Measuring CO_2 and CH_4 Emissions from Indianapolis: Preliminary Results from an Urban Atmospheric Inversion System

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NOAA ESRL GMD annual conference, 21 May, 2013

Outline

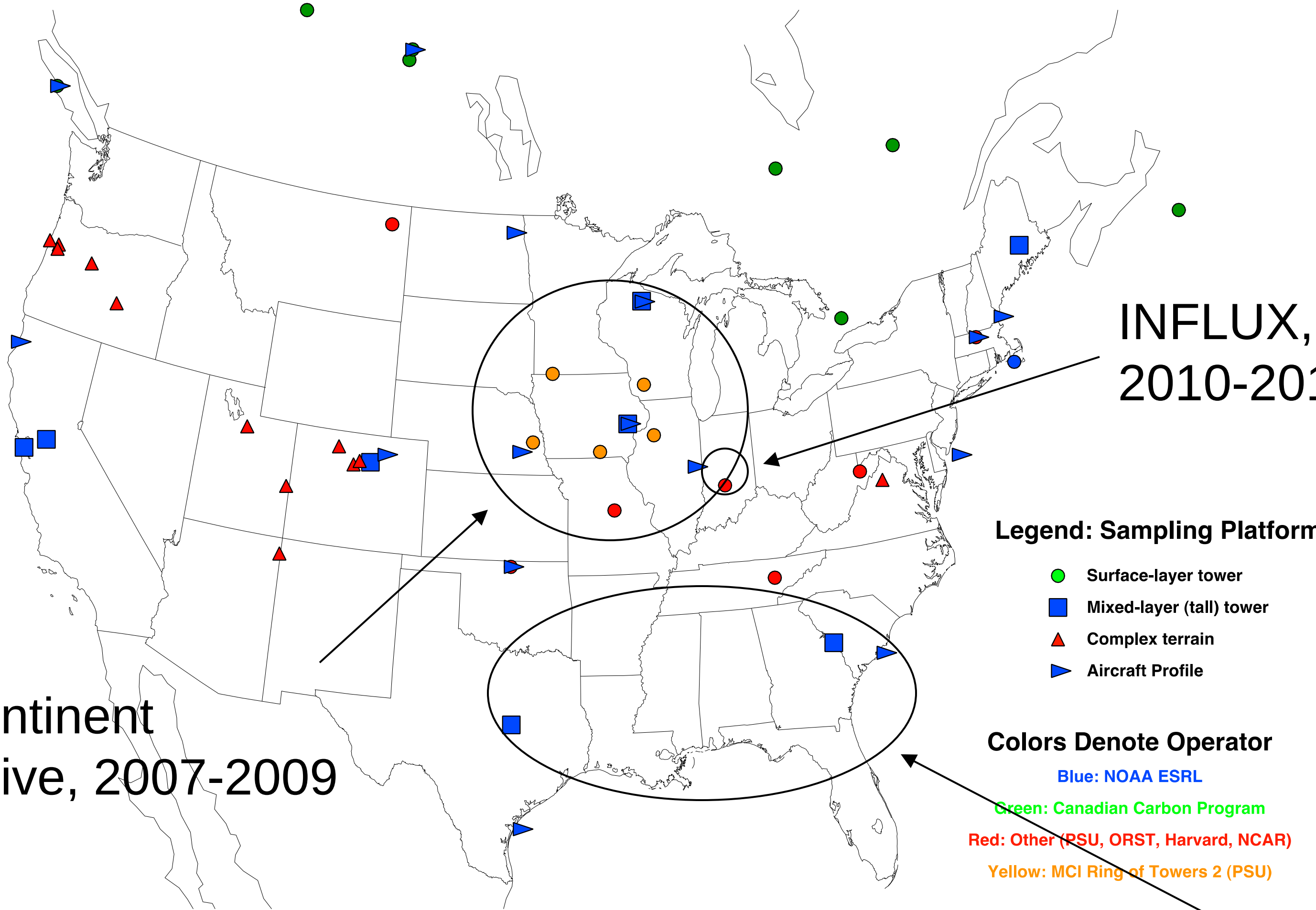
- Motivation, objectives
- Experimental design
- Observations
  - Aircraft observations / Whole-city flux estimates
  - Tower-based observations
- “Forward” simulations
  - Detectability experiment
  - Comparison to observations
- Atmospheric inversions
  - System design experiment
  - (Real data inversions)
- (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



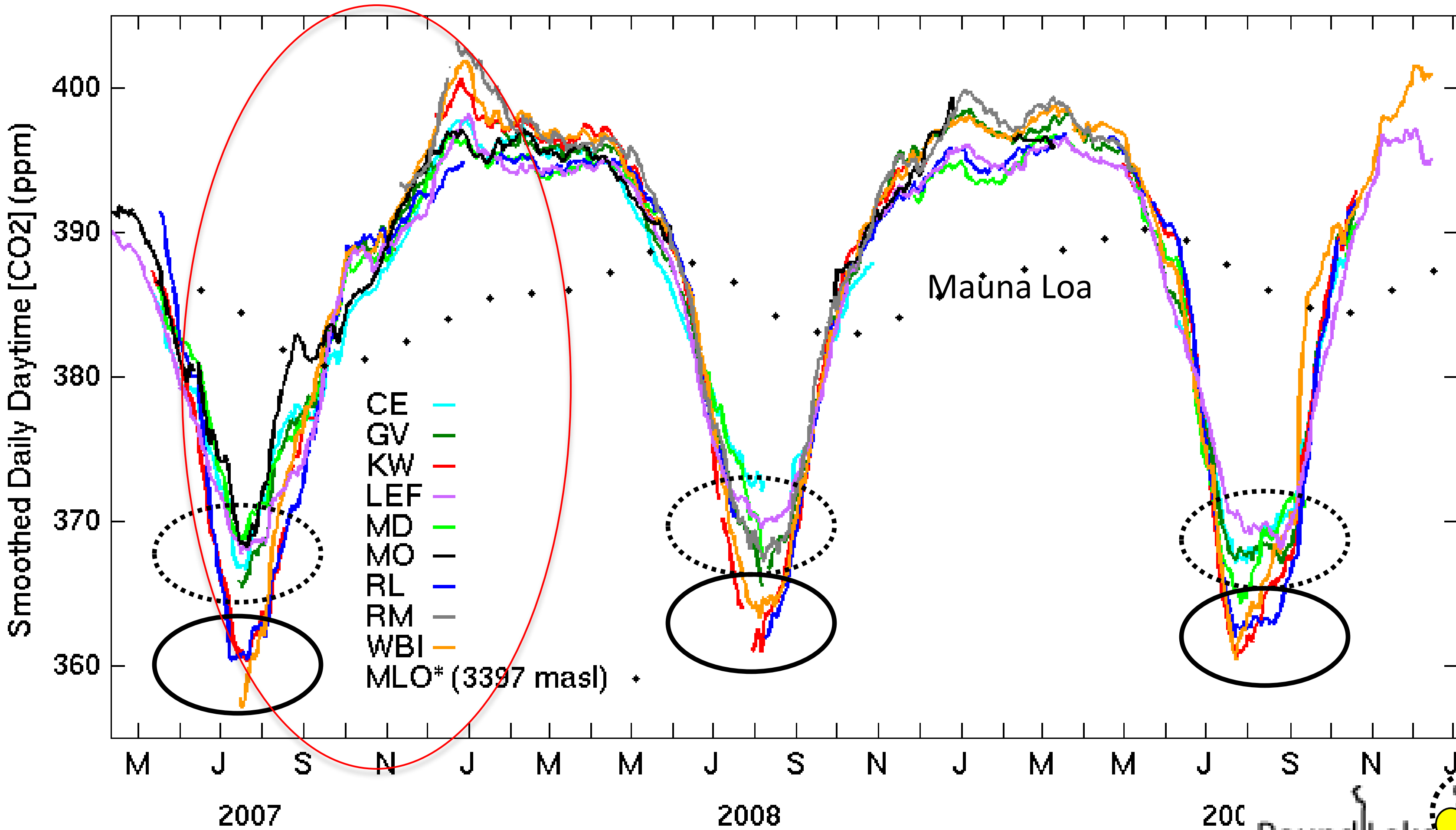
INFLUX, 2010-201?

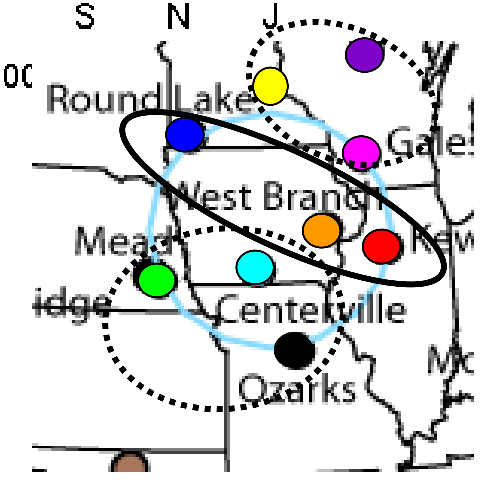
Midcontinent intensive, 2007-2009

Gulf coast intensive, 2013-201?

N. American tower CO2 network circa 2008

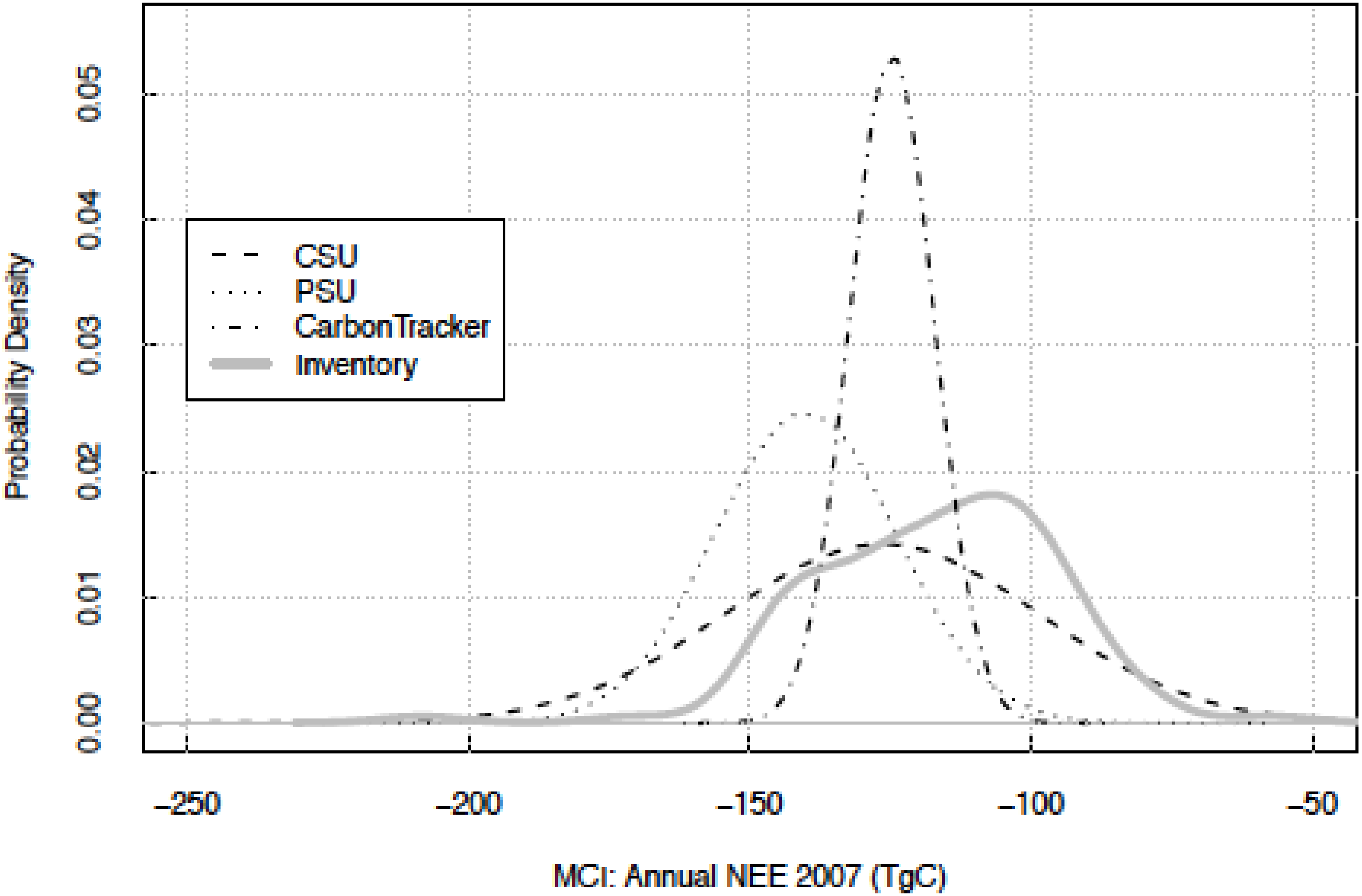
MCI 31 day running mean daily daytime average CO_2





- Large differences in seasonal drawdown, despite nearness of stations.
- 2 groups: 33-39 ppm drawdown and 24 – 29 ppm drawdown. Tied to density of corn.

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 14C, 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

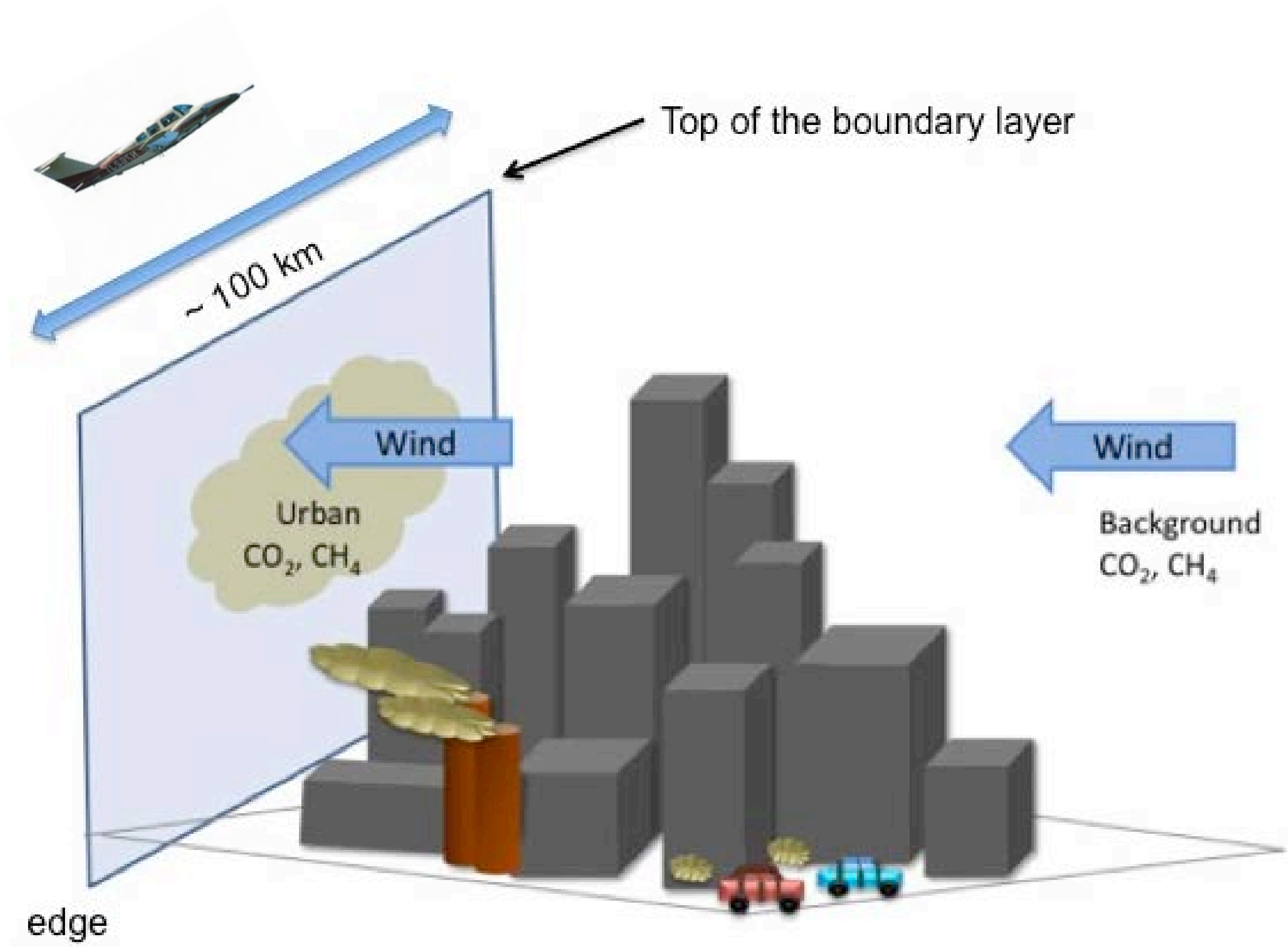
- 12 surface towers measuring CO_2 mixing ratios, 5 with CH_4, and 5 with CO. (Penn State)
- 4 eddy-flux towers from natural to dense urban landscapes. (Penn State)
- 5 automated flask samplers. (NOAA/CU)
- Periodic aircraft flights (~monthly) with CO2, CH4, and flask samples. (Purdue / NOAA)
- Periodic 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).

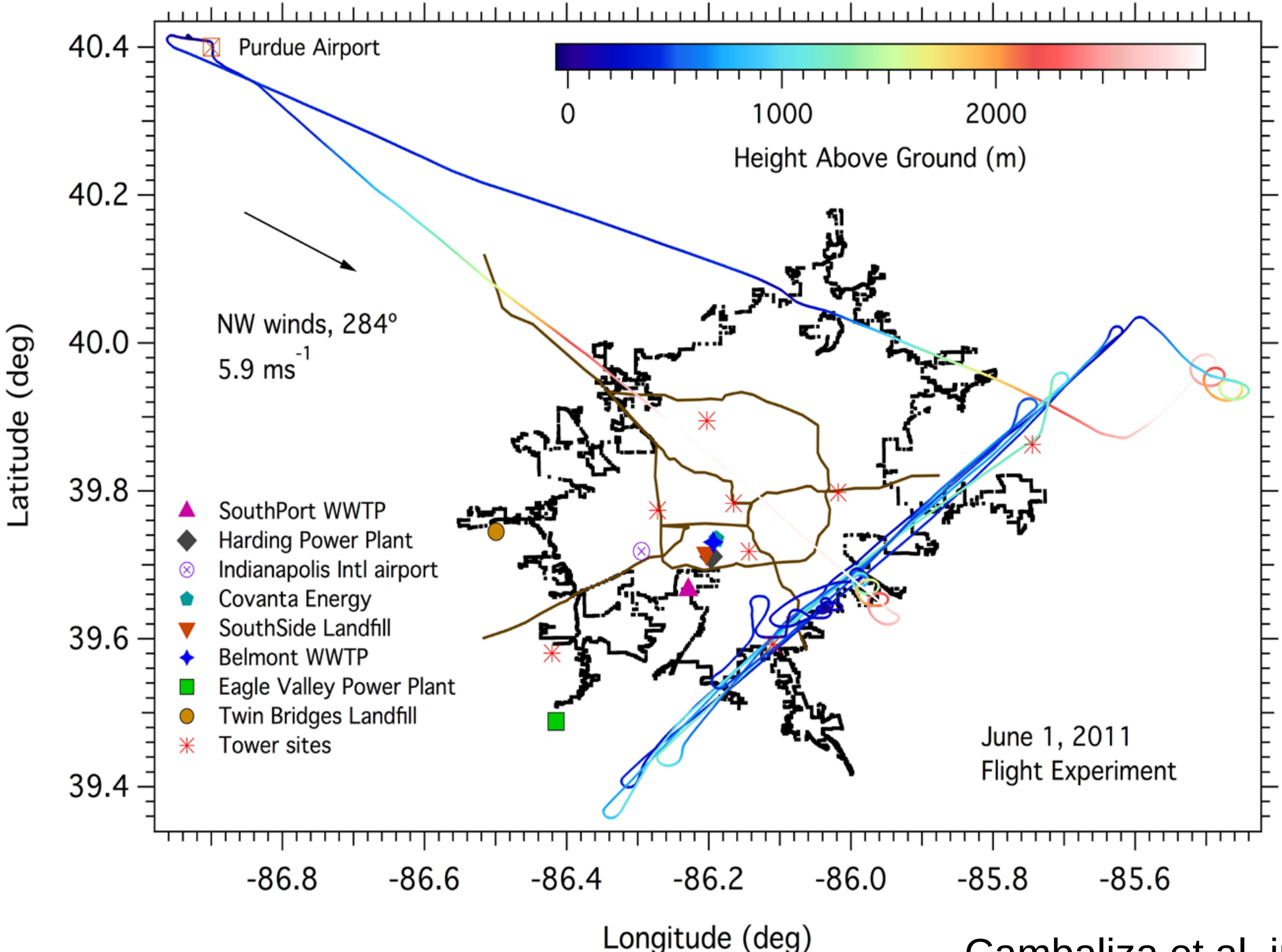
INFLUX observational results to date:
Whole-city mass-balance emissions estimates

Aircraft mass balance method



$$F_c = \int_0^{z_i} \int_{-x}^{+x} \left([C]_{ij} - \overline{[C]}_b \right) * U_{\perp ij} \, dx \, dz$$

June 1, 2011 Flight path

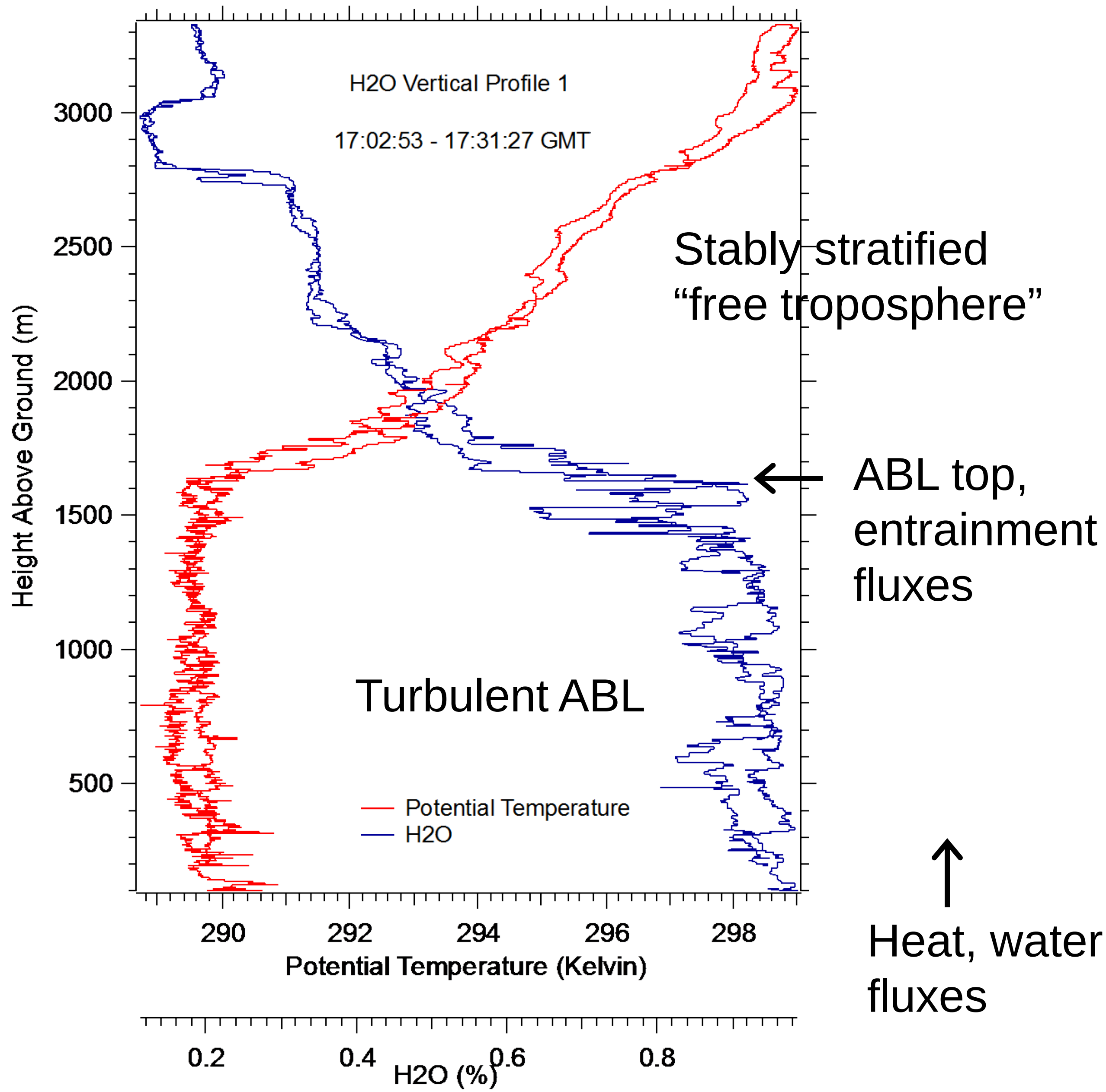


Cambaliza et al, in prep

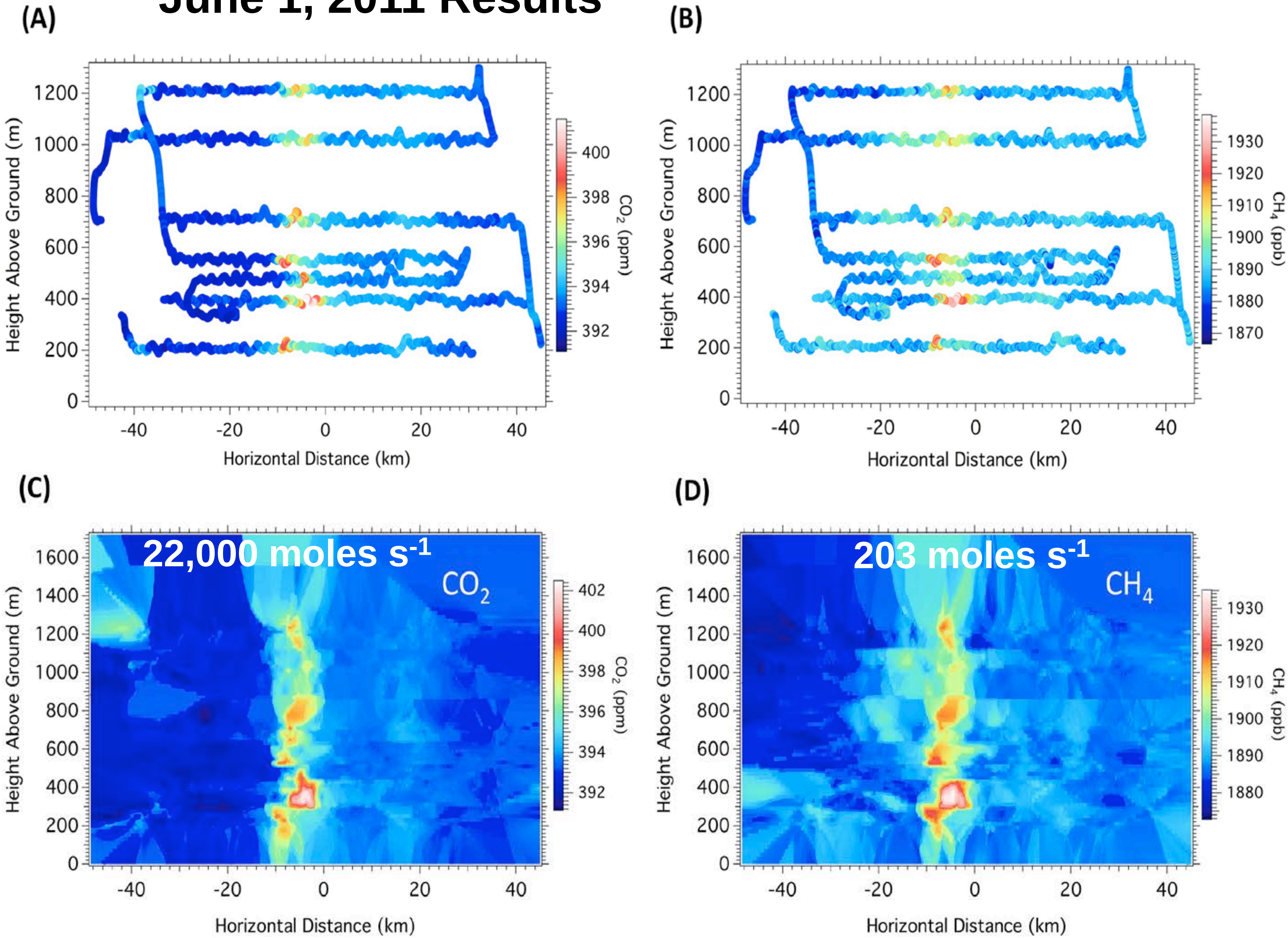
Vertical structure of the atmospheric boundary layer (ABL)

Vertical Profiles of Potential Temperature and H_2O (~ 1:00 to 1:30 p.m. EDT)

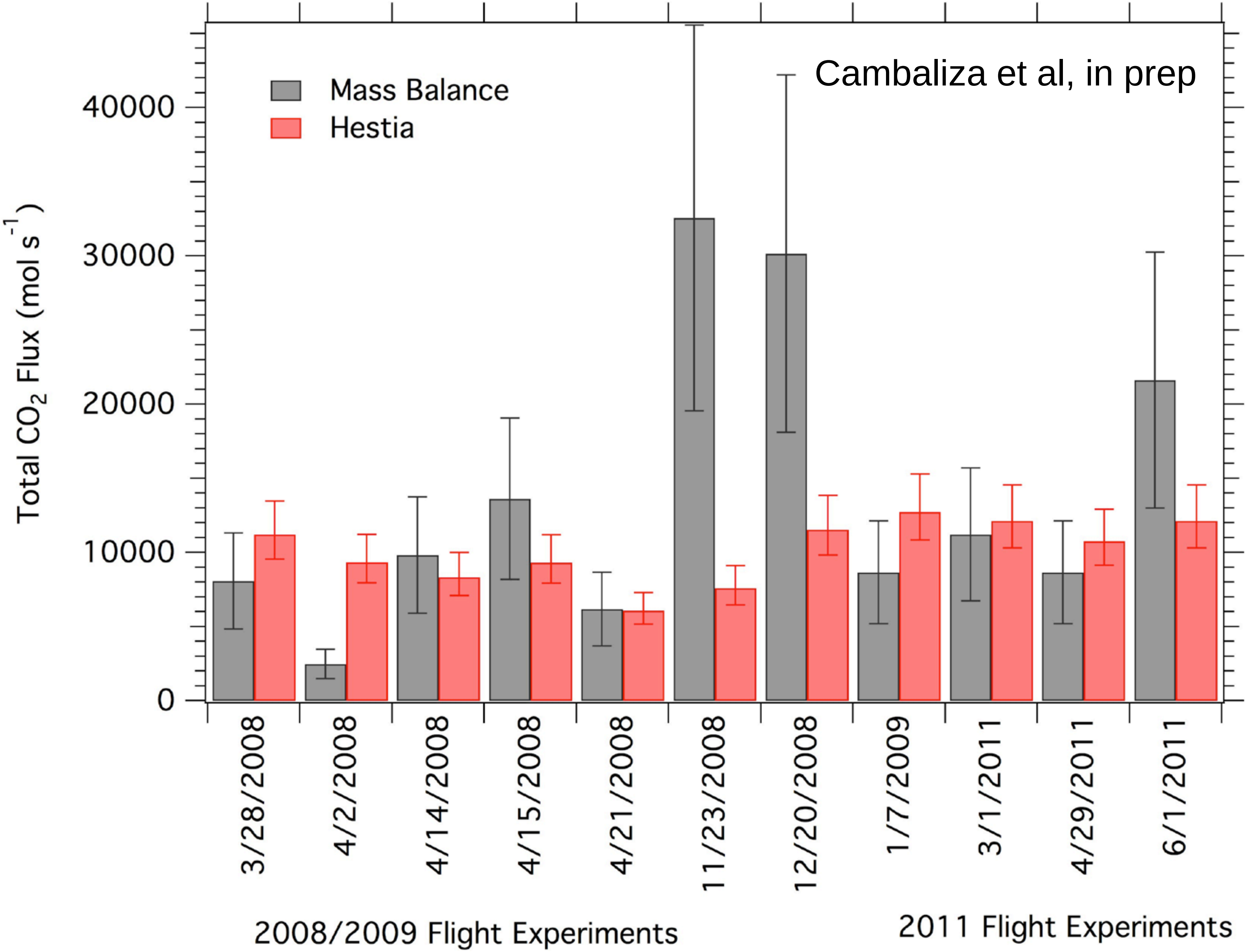
6 June, 2012



June 1, 2011 Results



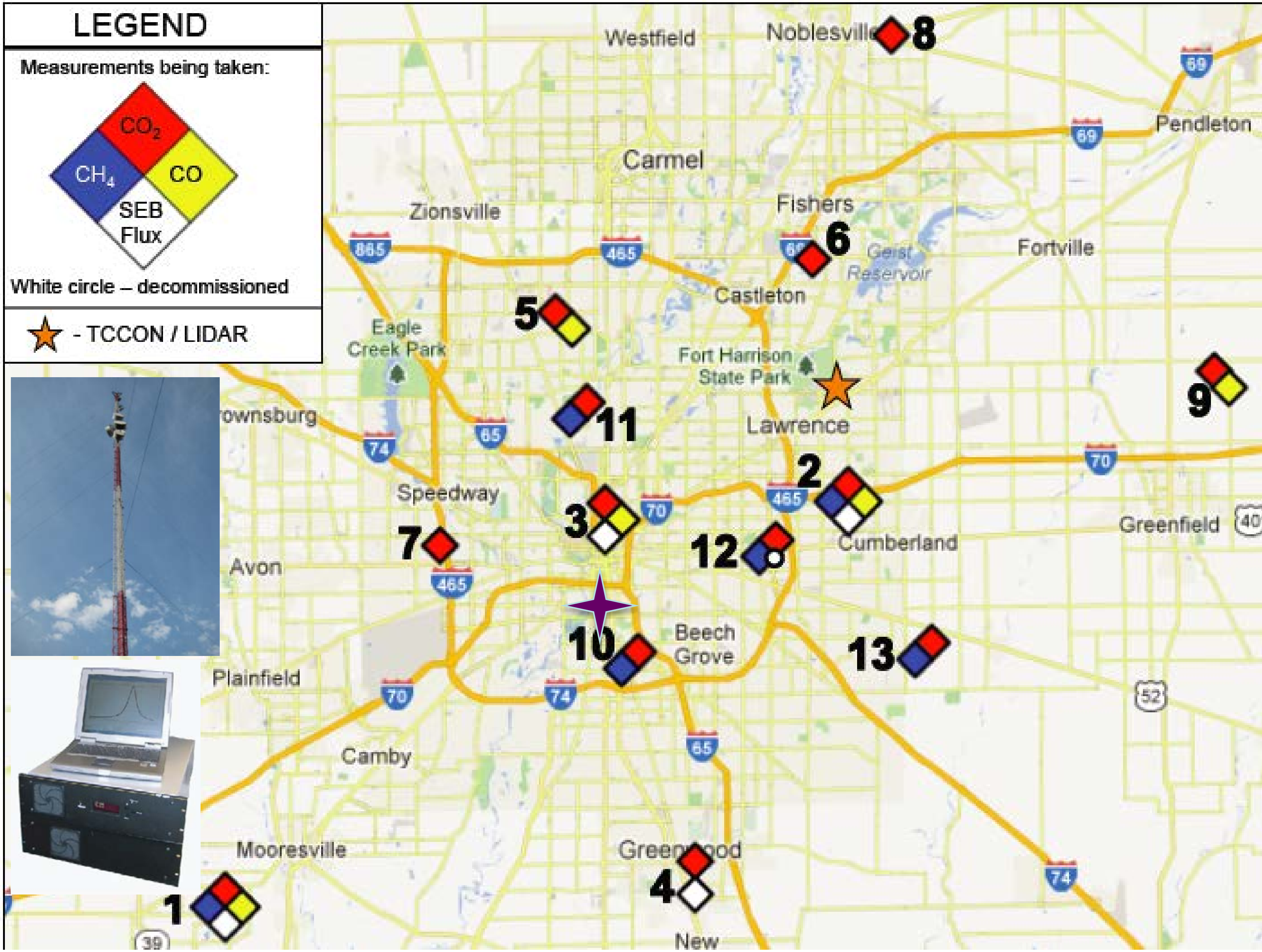
Cambaliza et al, in prep


Cambaliza et al, in prep
Mass Balance
Hestia
Total CO_2 Flux (mol s^{-1})
0
10000
20000
30000
40000
3/28/2008
4/2/2008
4/14/2008
4/15/2008
4/21/2008
11/23/2008
12/20/2008
1/7/2009
3/1/2011
4/29/2011
6/1/2011
2008/2009 Flight Experiments
2011 Flight Experiments

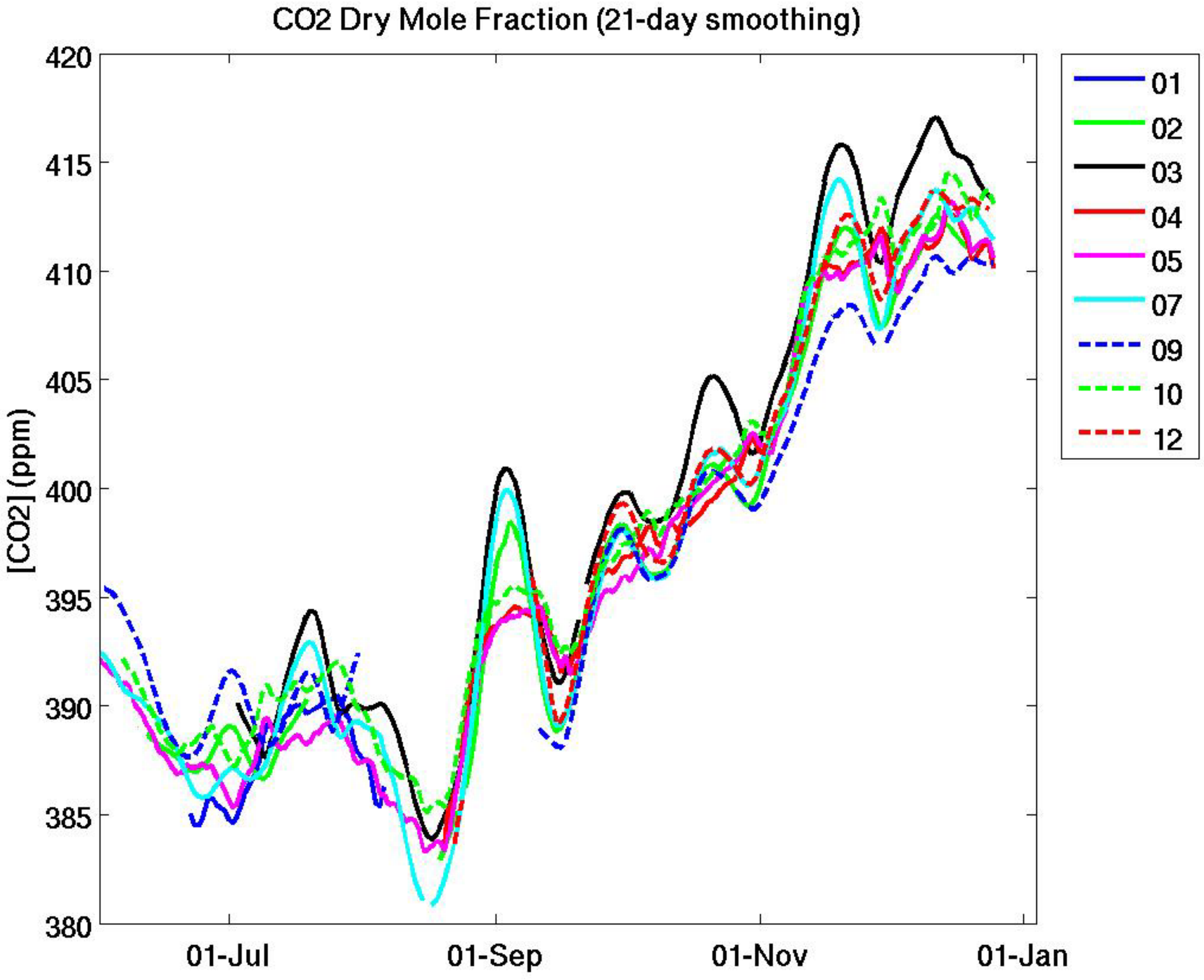
INFLUX tower-based observational results to date

INFLUX ground-based instrumentation

Picarro, CRDS sensors; NOAA automated flask samplers;
Communications towers ~100m AGL



Spatial gradients in [CO2] across INFLUX sites

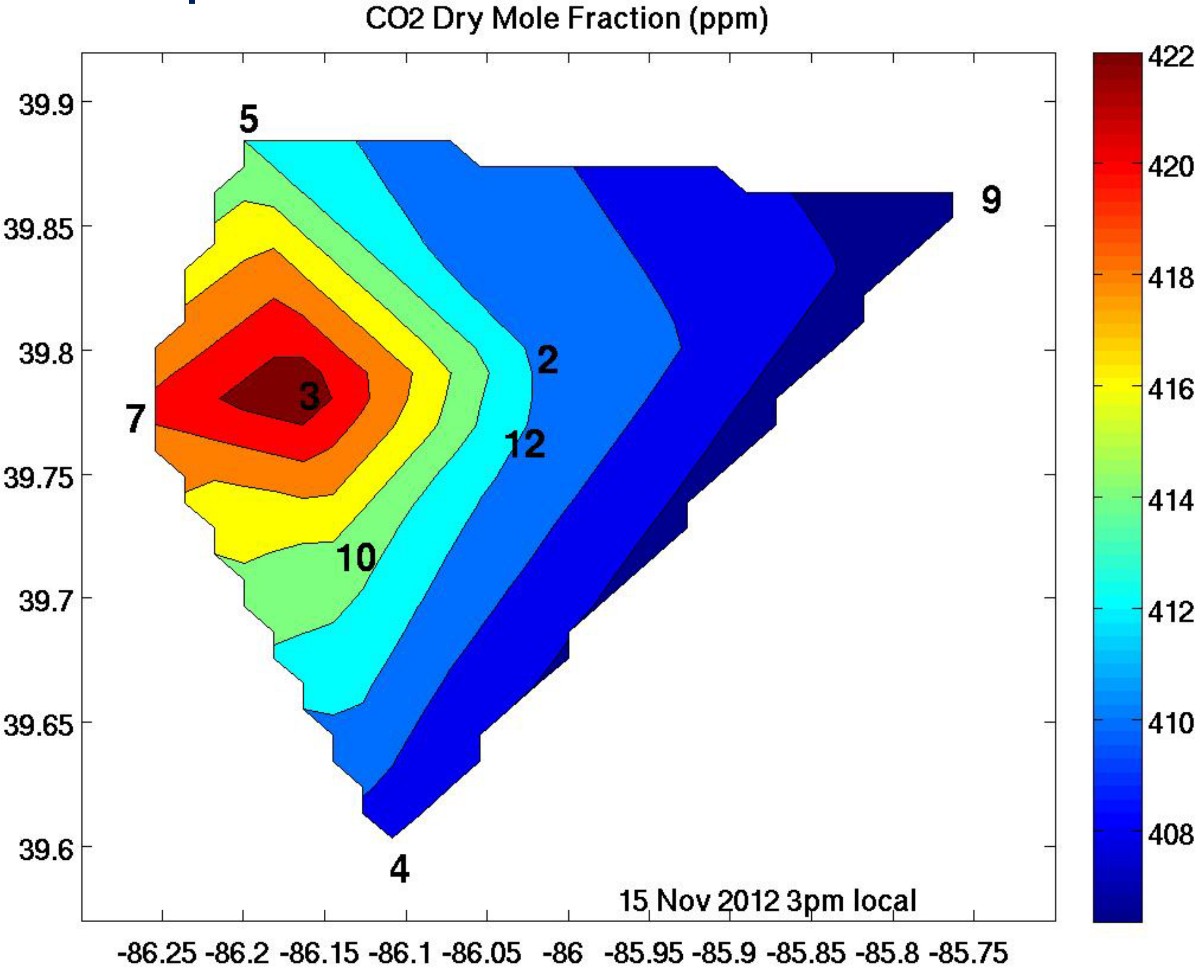


2012

- [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

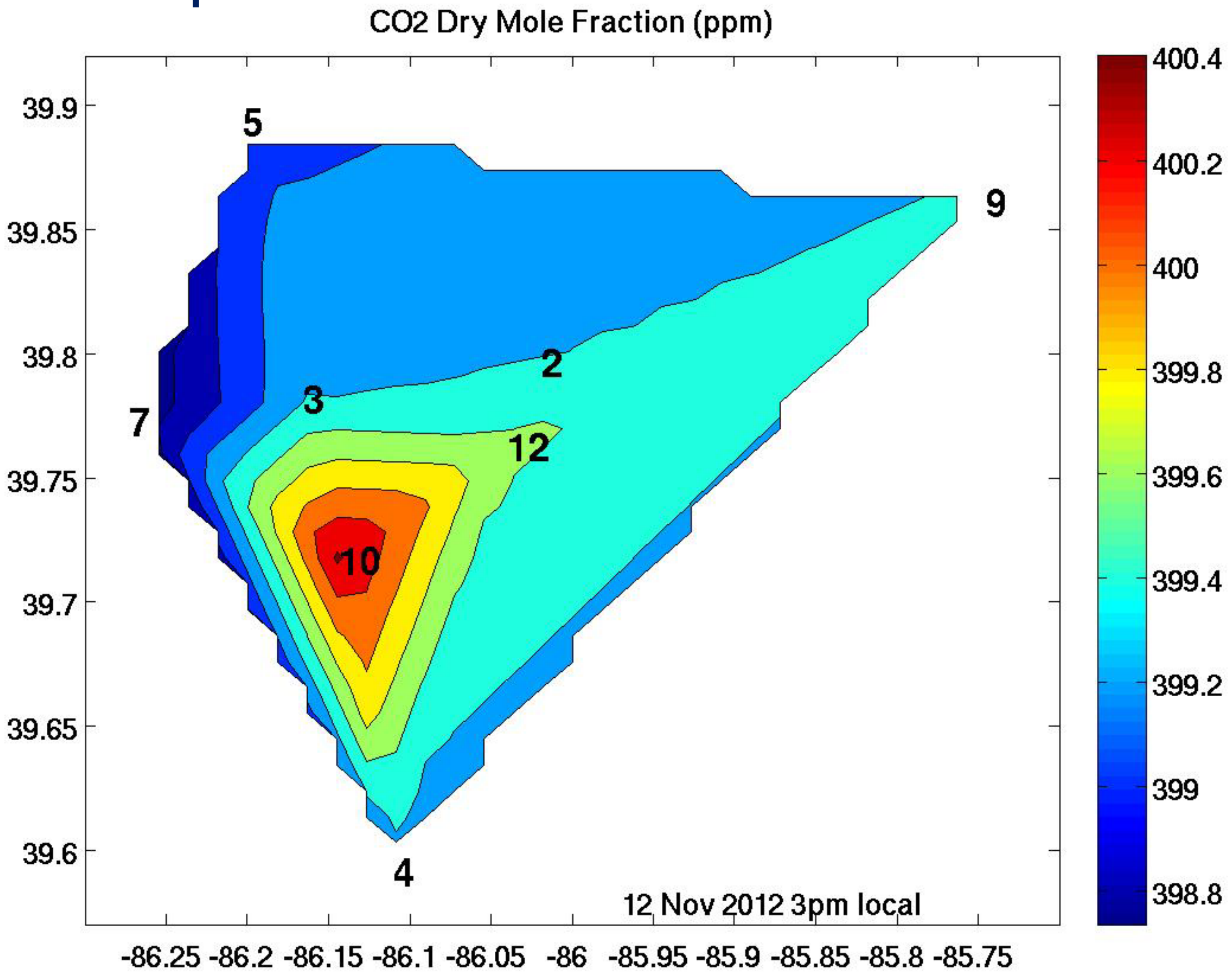
Observed: Dependence of CO_2 spatial gradient on wind speed



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

Light winds: 15 ppm difference midday

Observed: Dependence of CO_2 spatial gradient on wind speed

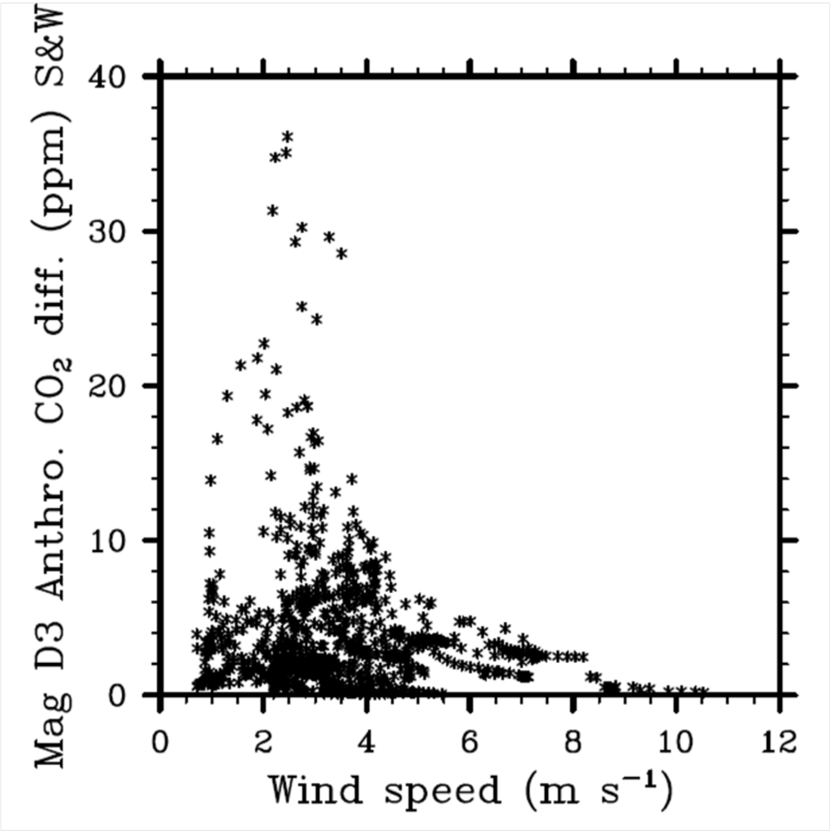


- 12 Nov 2012 at 3 pm local
- Winds: 9 m/s from the west

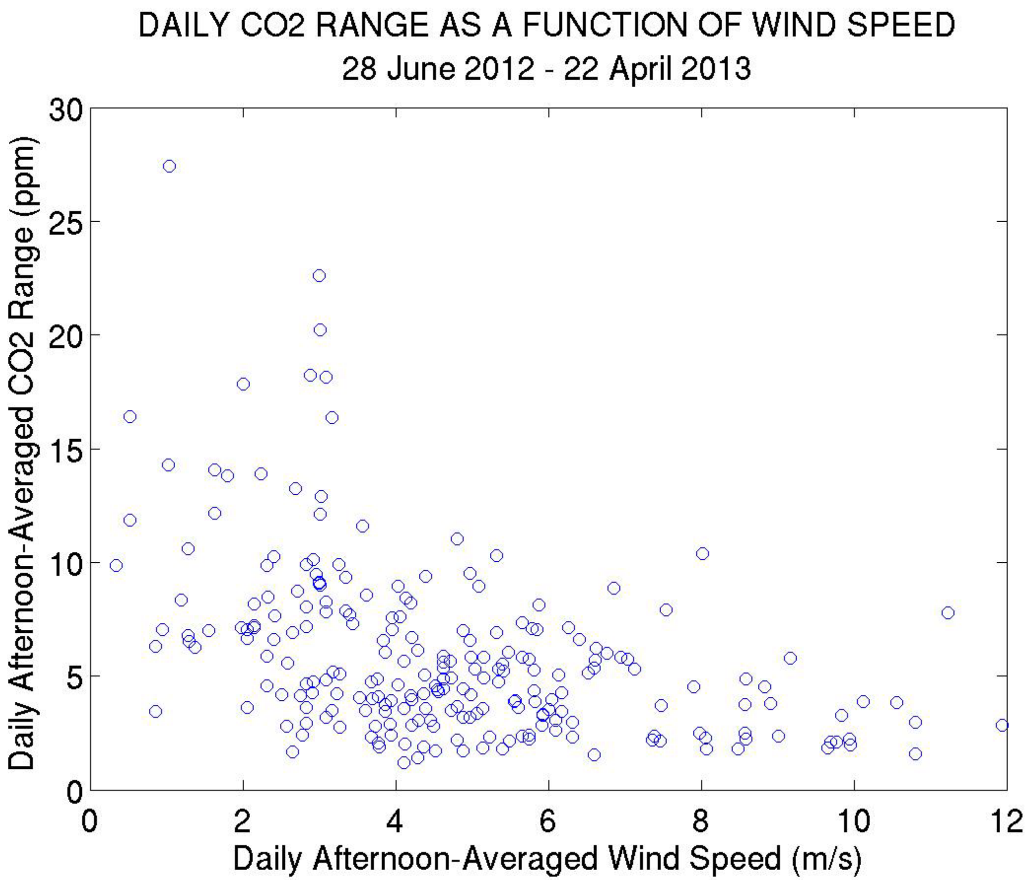
Strong winds: < 2 ppm difference midday

CO2 range as a function of wind speed

Model: Difference along domain-averaged wind direction



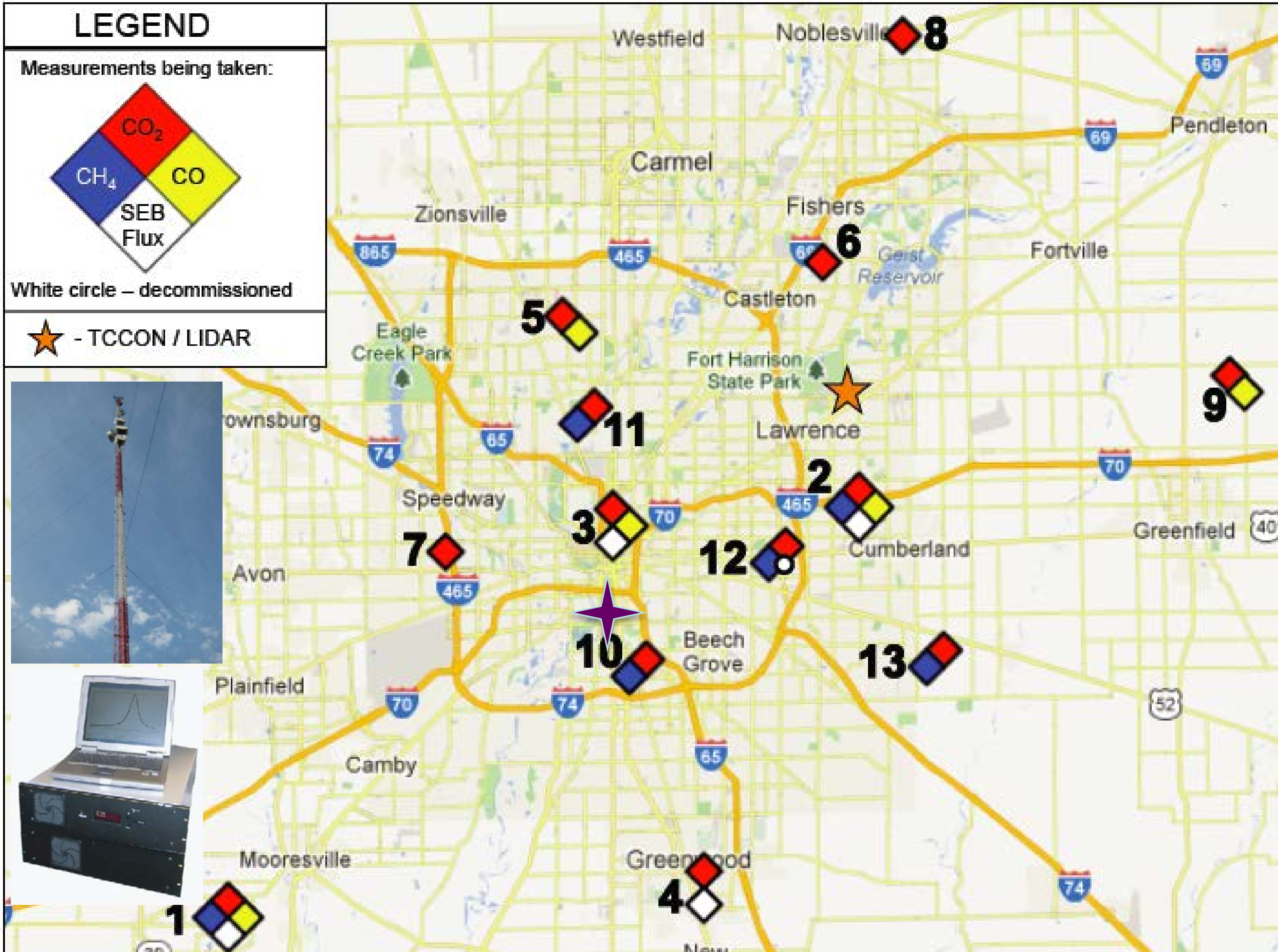
Observations: CO2 range amongst INFLUX sites



Cross city mole fraction enhancement is an inverse function of wind speed (and ABL depth).

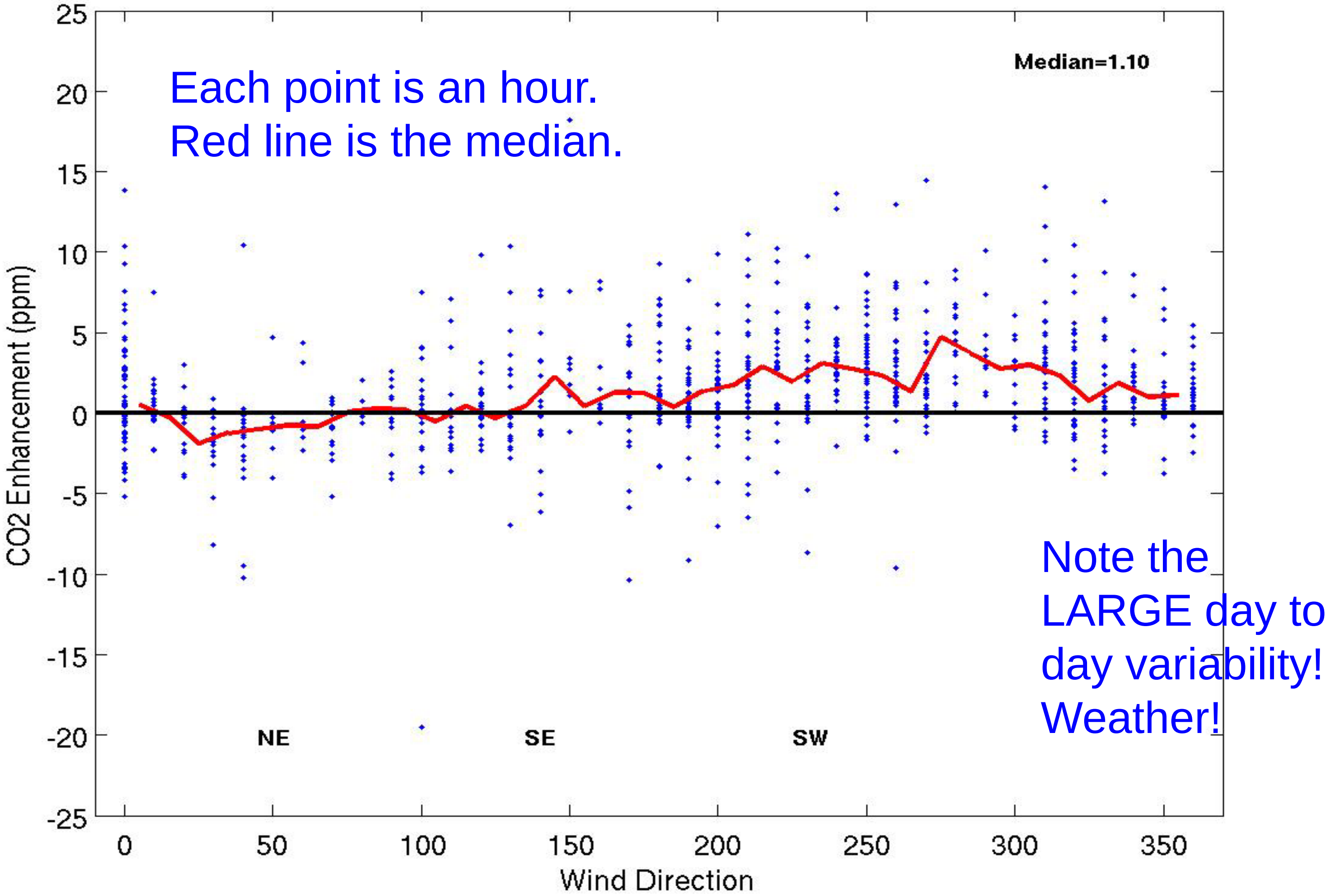
INFLUX ground-based instrumentation

Picarro, CRDS sensors; NOAA automated flask samplers;
Communications towers ~100m AGL

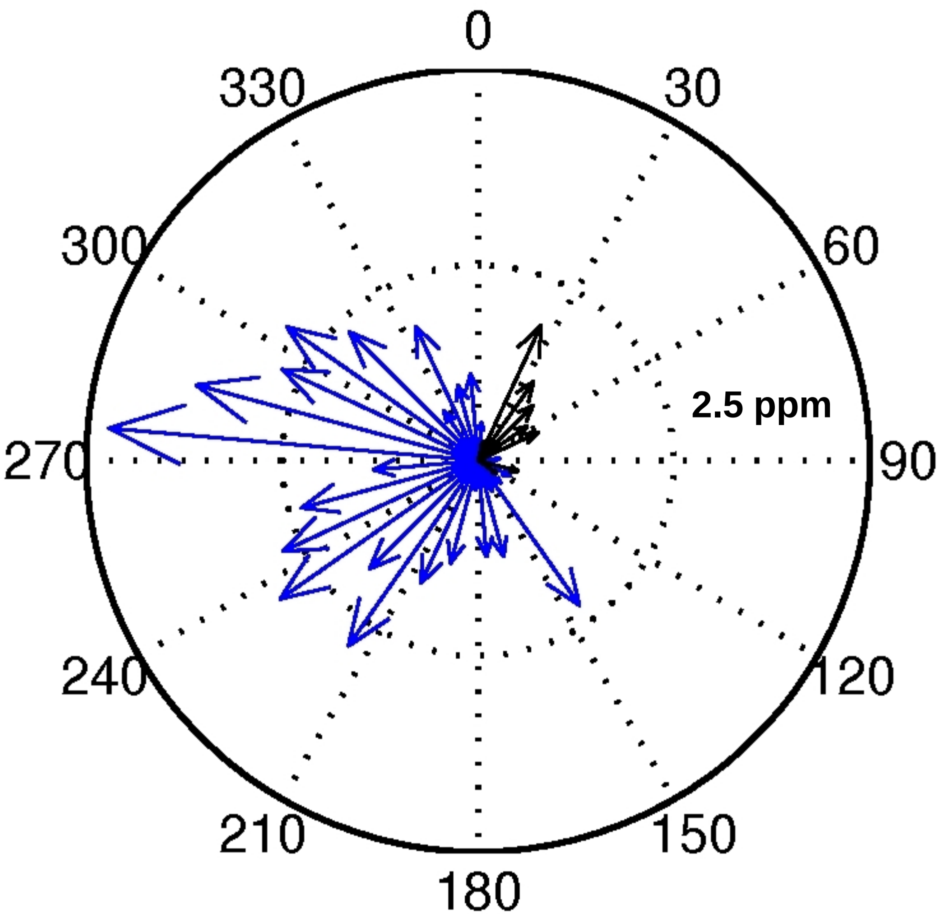


CO2 Enhancement (Site 02 – Site 01) as a Function of Wind Direction

April – November 2011 (Afternoon hours only)

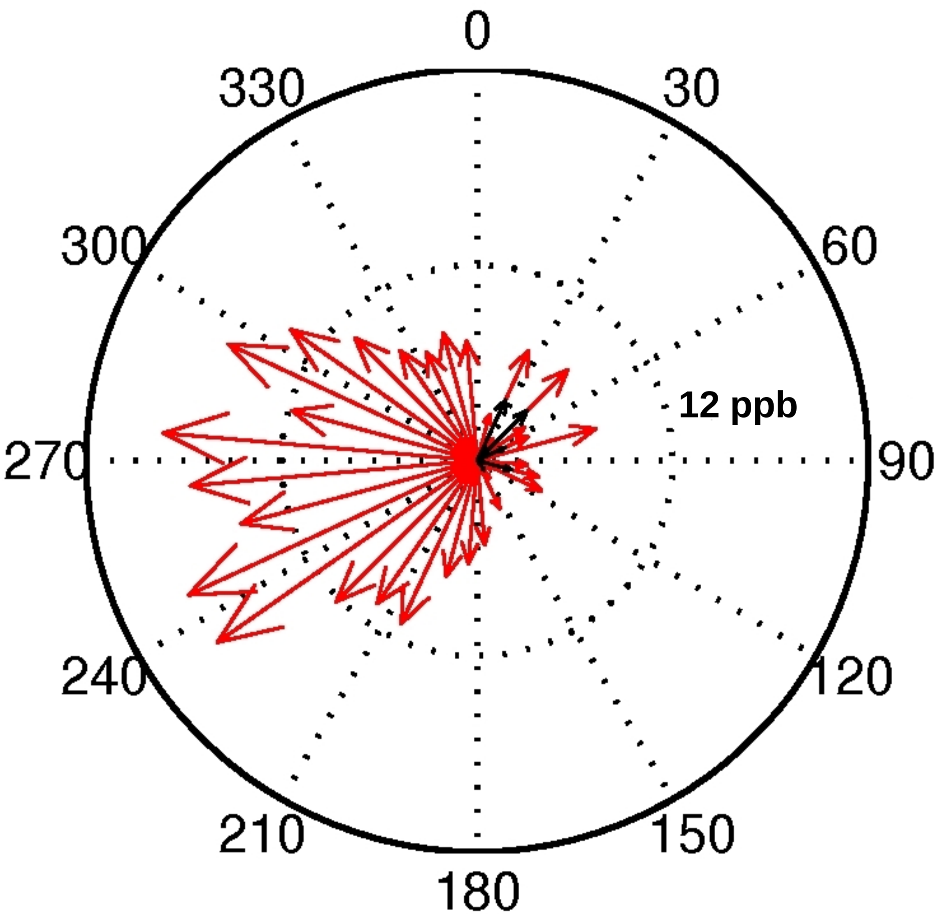


Median urban enhancement (Site 02 – Site 01): 100+ m AGL tower: CO_2



- 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

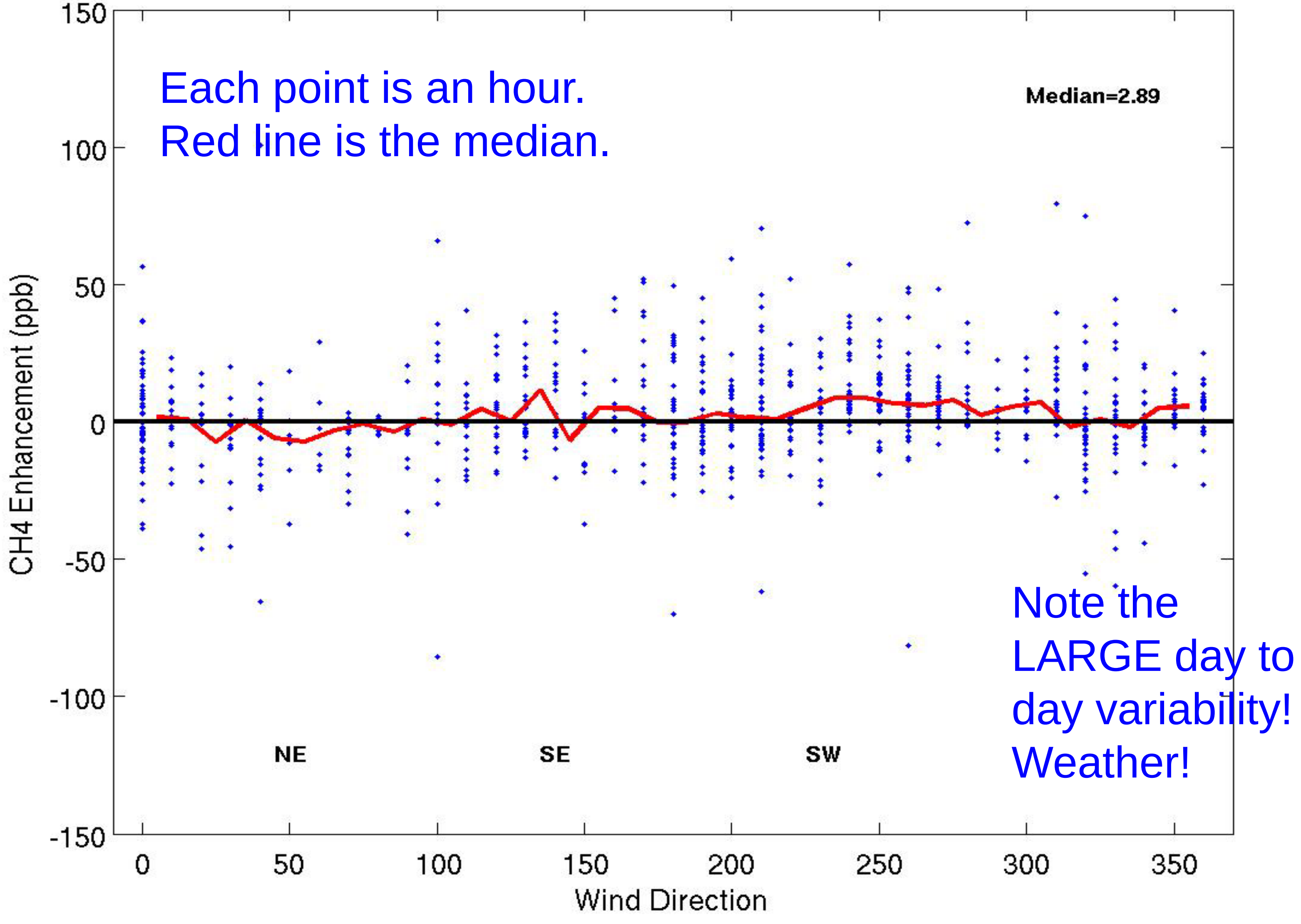
Median urban enhancement (Site 02 – Site 01): 100+ m AGL tower: CO



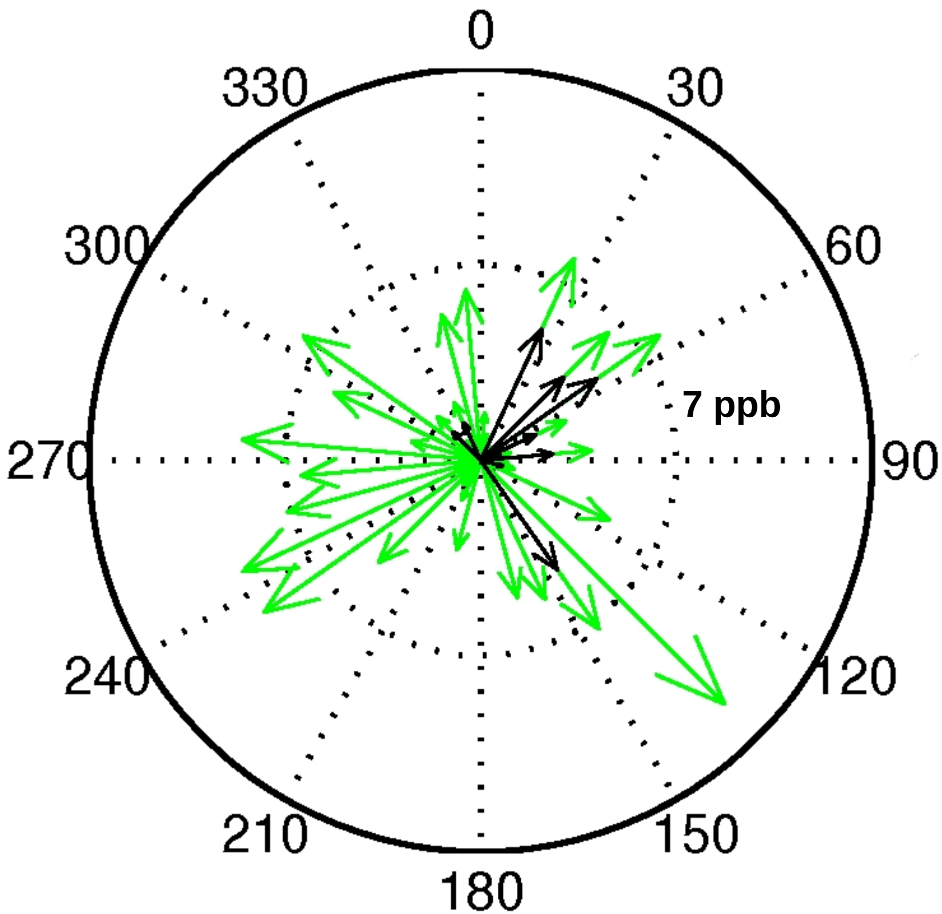
- Red arrows point to the sources of enhanced CO measured at Site 02, compared to Site 01
- Primarily from the west (urban center)
- Maximum *median* enhancements: ~ 20 ppb CO
- Tracer of combustion

CH4 Enhancement (Site 02 – Site 01) as a Function of Wind Direction

April – November 2011 (Afternoon hours only)

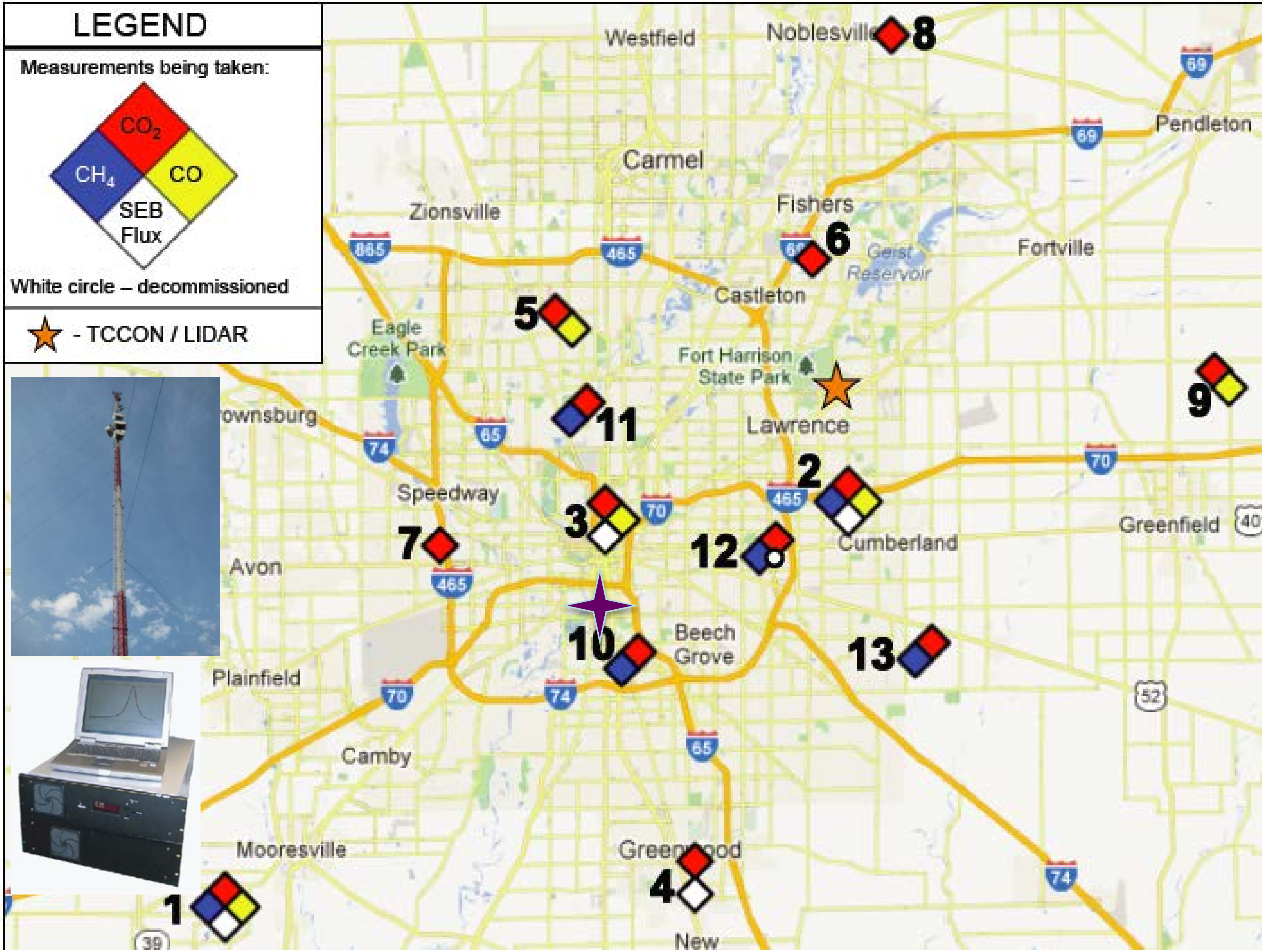


Median urban enhancement (Site 02 – Site 01): 100+ m AGL tower: CH_4



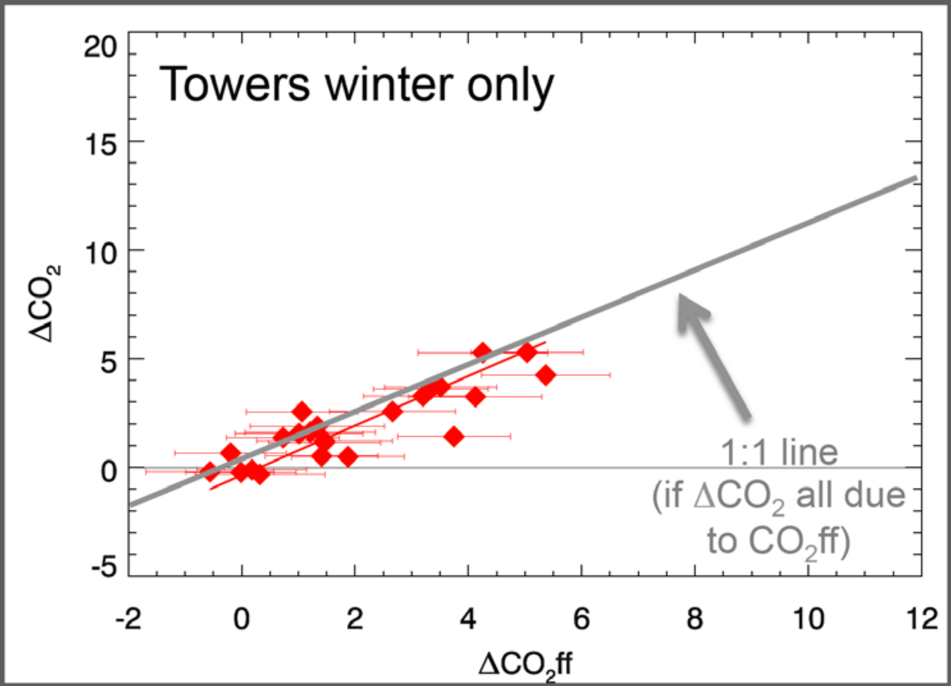
- Green arrows point to the sources of enhanced CH_4 measured at Site 02, compared to Site 01
- Large source to the southeast of Site 02, as well as to the west (urban center)
- Maximum *median* enhancements: ~ 10 ppb CH_4

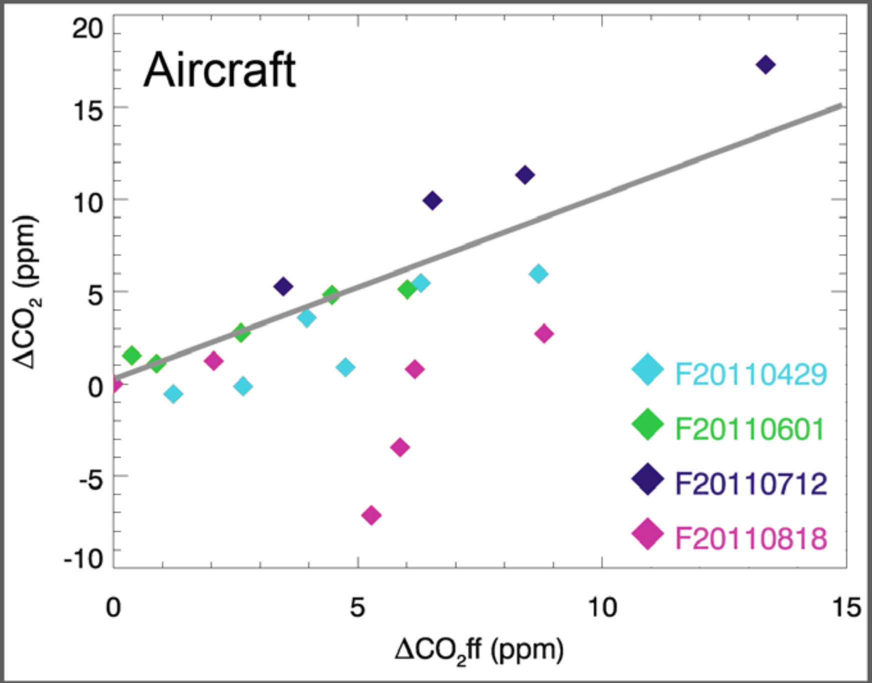
INFLUX ground-based instrumentation



Picarro, CRDS sensors; NOAA automated flask samplers;
Communications towers ~100m AGL

Contributions to CO_2 enhancement





$CO_2obs = CO_2bg + CO_2ff + CO_2bio + CO_2ocean$

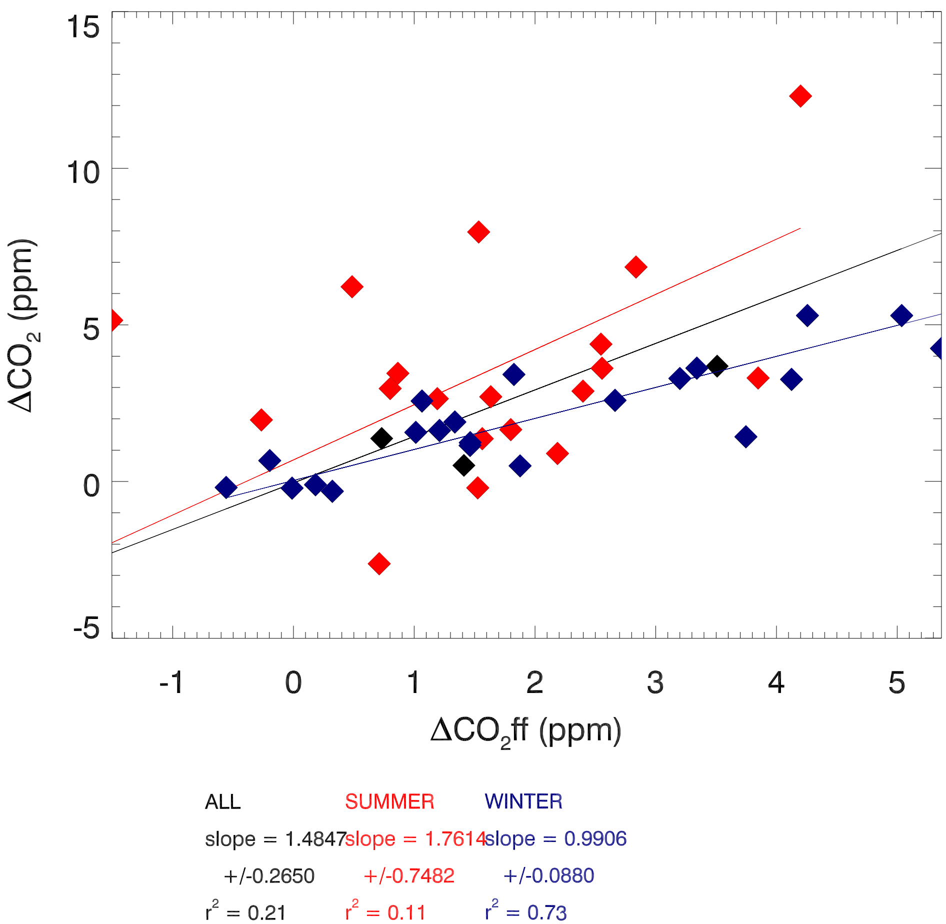
$\Delta CO_2 = \Delta CO_2ff + \Delta CO_2bio$

ΔCO_2 in winter can be entirely explained by CO_2ff addition

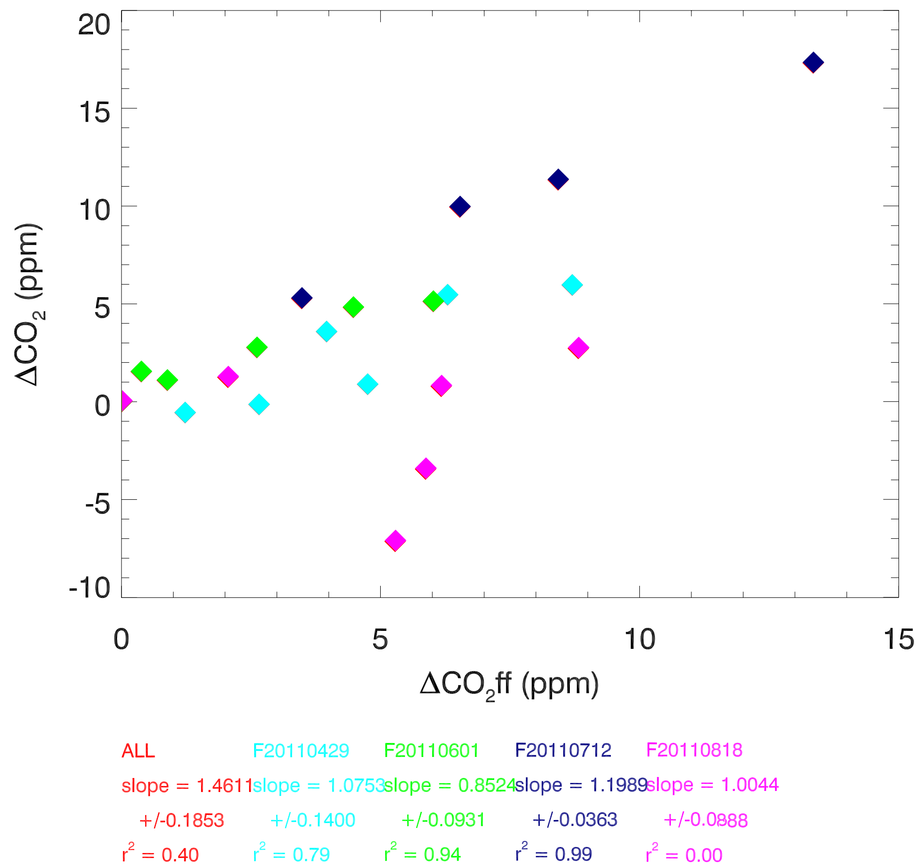
No apparent biosphere (respiration/ photosynthesis) contribution

	Slope (ppm/ppm)	**r^2**
Towers Winter	1.1±0.2	0.8
29 Apr 2011	1.1±0.1	0.8
1 Jun 2011	0.9±0.1	0.9
12 Jul 2011	1.2±0.1	1.0
18 Aug 2011	N/A	0.0

Towers



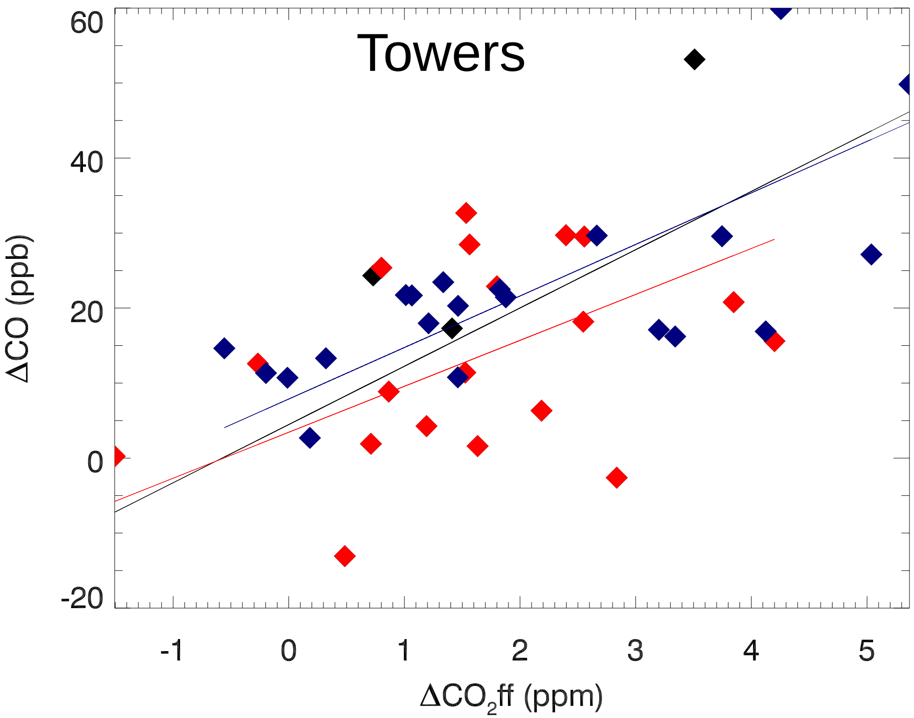
Aircraft



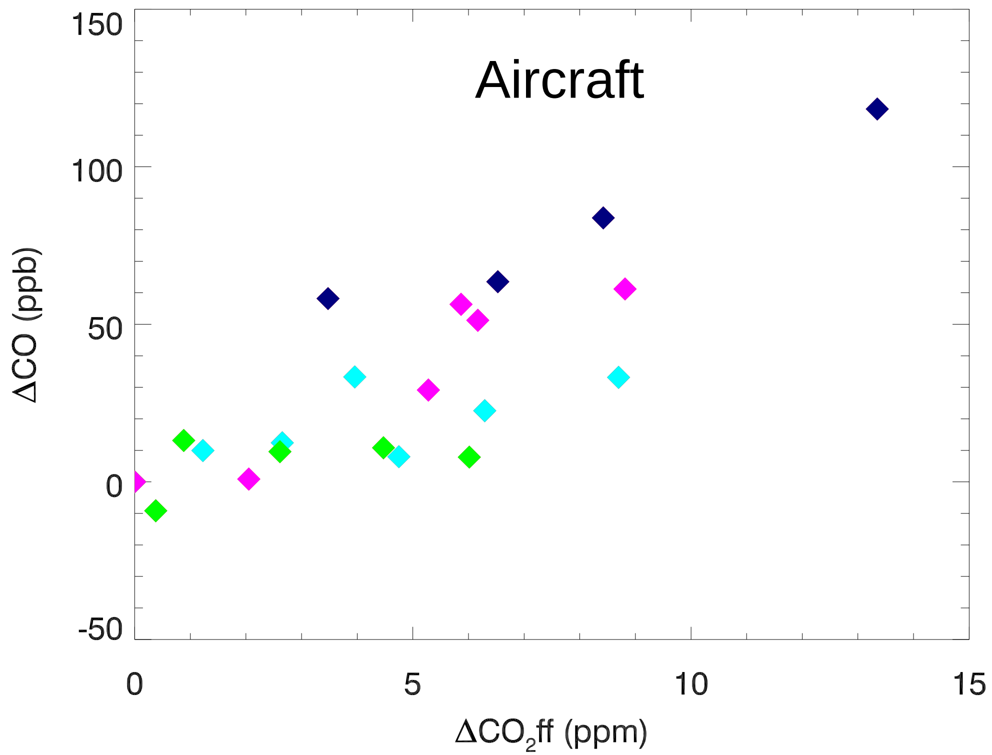
In winter, all ΔCO_2 is due to CO_2ff
In summer, not so much
Holds for both towers and aircraft

(Same as previous – just add summer to the towers plot.)

CO as a fossil fuel CO_2 tracer?



ALL	SUMMER	WINTER
slope = 7.7715	slope = 6.1261	slope = 6.8686
+/-1.4077	+/-2.0621	+/-1.5494
r^2 = 0.31	r^2 = 0.13	r^2 = 0.48



ALL	F20110429	F20110601	F20110712	F20110818
slope = 9.3535	slope = 3.9541	slope = 2.8982	slope = 6.5806	slope = 8.7217
+/-0.7525	+/-0.3751	+/-1.1592	+/-0.6351	+/-1.1723
r^2 = 0.69	r^2 = 0.40	r^2 = 0.26	r^2 = 0.95	r^2 = 0.88

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

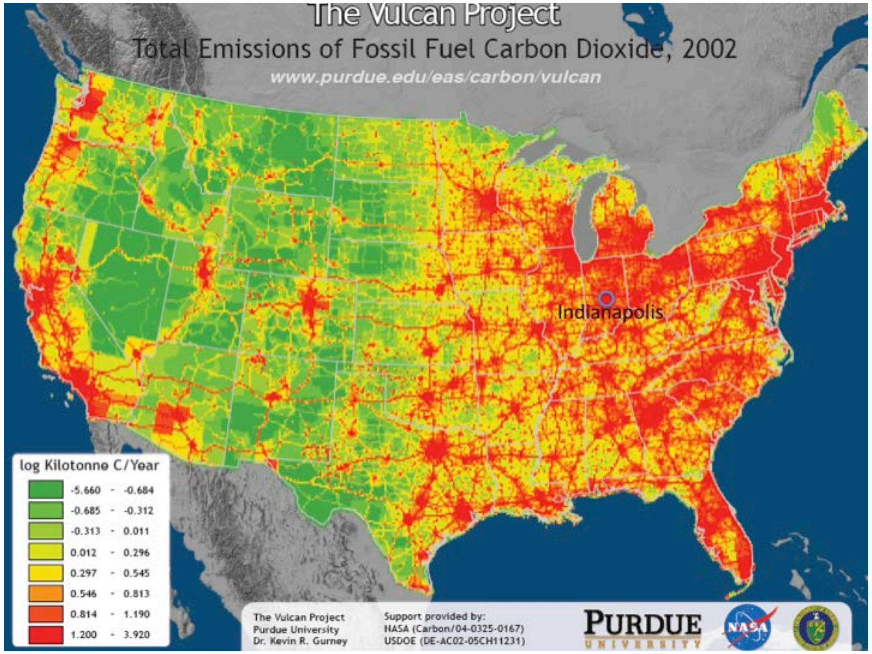
Observational summary

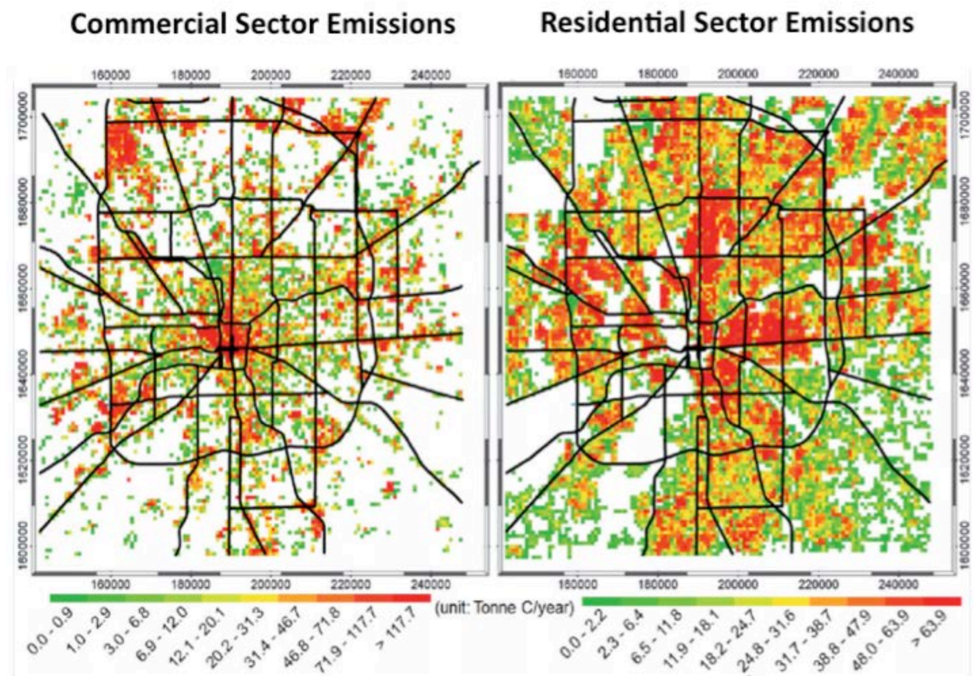
- Cross-city mole fraction differences clearly detected (given considerable averaging to see through the weather)
- Differences vary greatly with weather conditions
- Elevated sampling necessary to avoid strong surface gradients
- Winter, $CO_2 = CO_{2ff}$, and CO is a decent CO_{2ff} tracer. Summer, not so.

INFLUX numerical modeling and data analysis system

Inventory

Vulcan and Hestia Emission Inventories / Models





250m res - Indy.

Vulcan – hourly, 10km resolution for USA

- **See: Kevin Gurney/**
- **http://hestia.project.asu.edu/**

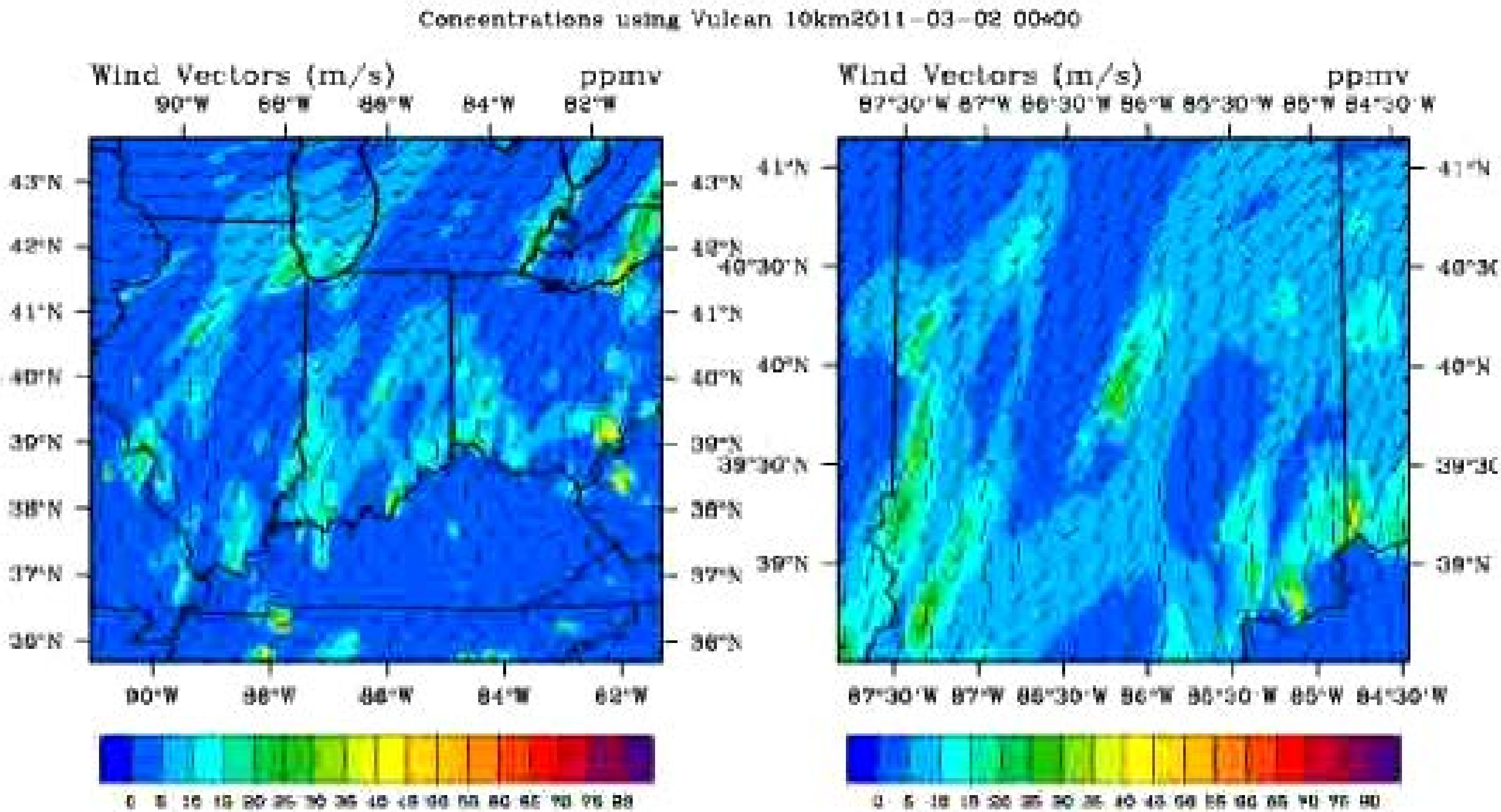
Hestia: high resolution emission data for the residential, commercial and industrial sectors, in addition to the transportation and electricity production sectors.

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



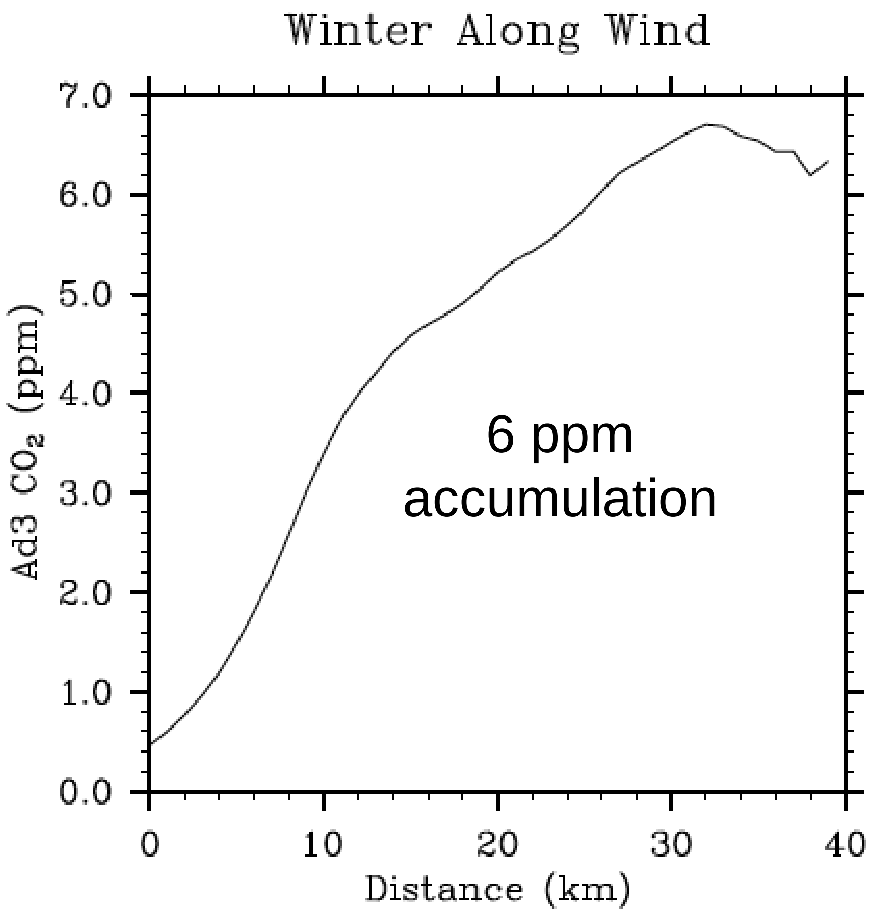
Anthropogenic CO2*: boundary conditions only*.

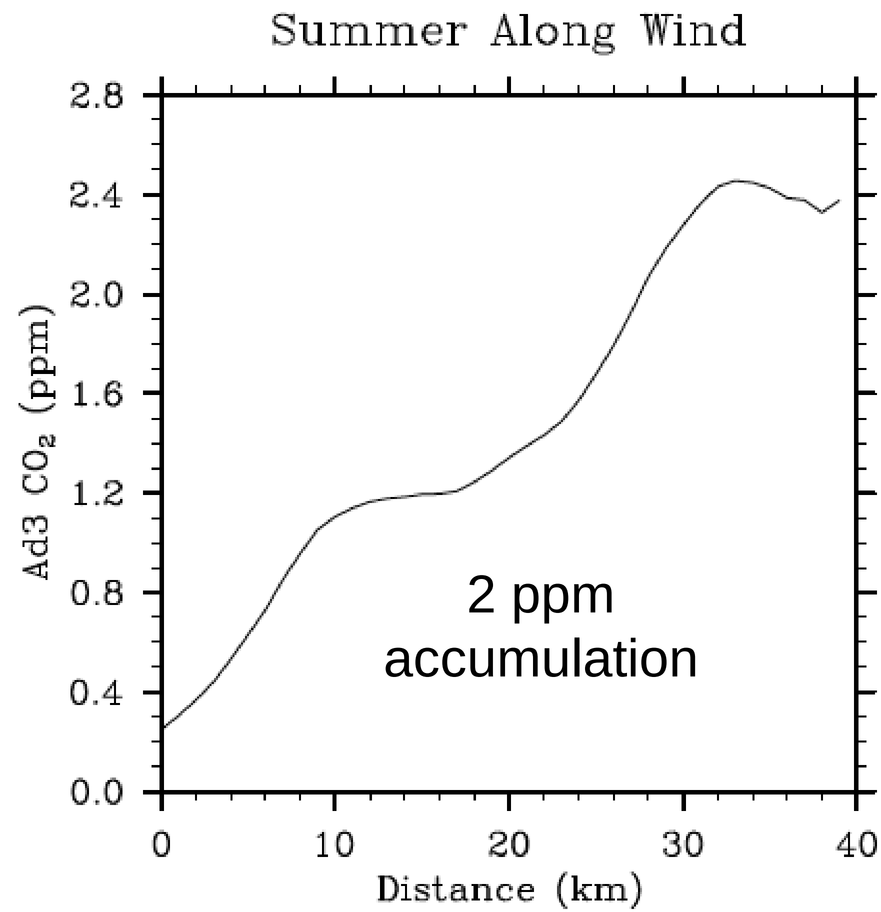
Note similarity to *weather* observed in site 1-2 differences.

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

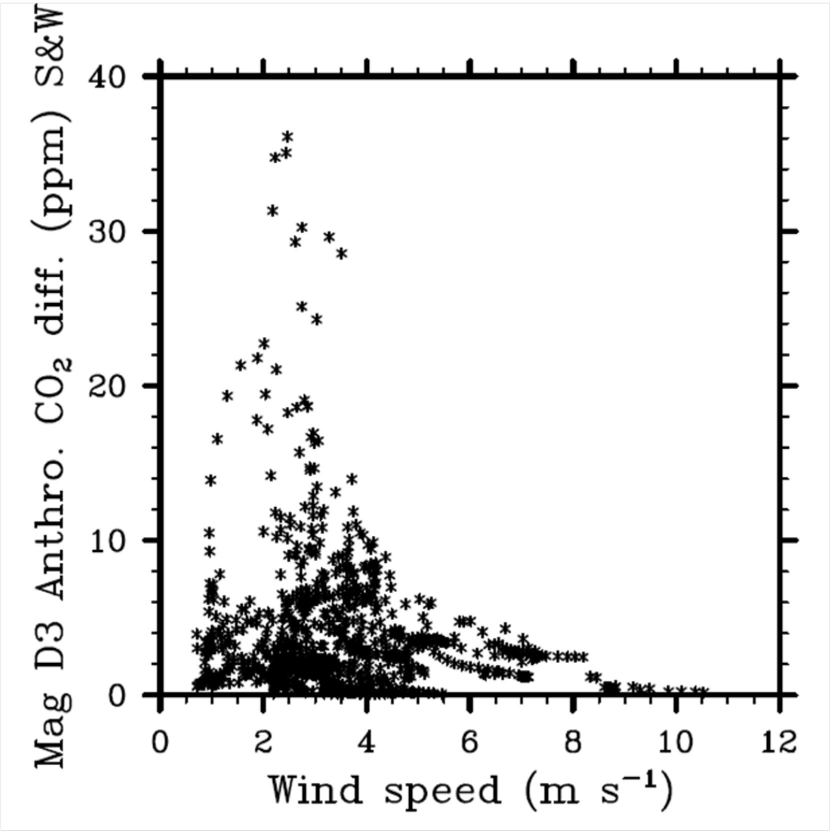




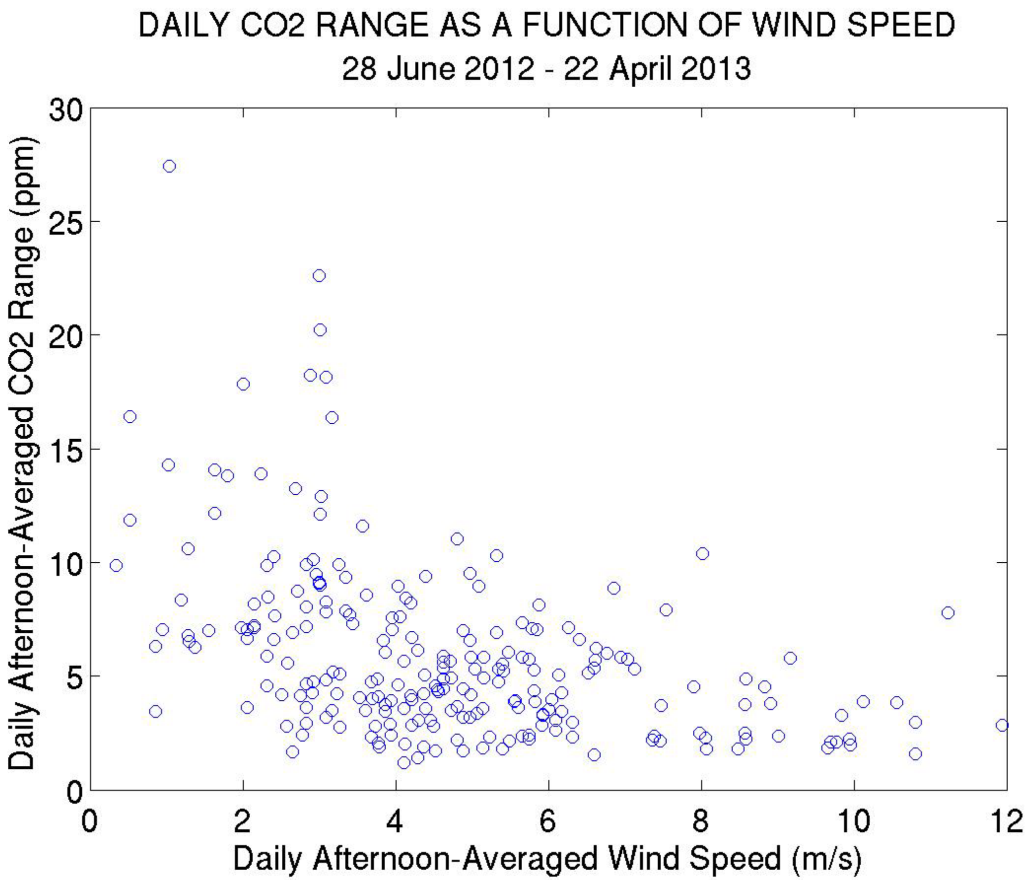
Deeper summer atmospheric boundary layer

CO2 range as a function of wind speed

Model: Difference along domain-averaged wind direction

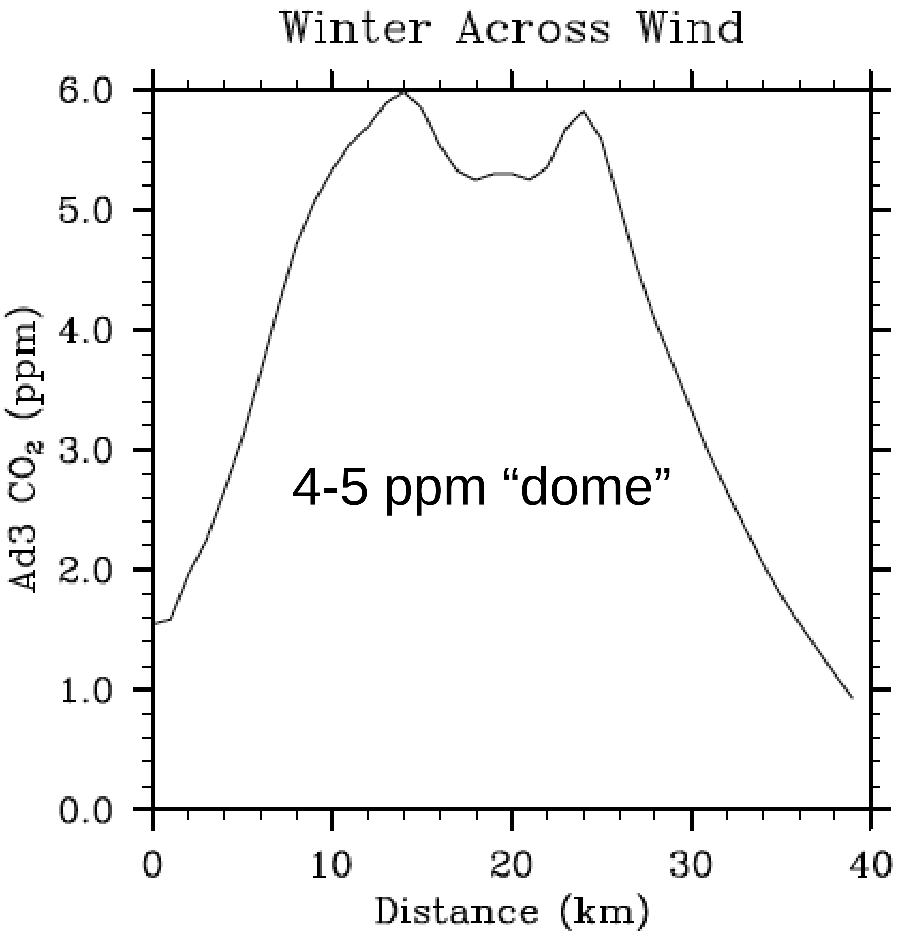


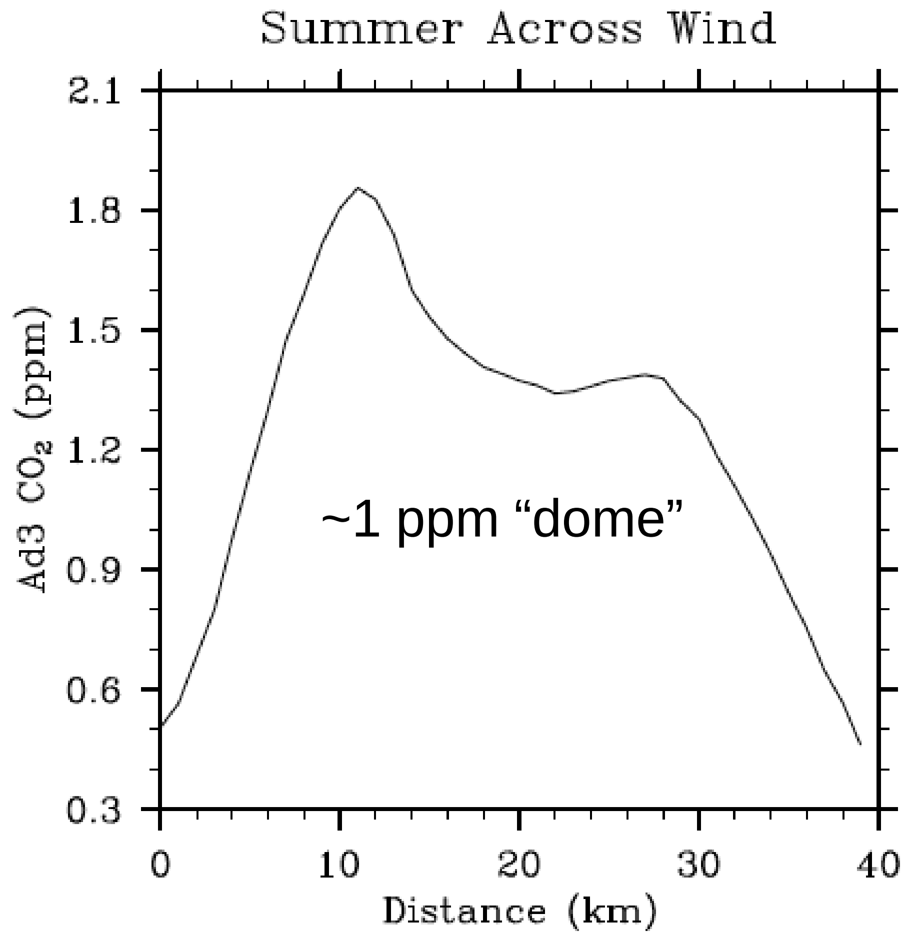
Observations: CO2 range amongst INFLUX sites



Cross city mole fraction enhancement is an inverse function of wind speed (and ABL depth).

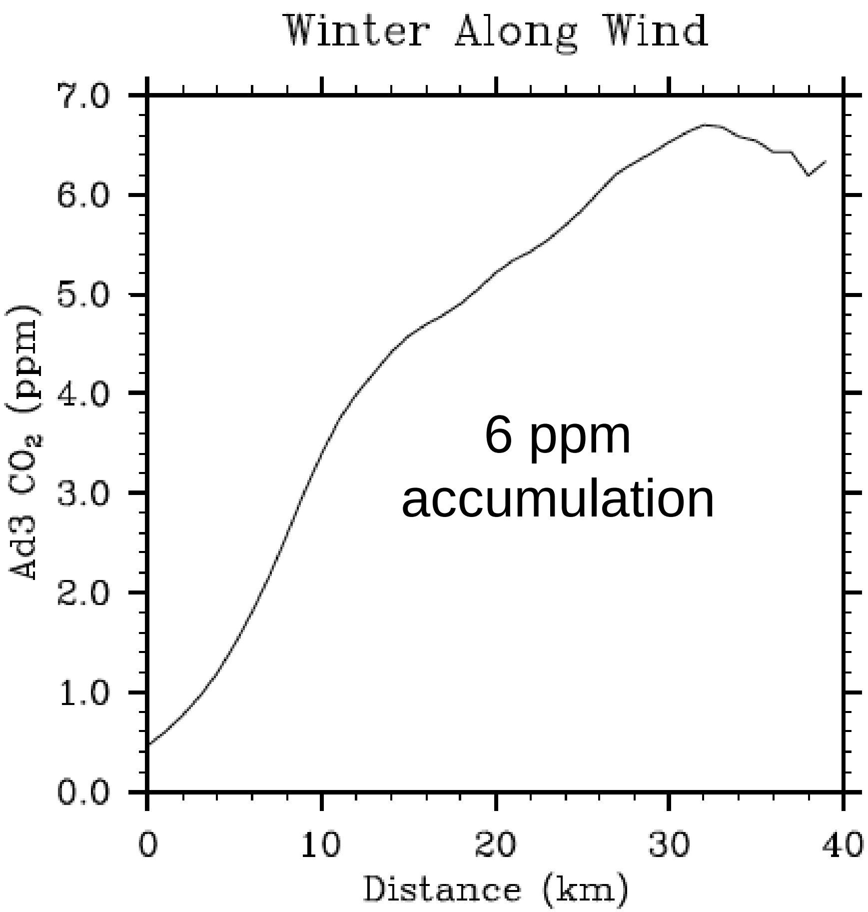
Monthly mean cross-wind CO_2: Anthropogenic CO_2 emissions within the domain

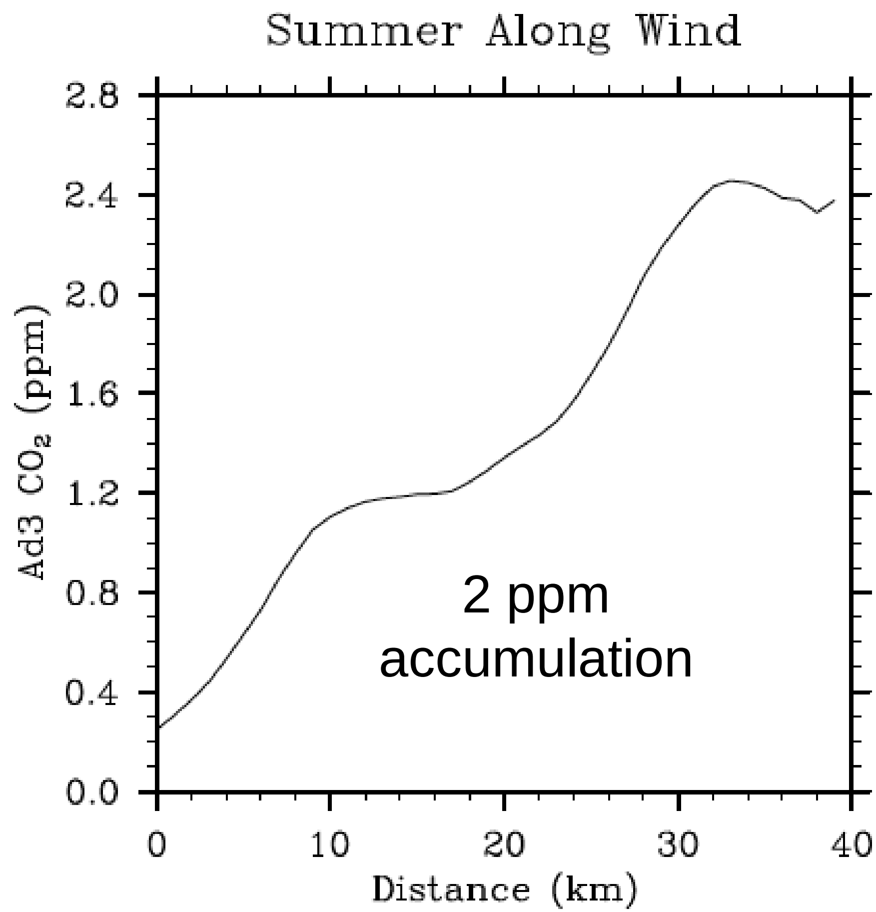




Deeper summer atmospheric boundary layer

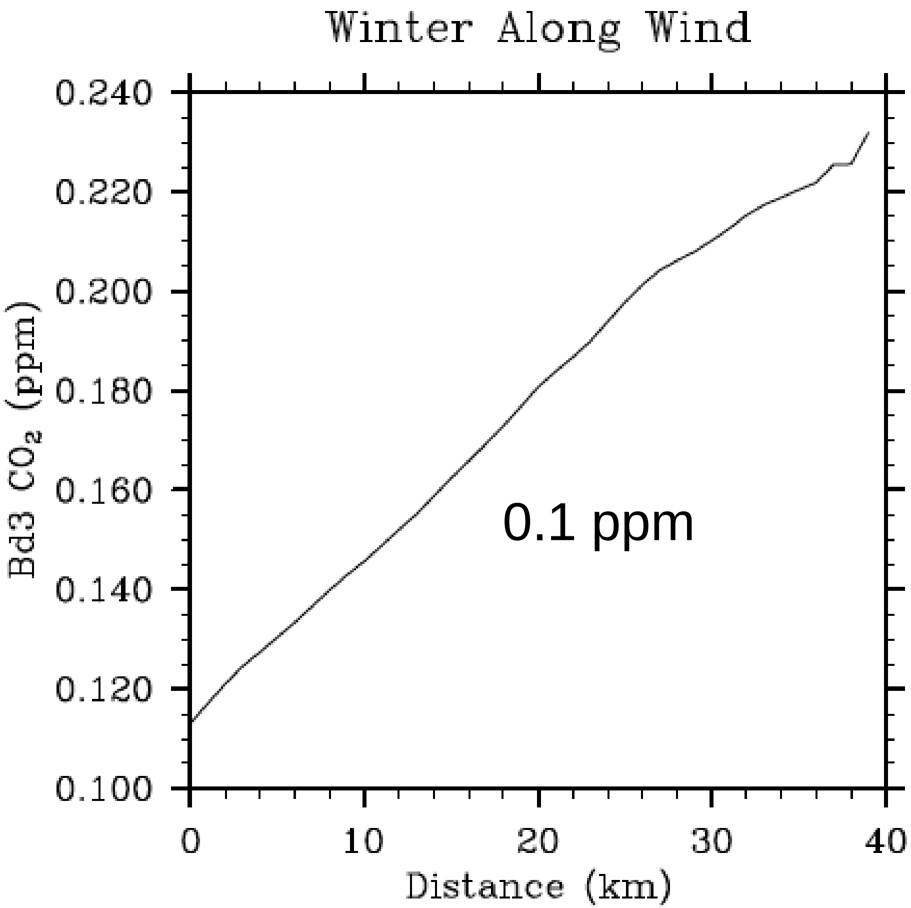
Monthly mean along-wind CO_2: Anthropogenic CO_2 emissions within the domain

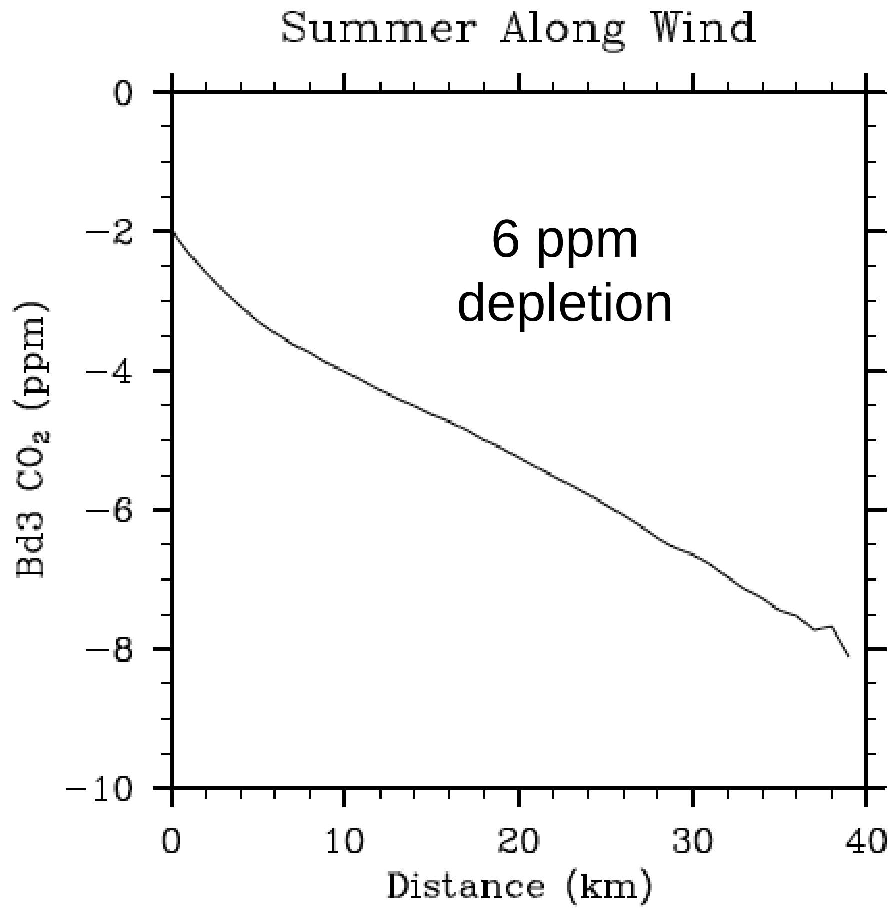




Deeper summer atmospheric boundary layer

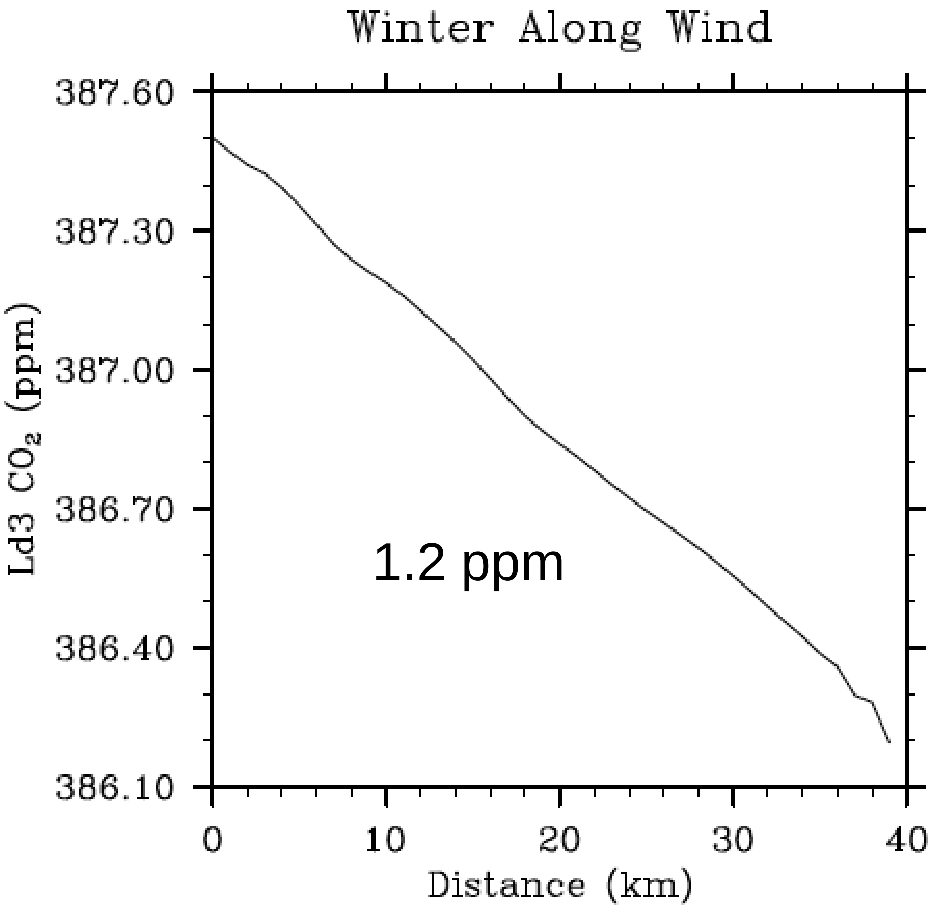
Monthly mean along-wind CO_2: Biological CO_2 fluxes within the domain

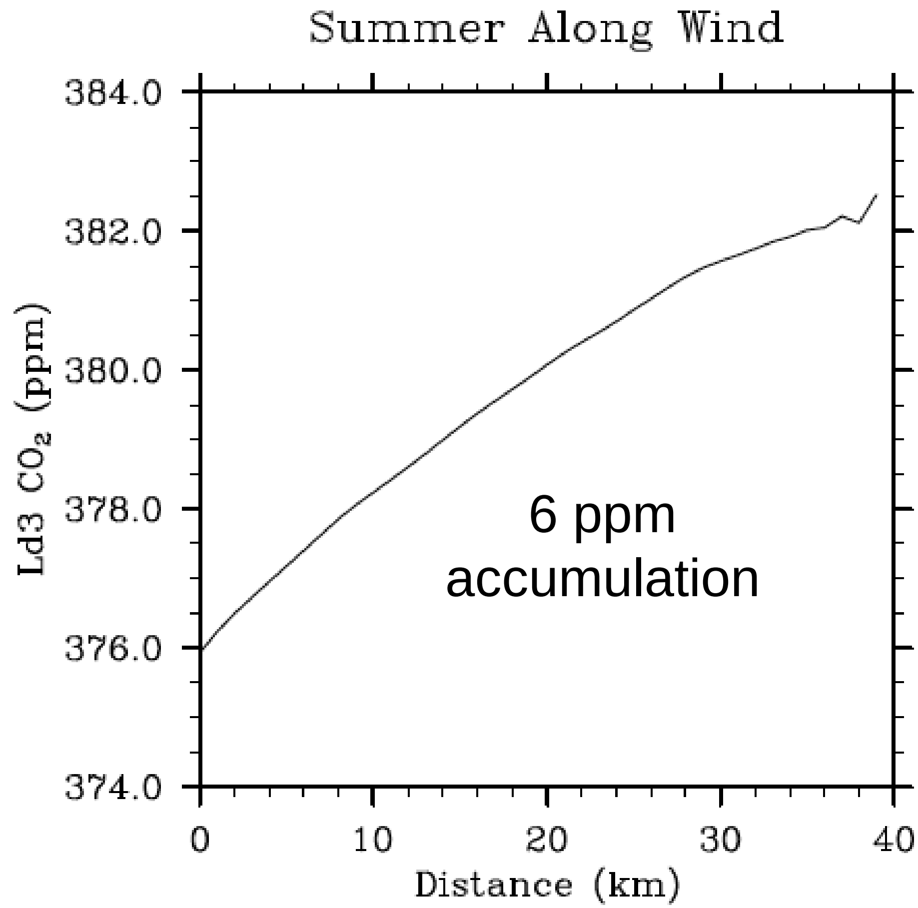




Large biological fluxes in the summer

Monthly mean along-wind CO_2: Total CO_2 boundary conditions





Forward simulation conclusions

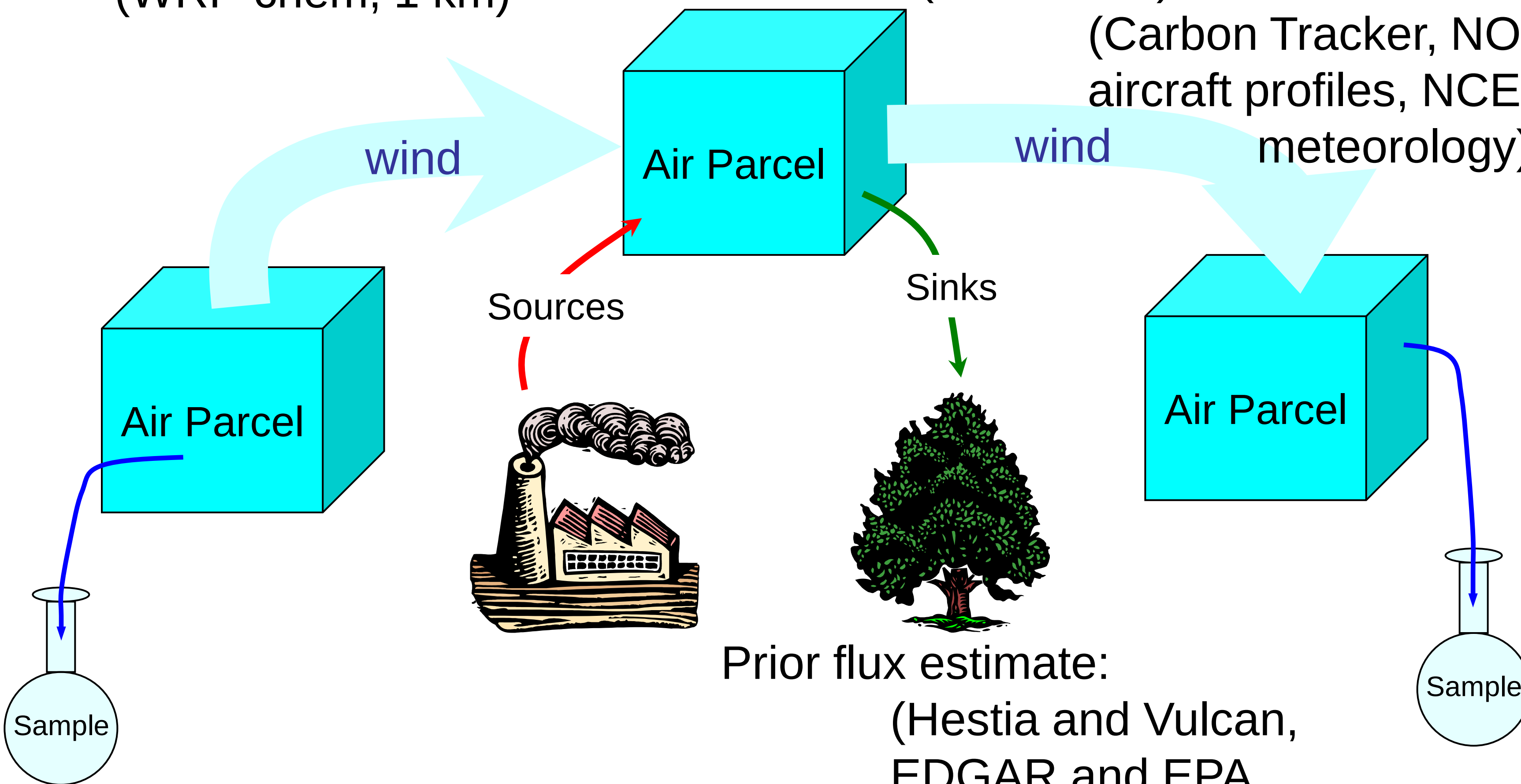
- Within-domain, anthropogenic fluxes easily detected in the winter.
- Summer anthropogenic signal must be deconvoluted from large biological signals.
  - Both within-domain, and lateral boundaries
- Weather signal reminiscent of observations.
  - Both boundary conditions and within domain
- Mean gradients 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)



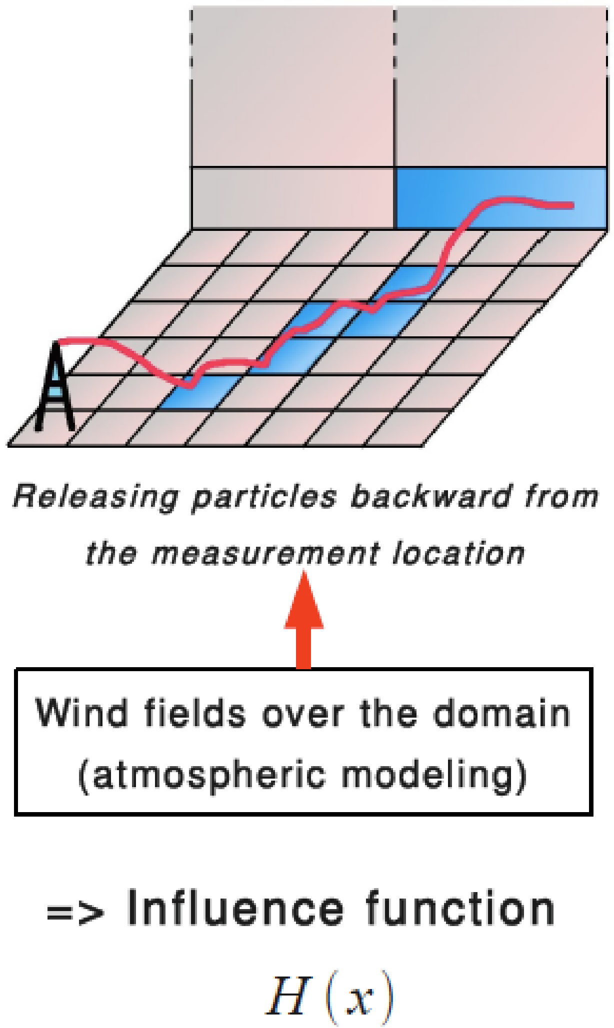
Prior flux estimate:
(Hestia and Vulcan,
EDGAR and EPA,
CT posterior and/or VPRM)

Network of tower-based GHG sensors:
(12 sites with CO_2, CH_4, CO and $^{14}CO_2$)

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.

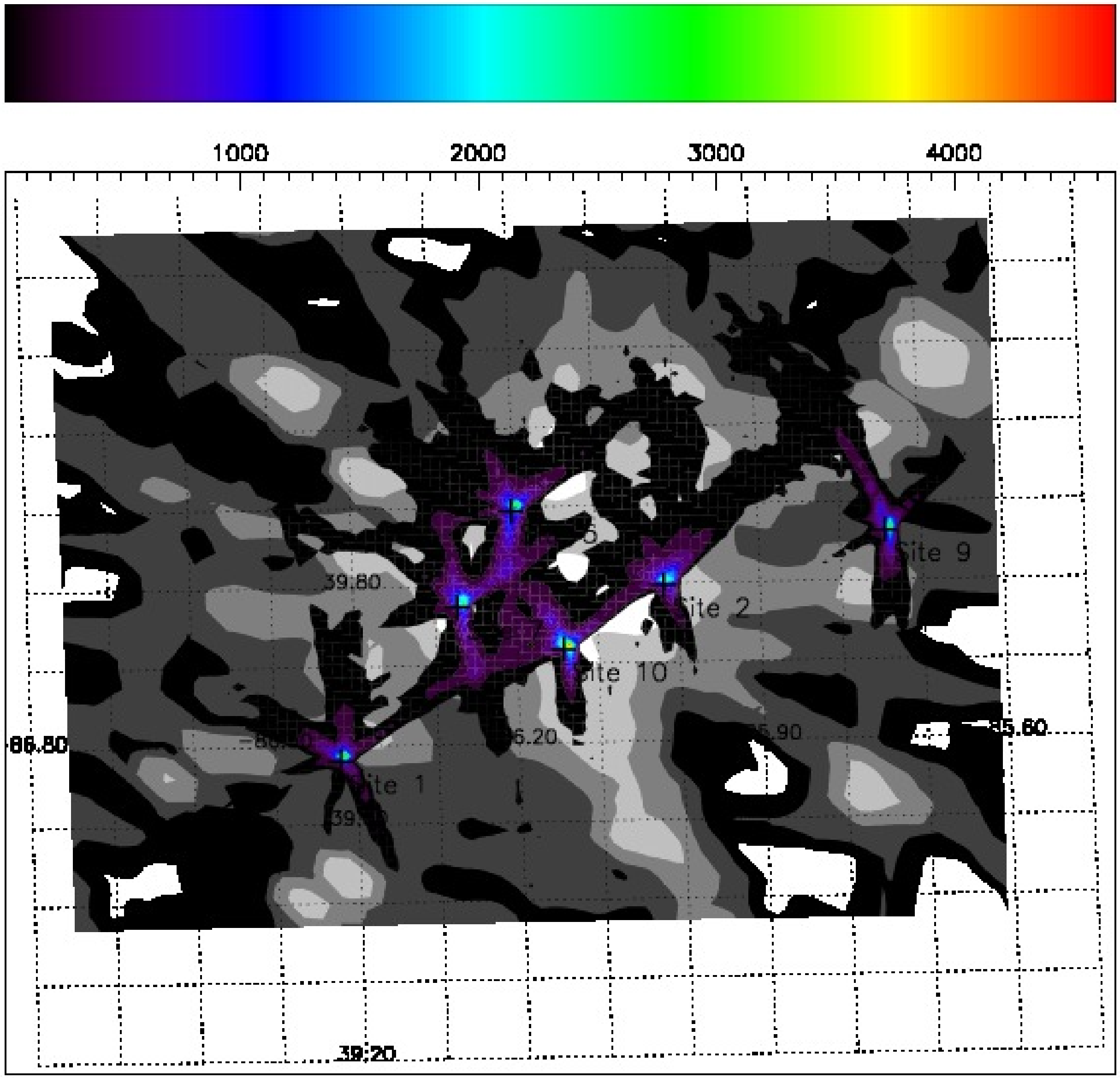


Lauvaux et al, 2012, ACP

Preliminary inversion system test

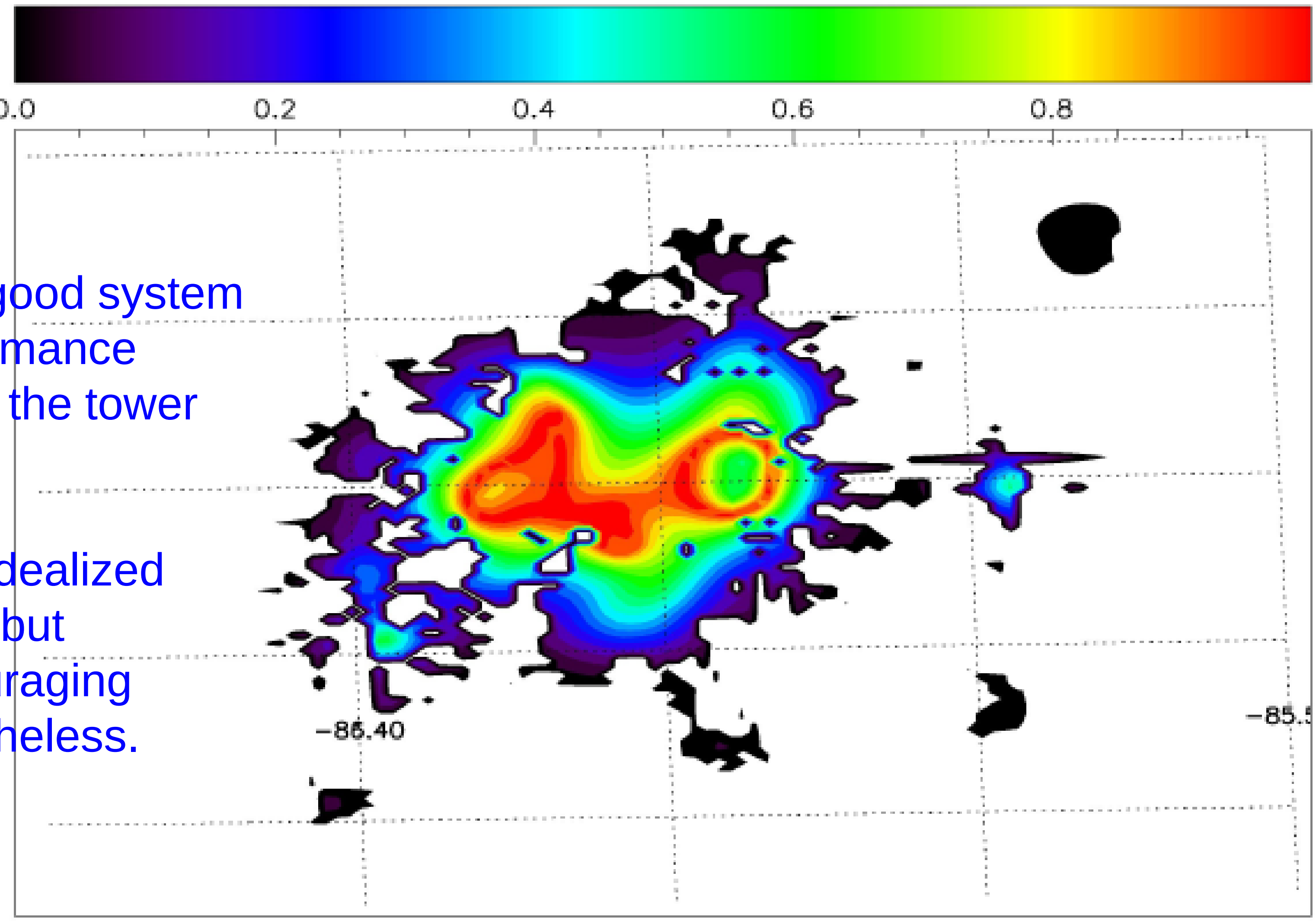
- 6 tower system tested, hourly daytime data
- Prior errors proportional to fluxes
- Prior error correlations 3km, isotropic, correlated with land cover
- Noise added with same spatial statistics, 80% of flux magnitude
- 7 day Bayesian matrix inversion, November
- No biogenic fluxes, no boundary conditions

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



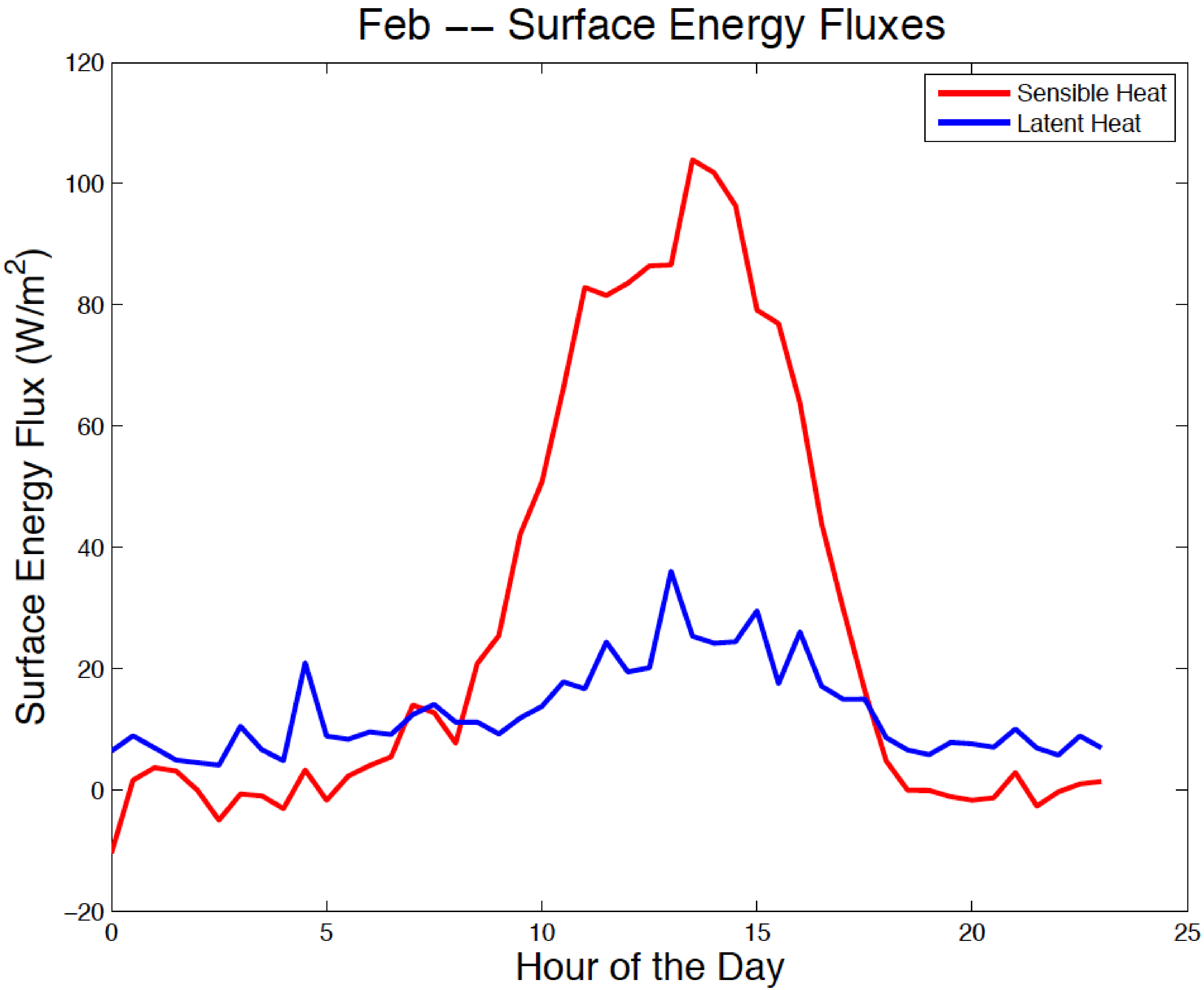
Very good system performance within the tower array.

Very idealized case, but encouraging nonetheless.

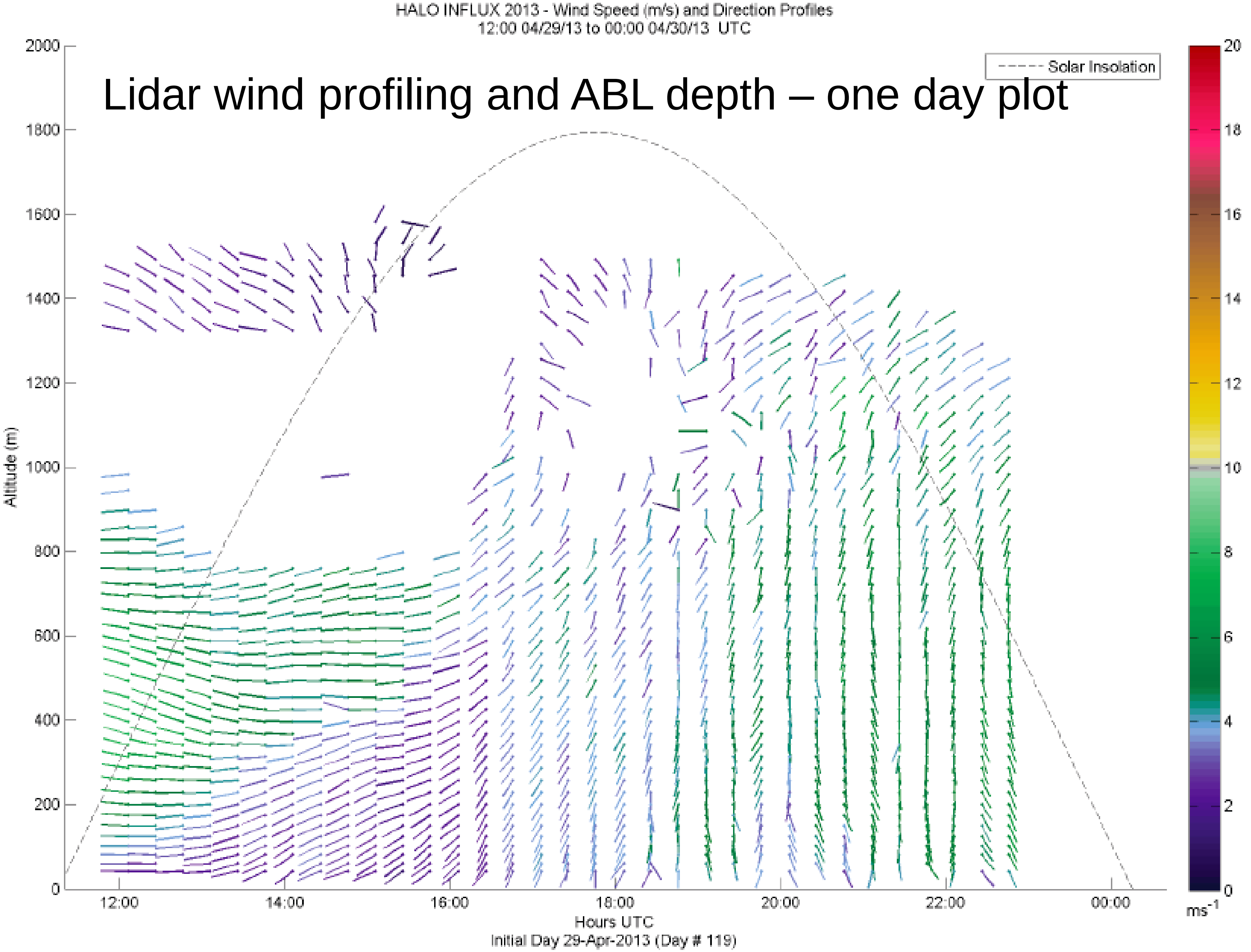
1 = perfect correction to prior fluxes

Data for atmospheric transport evaluation

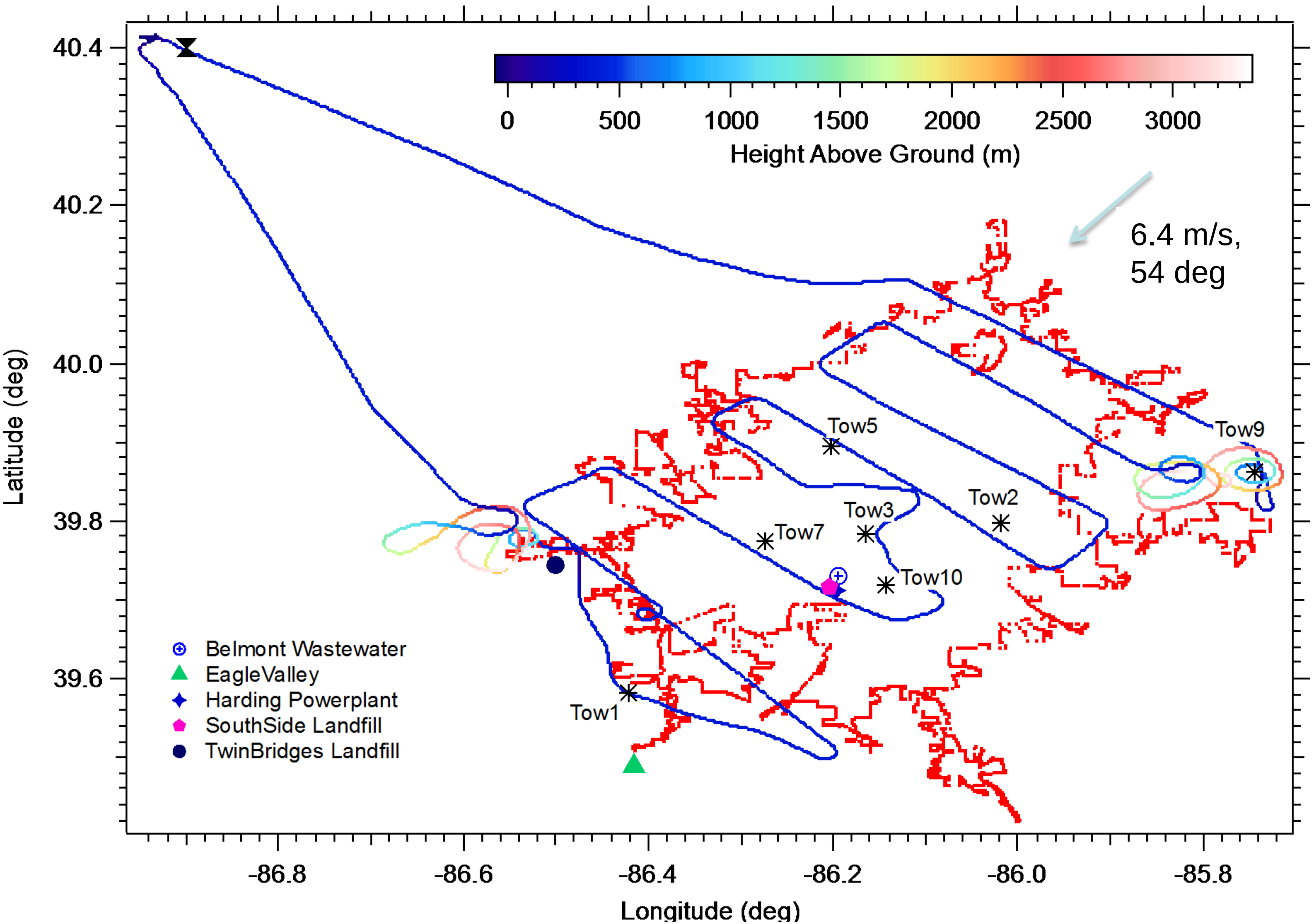
Local surface met stations


Feb -- Surface Energy Fluxes
Sensible Heat
Latent Heat
Surface Energy Flux (W/m^2)
Hour of the Day
120
100
80
60
40
20
0
−20
0
5
10
15
20
25

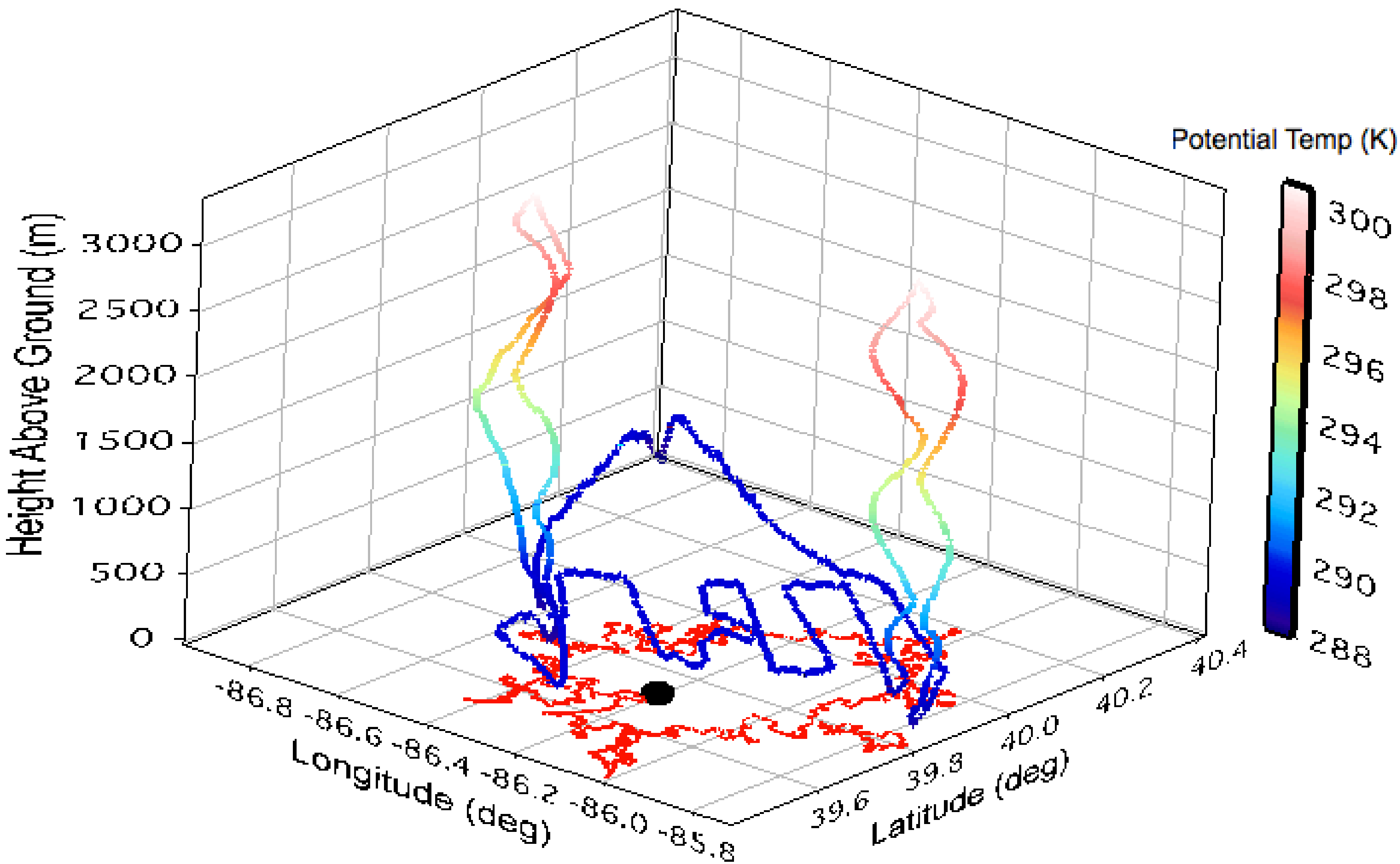
Lidar wind profiling and ABL depth – one day plot



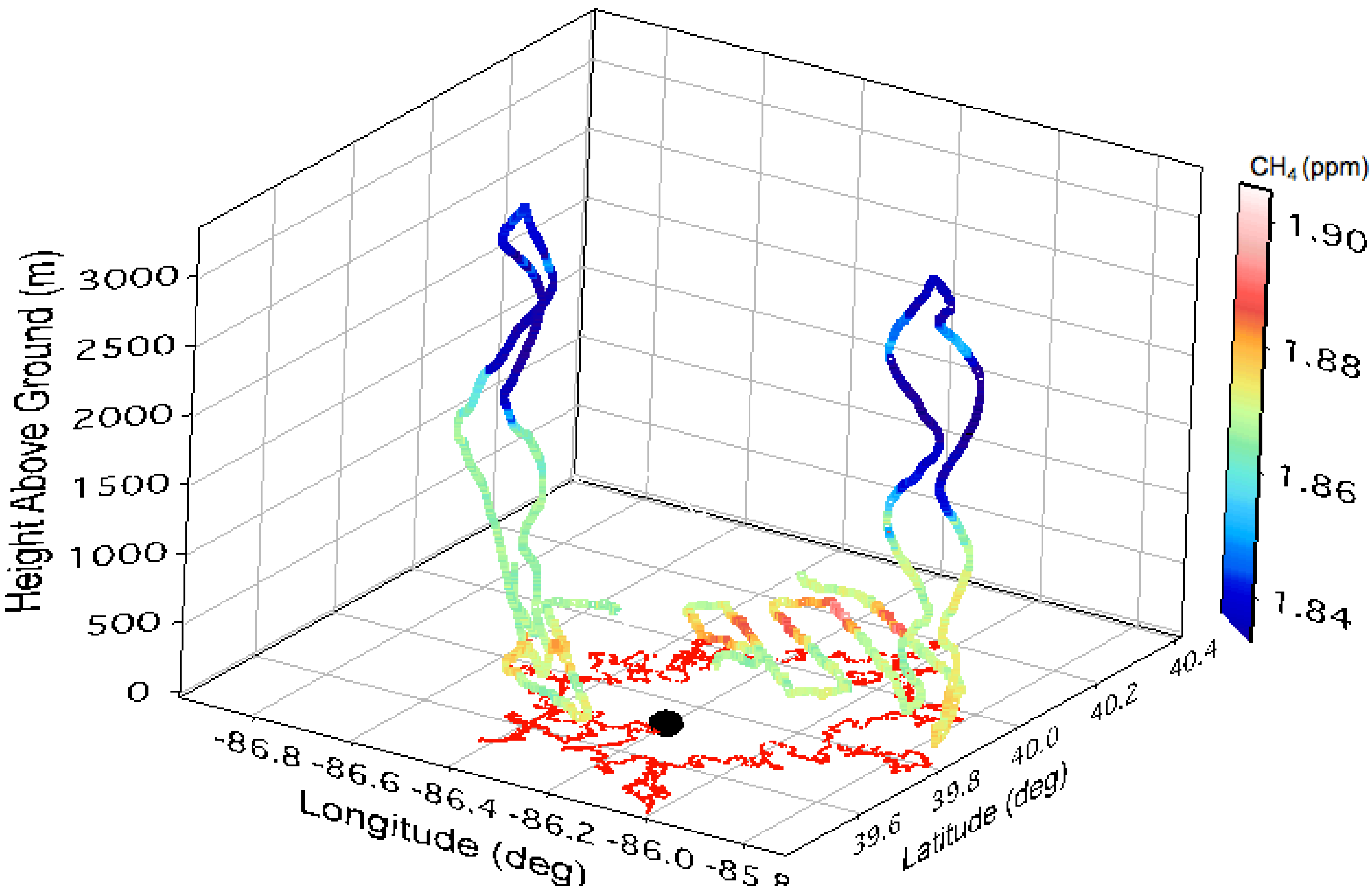
June 6, 2012 Flight Path



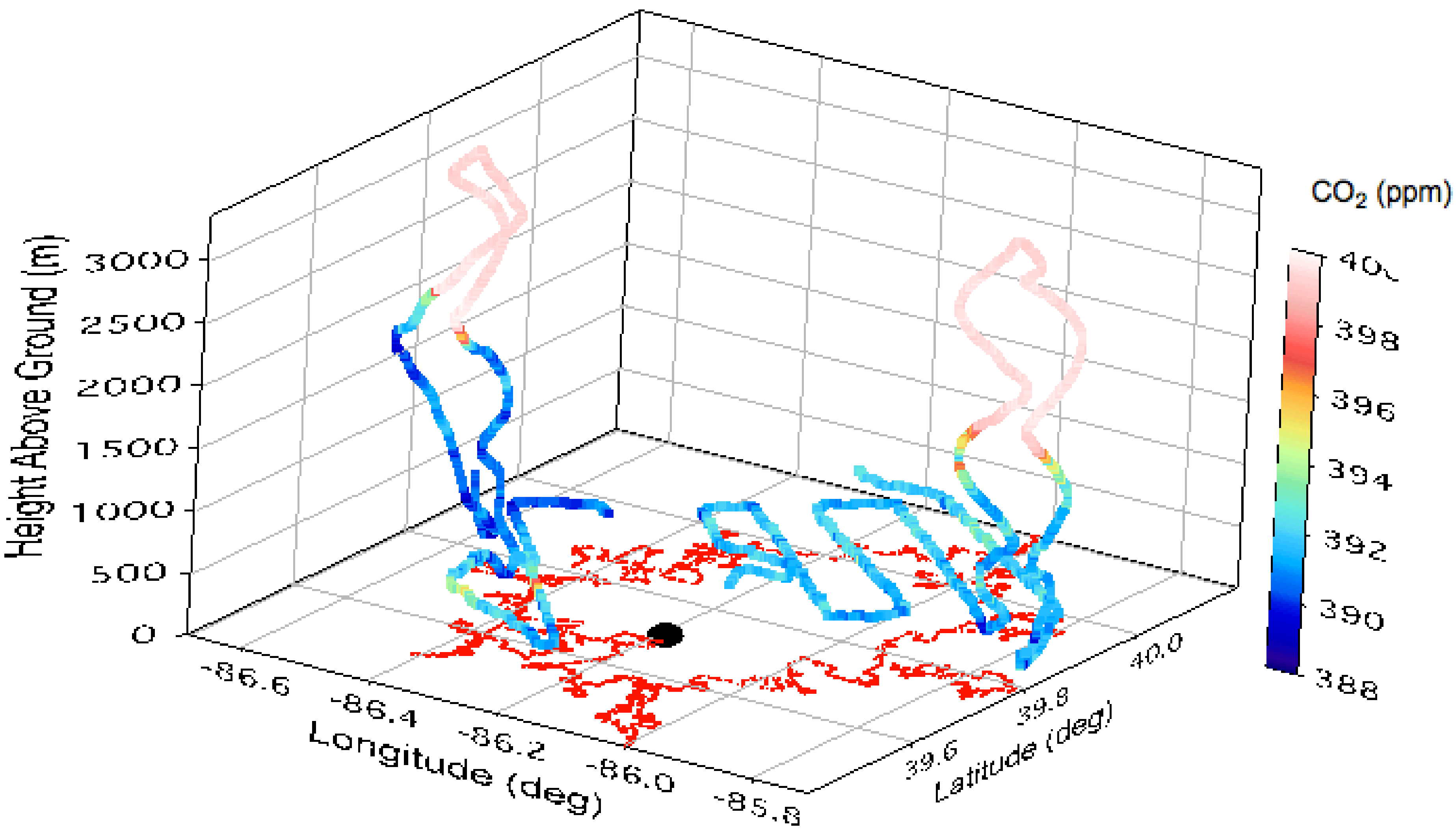
3D distribution of Potential Temperature



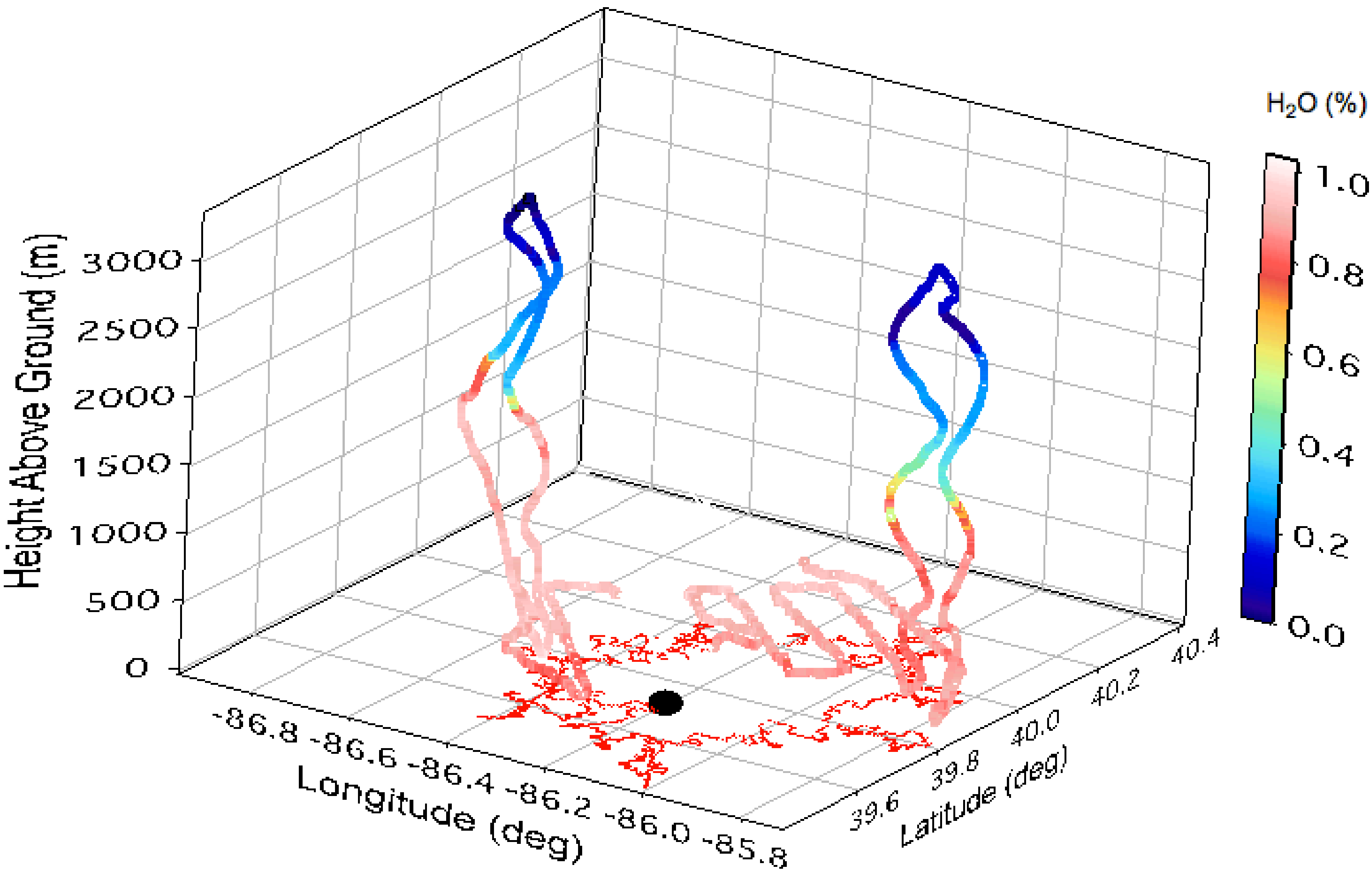
3D distribution of CH_4



3D distribution of CO_2 (black dot is Harding St. Power Plant)



3D distribution of H_2O



Conclusions

- Whole city flux estimates obtained. ~30-40% uncertainty? Aircraft.
- Tower observations detect a clear urban signal in both CO_2 and CH_4 (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.