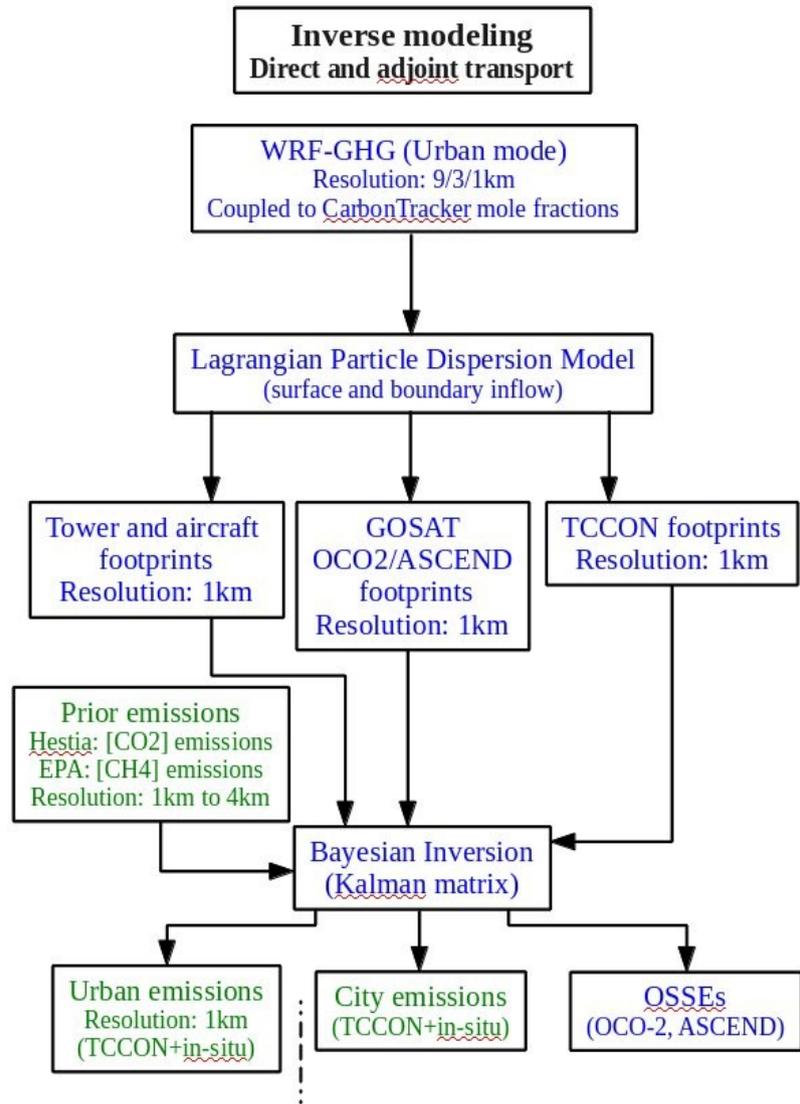


Contribution from each sector on the modeled atmospheric CO2 mixing ratios at each tower for Oct-Nov 2011 (fraction of the total signals) at 1km resolution using Hestia

*- Observing network dominated by traffic and power plant emission signals*

*- Large variability in power plant contribution for each site and large seasonal amplitude (supply energy for Air Conditioning)*

# Urban inversion framework



Flow chart of the TCCON/in-situ inverse system at 1km resolution over the Indianapolis urban area

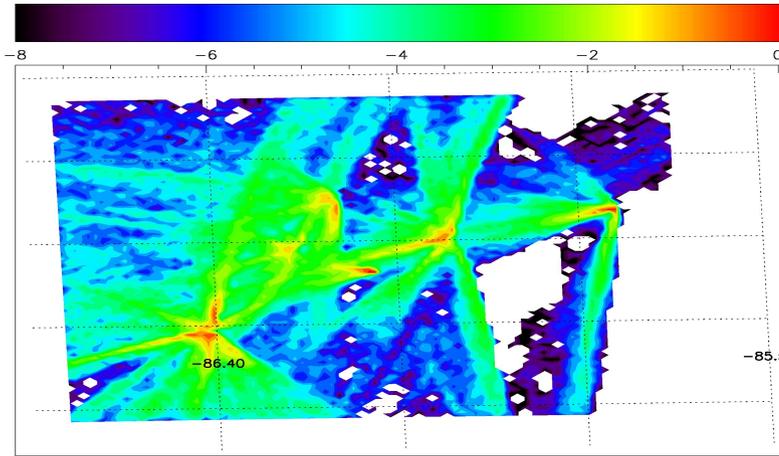
## *High resolution inverse modeling*

- Atmospheric model configuration : 9km/3km/1km (nesting) in FDDA mode
- Coupled to LPDM at 1km using Turbulent Kinetic Energy fields

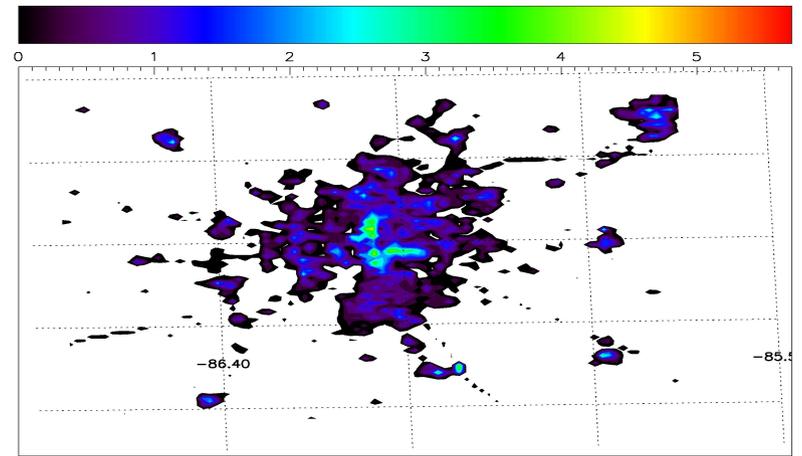
## *Inversion framework*

- Kalman matrix inversion with fixed flux distribution (hyper-parameter space) with Gaussian assumption
- Boundary inflow not included in the inversion : ring of towers deployed to provide upwind conditions
- Observing System Simulation Experiment (OSSE) : hourly concentrations from 6 towers
- Prior emissions from Hestia at 1km resolution
- Prior emission errors : variances scaled with the emissions and correlation length of 3km across urban pixels only

# INFLUX: Urban scale emissions



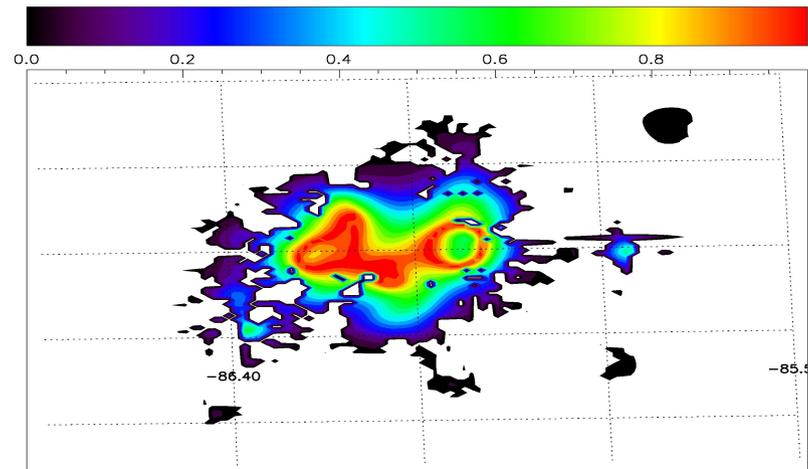
Aggregated surface footprints from 6 towers of INFLUX over 4 days, in log(particles).



Posterior fluxes using 7 surface towers over Indianapolis (4-day inverse retrieval) in  $\text{g.m}^{-2}.\text{d}^{-1}$

## *Urban inversion over 4 days: Observing System Simulation Experiment (OSSE)*

- Observation network offers a significant constraint over the city, very localized for any given day depending on wind direction and speed
- 80% of original perturbations recovered assuming a perfect transport model (i.e. 25% of the emissions) and correlation length of 3km
- Gain and error reduction largely constrained by spatial correlation in prior emission errors



Flux gain using 7 surface towers over Indianapolis (4-day inverse retrieval) from 0 to 1

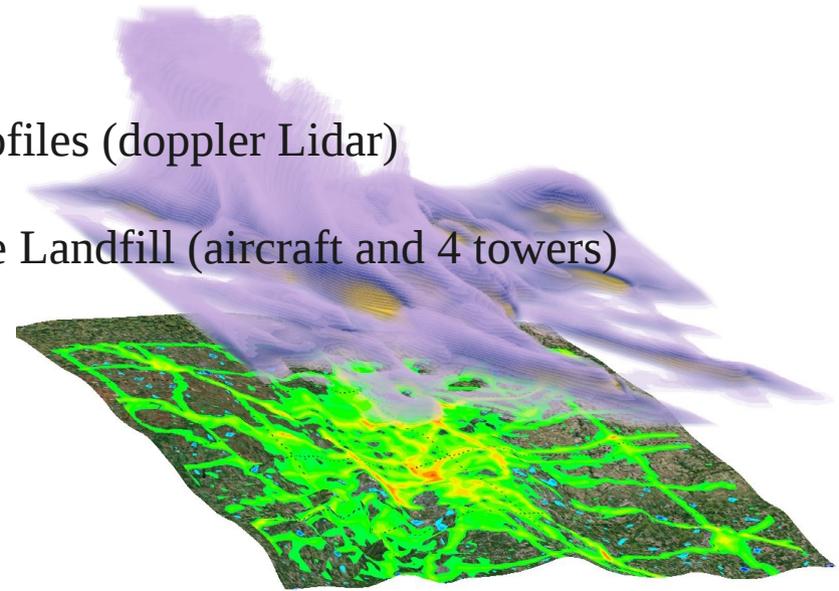
# Conclusions and future work

## *Evaluation of FDDA mode and physics*

- Limited impact of FDDA on CO<sub>2</sub> vertical gradients
- Energy and Building models not significantly different than NOAA urban scheme in low to medium population density areas
- Modeling system able to simulate the variability and magnitude at high resolution

## *Perspectives*

- Detection of trends in emissions between 2002 and 2011
- Real-time data assimilation system: Ingestion of vertical profiles (doppler Lidar)
- Plume analysis using CH<sub>4</sub> mixing ratios from the SouthSide Landfill (aircraft and 4 towers)



Map of road emissions from Hestia with their respective atmospheric modeled CO<sub>2</sub> concentration using the WRF-FDDA system (1km) on Oct 7<sup>th</sup>, 2011 at 5pm (LST)