Atmospheric Constraints on Methane Inventories: How Much Do We Know and How do We Know It?

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with contributions from many, many colleagues. Please see our list of citations.

Stakeholder Workshop:
EPA GHG Data on Natural Gas and Petroleum Systems
7 November, 2019 Pittsburg, PA

Outline

Introduction to the challenges of complementary methods.

Describe atmospheric methods for deriving regional methane emissions. How we can account for:

- Multiple regional sources
- Day / night emissions
- Background contamination
- Variations in emission over time?

Review some recent atmospheric studies of oil/gas methane emissions:

- Airborne/ automobile site-based work synthesized by EDF
- Princeton study
- Penn State airborne work

Outline research needs moving forward

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What's the issue?
Why use atmospheric methods?
Why are there disagreements among methods?

PennState

What's the issue?

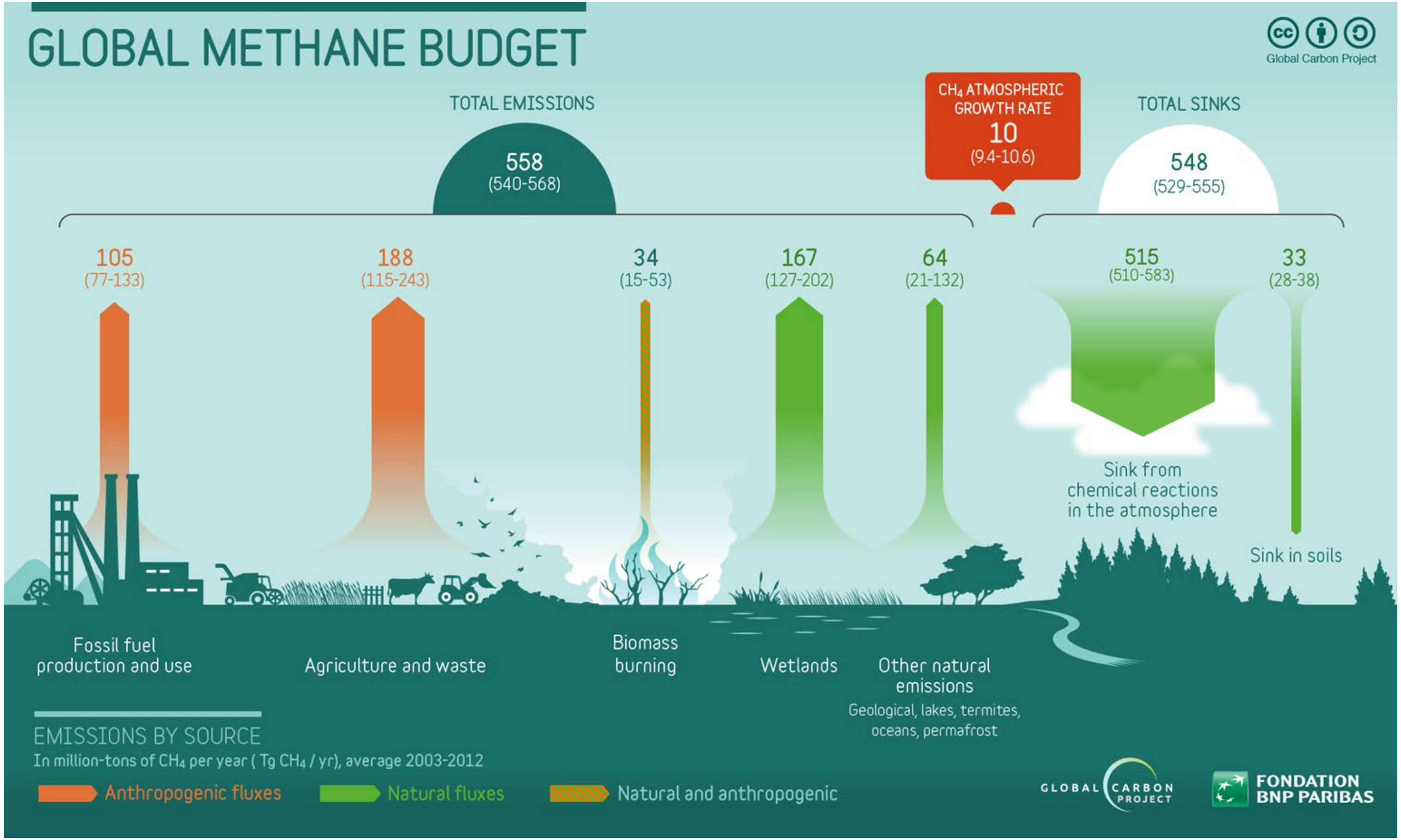
Why use atmospheric methods?

Why are there disagreements among methods?

How do we know methane emissions?
How well do we know methane emissions?

- Our understanding of the *global* methane budget comes from *atmospheric measurements*.
- While the total of global emissions is pretty well known, the uncertainty *by source* or *by region* can be quite large.

We know total global emissions because we know the total amount of methane in the atmosphere. *Not* because we added up all the pieces.



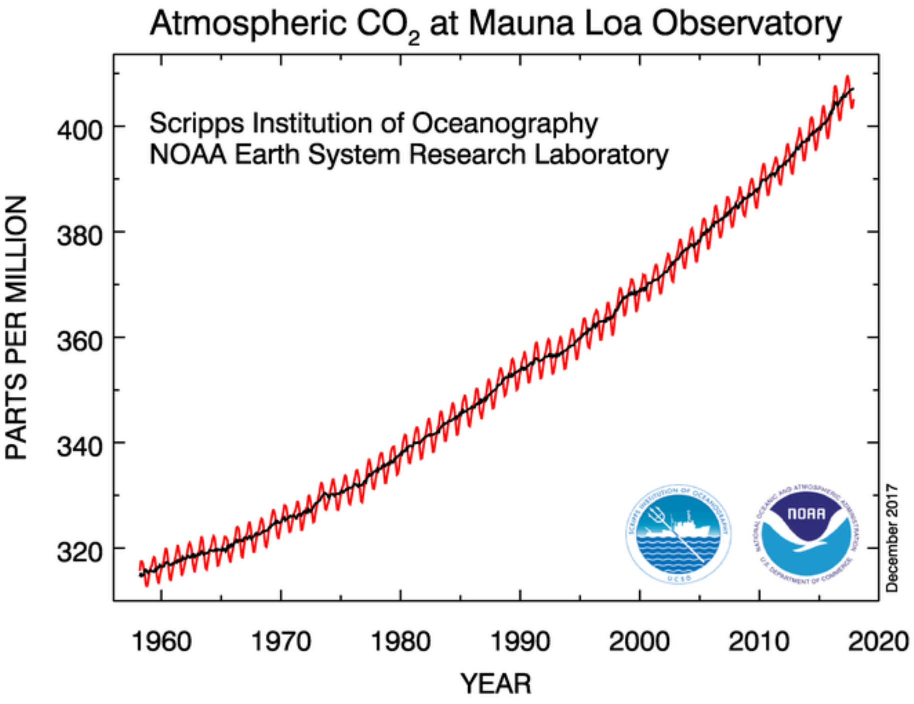
Notes:

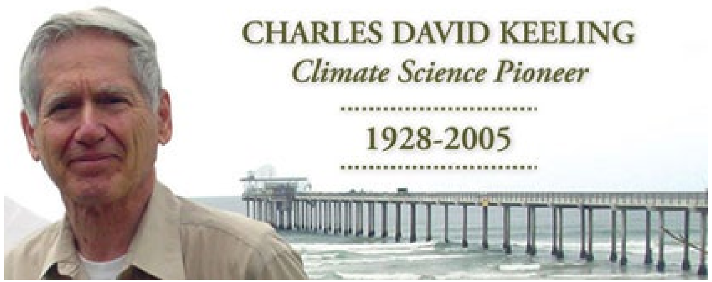
- Multiple significant sources. None is dominant.

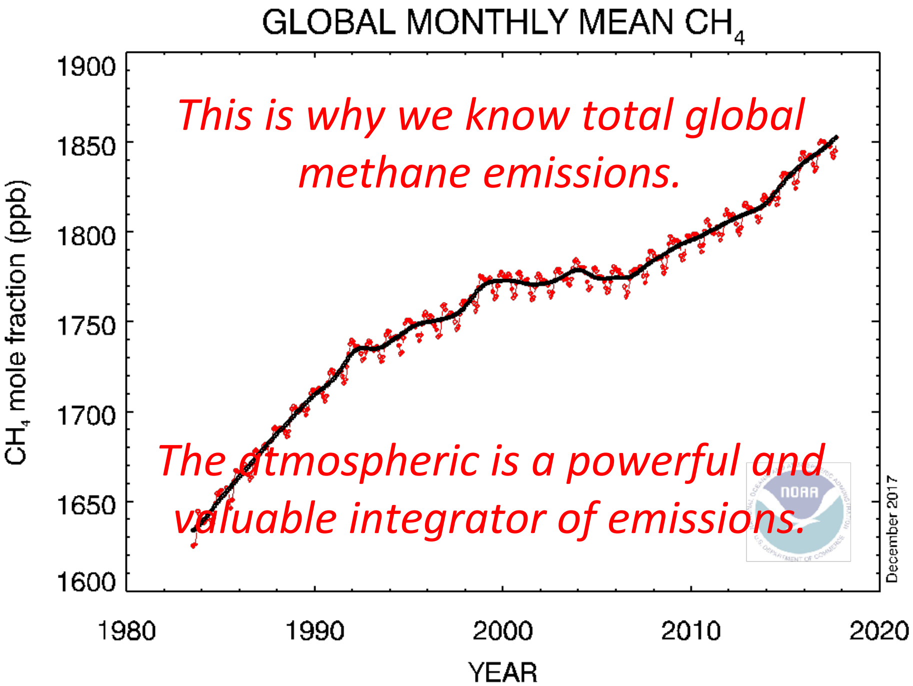
- Large uncertainty bounds. (Why?)

- Units are $TgCH_4$ per year

Global Carbon Project, 2017





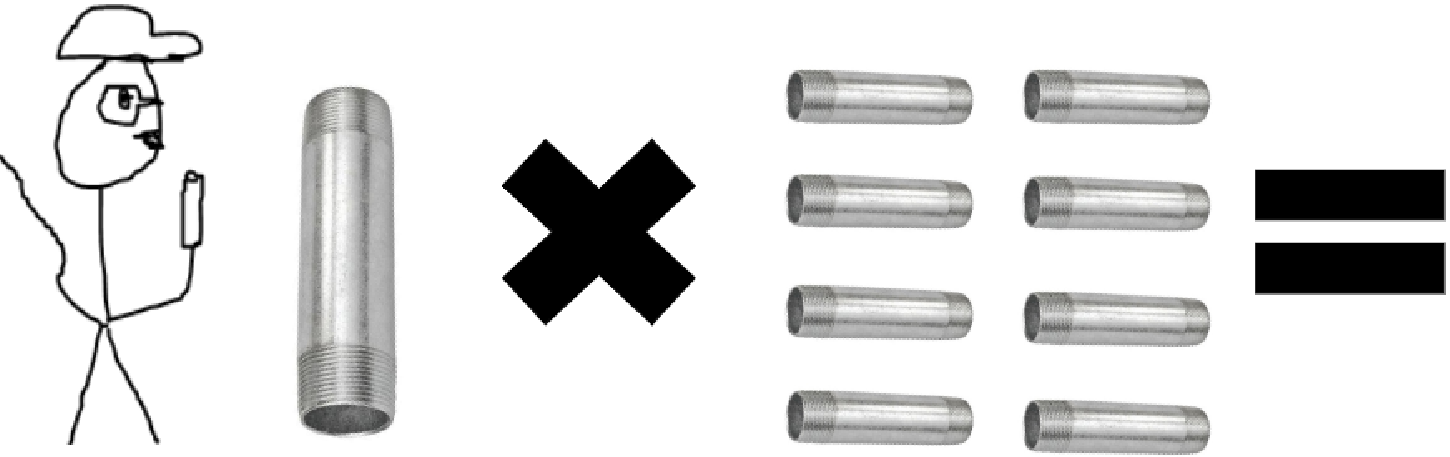


Observations of CO_2 from the top of Mauna Loa, Hawaii.

And observations of methane averaged across the global network.

What's the issue?
Why use atmospheric methods?
Why are there disagreements among methods?

Method 1: Bottom-up Approach



Total Emissions

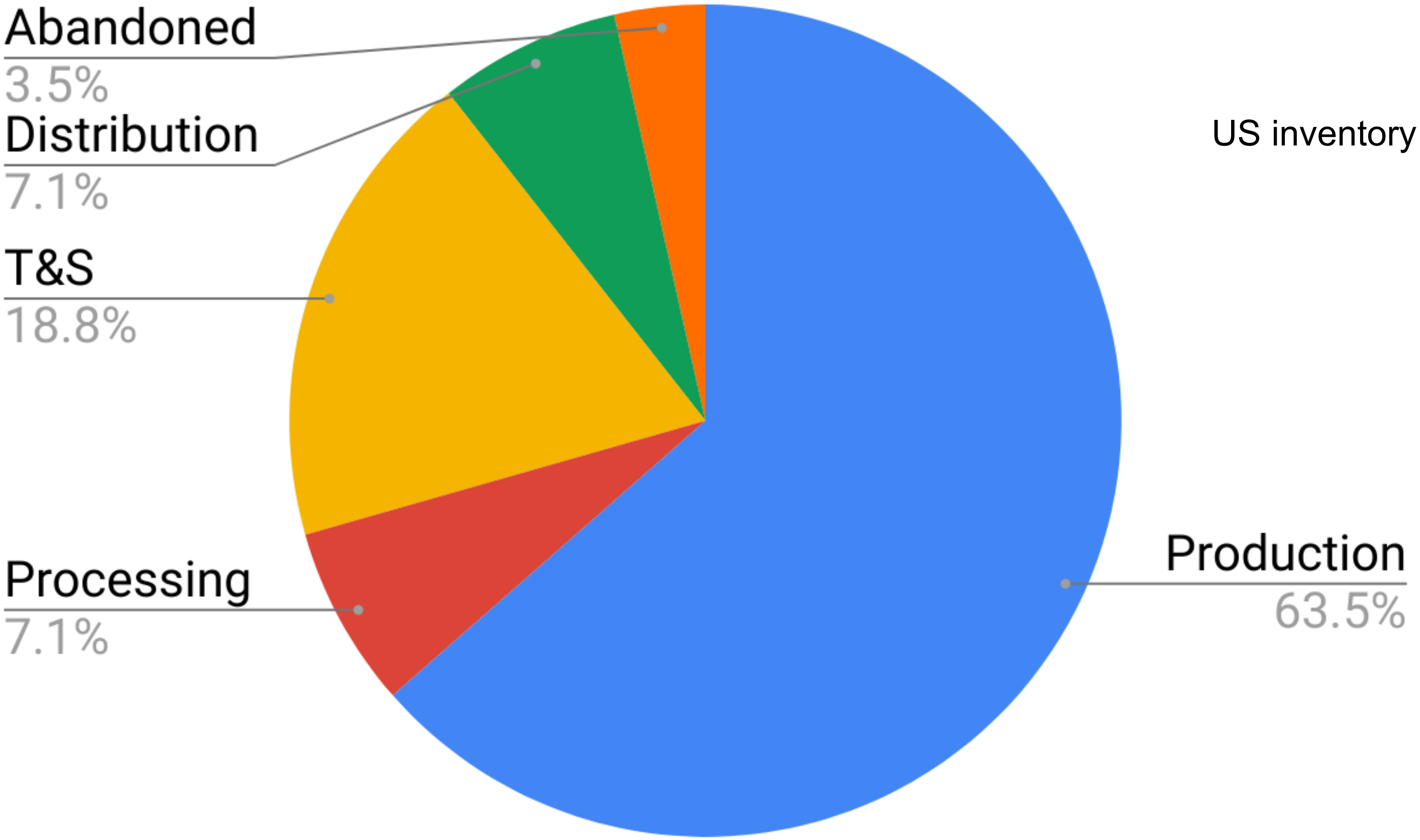
	2014 EPA Inventory Values				
Activity	Activity Data		Emission Factor (Potential)[aa]		Calculated Potential Emissions (Mg)
Fugitives					
Pipeline Leaks	301,748	miles[a]	1.55	scfd/mile[b]	3,296.3

Table A-134: 2014 Data and Calculated CH_4 Potential Emissions (Mg) for the Natural Gas Production Stage

Activity	2014 EPA Inventory Values		
	National Activity Data	National Emission Factor or Range of Regional Values (Potential)[aa]	Calculated Potential (Mg)[bb]
Gas Wells			
Associated Gas Wells	503,873 wells[a,1,cc]	NA[dd]	0.0
Non-associated Gas Wells (less fractured wells)	205,363 wells[a,1]	7.43-42.49 scfd/well[b]	17,754.5
Gas Wells with Hydraulic Fracturing	250,777 wells[a,1]	7.59-42.49 scfd/well[b]	35,085.1
Well Pad Equipment			
Heaters	99,038 heaters[c,d,2]	14.87-67.29 scfd/heater[b]	23,953.4
Separators	306,377 separators[c,d,2]	0.94-142.27 scfd/separator[b]	118,591.2
Dehydrators	17,126 dehydrators[c,d,2]	23.18-106.25 scfd/dehydrator[b]	8,417.5
Meters/Piping	523,885 meters[c,d,2]	9.43-61.68 scfd/meter[b]	107,173.2
Compressors	48,518 compressors[c,d,2]	263.85-312.19 scfd/compressor[b]	96,170.6
Gathering and Boosting			
Gathering and Boosting Stations*	4,999 stations[e,2]	53,066 scfd CH4/station[e]	1,864,870.3
Pipeline Leaks	431,051 miles[f,2]	52.38-61.97 scfd/mile[b]	169,701.4
Drilling, Well Completion, and Well Workover			
Gas Well Completions without Hydraulic Fracturing	767 completions/year[g]	707.23-854.65 scf/completion[b]	11.3
Gas Well Workovers without Hydraulic Fracturing	8,933 workovers/year[a,2]	2,367.7-2,861.3 scf/workover[b]	445.8
Hydraulic Fracturing Completions and Workovers that vent*	1,791 completions and workovers/year[c]	36.82 MT/(completion or workover)[h]	65,940.7
Flared Hydraulic Fracturing Completions and Workovers*	548 completions and workovers/year[c]	4.91 MT/(completion or workover)[h]	2,690.6
Hydraulic Fracturing Completions and Workovers with RECs*	1,043 completions and workovers/year[c]	3.24 MT/(completion or workover)[h]	3,379.6
Hydraulic Fracturing Completions and Workovers with RECs that flare*	1,979 completions and workovers/year[c]	4.88 MT/(completion or workover)[h]	9,653.4
Well Drilling	18,837 wells[i,1]	2,505.9-2,965.0 scf/well[j]	971.6
Normal Operations			
Pneumatic Device Vents*	834,919 controllers[c,d,2]	176.74-209.12 scfd/device[c,d]	1,105,119.0
Pneumatic Device Vents - Low Bleed (LB)	226,280 controllers[c,d,2]	22.52-26.64 scfd/device[c,d]	Aggregated
Pneumatic Device Vents - High Bleed (HB)	29,006 controllers[c,d,2]	612.66-724.91 scfd/device[c,d]	Aggregated
Pneumatic Device Vents - Intermittent Bleed (IB)	579,633 controllers[c,d,2]	215.13-254.55 scfd/device[c,d]	Aggregated
Chemical Injection Pumps*	83,249 active pumps[c,d,2]	208.89-252.30 scfd/pump[c,d]	128,876.5
Kimray Pumps	5,012,753 MMscf/yr[b,2]	977.5-1,156.6 scf/MMscf[b]	100,857.2
Dehydrator Vents	5,625,985 MMscf/yr[b,2]	271.58-321.34 scf/MMscf[b]	31,448.3
Condensate Tank Vents			
Condensate Tanks without Control Devices	139 MMbbl/yr[k,1]	21.87-302.75 scf/bbl[L]	253,092.6
Condensate Tanks with Control Devices*	139 MMbbl/yr[k,1]	4.37-60.55 scf/bbl[l]	50,618.5
Compressor Exhaust Vented			
Gas Engines	51,648 MMHPhr[b,2]	0.237-0.280 scf/HPhr[b]	249,756.3
Well Clean Ups			
Liquids Unloading with Plunger Lifts*	22,477 venting wells[a,m,2]	2,856-1,137,406 scfy/venting well[m]	112,568.8
Liquids Unloading without Plunger Lifts*	37,912 venting wells[a,m,2]	77,891-2,002,960 scfy/venting well[m]	148,075.1
Blowdowns			
Vessel Blowdowns	422,542 vessels[b,2]	76.86-90.94 scfy/vessel[b]	668.5
Pipeline Blowdowns	431,051 miles (gathering)[b,2]	304.49-360.28 scfy/mile[b]	2,702.9
Compressor Blowdowns	48,518 compressors[b,2]	3,719-4,400 scfy/compressor[b]	3,713.8
Compressor Starts	48,518 compressors[b,2]	8,320-9,844 scfy/compressor[b]	8,308.4
Upsets			
Pressure Relief Valves	1,015,507 PRV[b,2]	33.50-39.64 scfy/PRV[b]	700.3
Mishaps	107,763 miles[f,2]	659.24-780.03 scf/mile[b]	1,463.0
Produced Water from Coal Bed Methane Wells			
Black Warrior	5,480 wells[o]	0.0023 kt/well[n,1]	12,790.5
Powder River	20,596,530,150 gal produced water[n]	2.3E-09 kt/gal water drainage[n,1]	47,627.3
Offshore Platforms			
Shallow Water Gas Platforms (Gulf of Mexico and Pacific)	1,973 shallow water gas platforms[p,3]	8,899 scfd/platform[q]	123,460.0

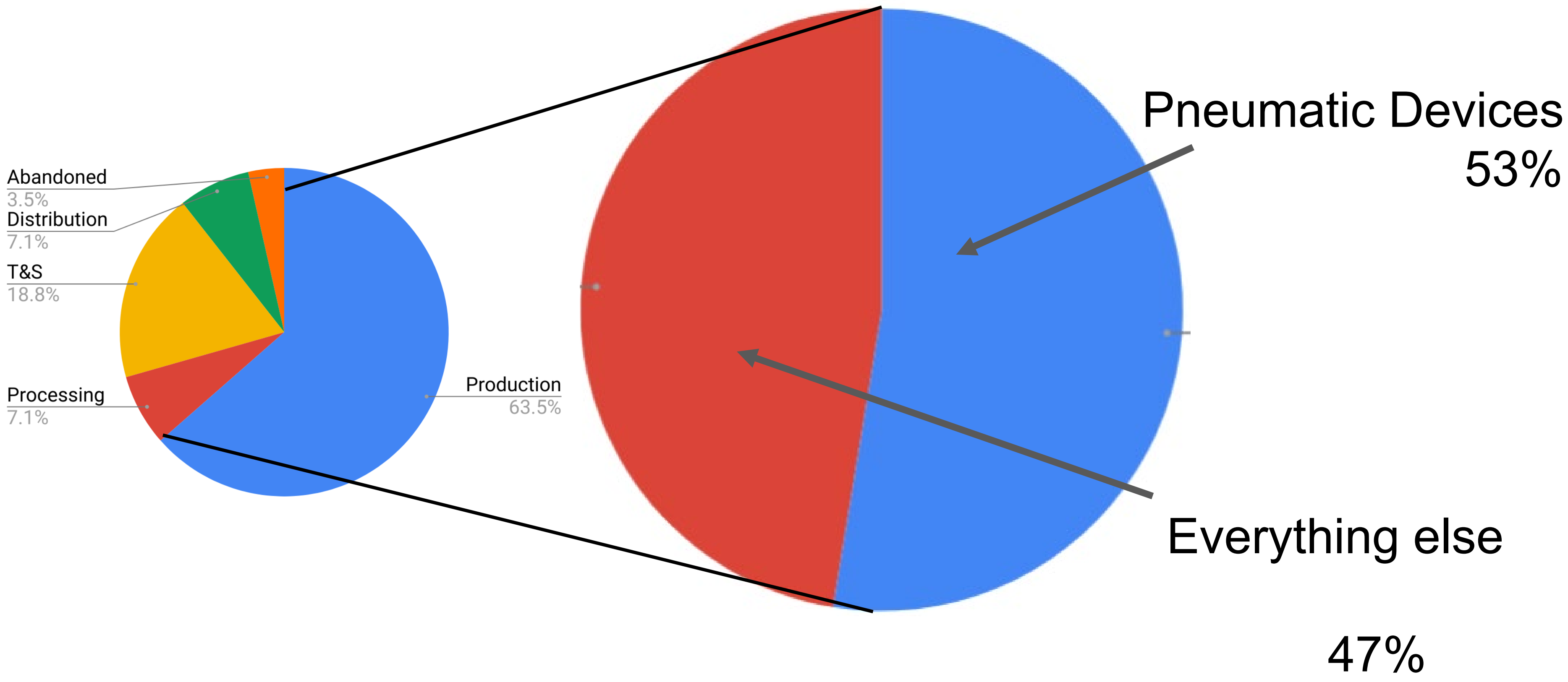
Activity	Activity Data		Emission Factor (Potential)[aa]		Calculated Potential Emissions (Mg)
Fugitives					
Pipeline Leaks	301,748	miles[a]	1.55	scfd/mile[b]	3,296.3
*Compressor Stations (Transmission)**					
Station Total Emissions	1,834	stations[c,d,2]	44,459	scfd/station[c,d,bb]	573,179.2
Station + Compressor Fugitive Emissions	5,221	compressors[c,d,2]	9,104	scfd/station[c,d,bb]	117,370.9
Reciprocating Compressor	2,173	compressors[c,d,2]	9,246	scfd/compressor[c,d,bb]	339,361.9
Centrifugal Compressor (wet seals)	869	compressors[c,d,2]	9,673	scfd/compressor[c,d,bb]	59,092.2
Centrifugal Compressor (dry seals)	1,304	compressors[c,d,2]	6,259	scfd/compressor[c,d,bb]	57,354.2
*Compressor Stations (Storage)**					
Station Total Emissions	356	stations[c,d,2]	52,604	scfd/station[c,d,bb]	131,647.9
Station + Compressor Fugitive Emissions	356	stations[c,d,2]	10,100	scfd/station[c,d,bb]	25,276.0
Reciprocating Compressor	1,520	compressors[c,d,2]	9,957	scfd/compressor[c,d,bb]	106,371.9
Wells (Storage)	19,522	wells[b,2]	114.50	scfd/well[b]	15,714.0
M&R (Trans. Co. Interconnect)	2,686	stations[e,2]	3,984	scfd/station[b]	75,230.0
M&R (Farm Taps + Direct Sales)	79,646	stations[e,2]	31.20	scfd/station[b]	17,468.9
Normal Operation					
Dehydrator vents (Transmission)	1,169,007	MMscf/yr[b,2]	93.72	scf/MMscf[b]	2,110.1
Dehydrator vents (Storage)	2,169,267	MMscf/yr[b,2]	117.18	scf/MMscf[b]	4,895.8
Compressor Exhaust					
Engines (Transmission)	53,295	MMHPhr[b,2]	0.24	scf/HPhr[b]	246,351.2
Turbines (Transmission)	12,717	MMHPhr[b,2]	0.01	scf/HPhr[b]	1,396.1
Engines (Storage)	5,339	MMHPhr[b,2]	0.24	scf/HPhr[b]	24,677.0
Turbines (Storage)	1,875	MMHPhr[b,2]	0.01	scf/HPhr[b]	205.9
Generators (Engines)	2,608	MMHPhr[b,2]	0.24	scf/HPhr[b]	12,055.2
Generators (Turbines)	31	MMHPhr[b,2]	0.01	scf/HPhr[b]	3.4
*Pneumatic Devices Trans + Stor**					
Pneumatic Devices Transmission	47,140	devices[c,d,2]	30,611	scfy/device[c,d,bb]	27,792.1
(High Bleed)	4,129	devices[c,d,2]	151,969	scfy/device[c,d,bb]	12,085.2
(Intermittent Bleed)	39,216	devices[c,d,2]	19,712	scfy/device[c,d,bb]	14,888.7
(Low Bleed)	3,795	devices[c,d,2]	11,196	scfy/device[c,d,bb]	818.2
Pneumatic Devices Storage	23,964	devices[c,d,2]	63,622	scfy/device[c,d,bb]	29,364.5
(High Bleed)	8,379	devices[c,d,2]	147,983	scfy/device[c,d,bb]	23,882.0
(Intermittent Bleed)	13,482	devices[c,d,2]	19,333	scfy/device[c,d,bb]	5,020.1
(Low Bleed)	2,103	devices[c,d,2]	11,414	scfy/device[c,d,bb]	462.3
Routine Maintenance/Upsets					
Pipeline venting	301,748	miles[a,1]	31.65	Mscfy/mile[b]	183,939.2
Station venting Trans + Storage					
Station Venting Transmission	1,834	compressor stations[c,d,2]	4,359	Mscfy/station[b]	153,965.5
Station Venting Storage	356	compressor stations[c,d,2]	4,359	Mscfy/station[b]	29,887.7
LNG Storage					
LNG Stations	70	stations[f,g,3]	21,507	scfd/station[b]	10,622.8
LNG Reciprocating Compressors	270	compressors[f,g,3]	21,116	scfd/compressor[b]	40,146.5
LNG Centrifugal Compressors	64	compressors[f,g,3]	30,573	scfd/compressor[b]	13,766.0
LNG Compressor Exhaust					
LNG Engines	579	MMHPhr[f,g,3]	0.24	scf/HPhr[b]	2,677.7
LNG Turbines	113	MMHPhr[f,g,3]	0.01	scf/HPhr[b]	12.4
LNG Station venting	70	stations[f,g,3]	4,359	Mscfy/station[b]	5,898.6
LNG Import Terminals					
LNG Stations	8	stations[f,g,3]	21,507	scfd/station[b]	1,270.0
LNG Reciprocating Compressors	41	compressors[f,g,3]	21,116	scfd/compressor[b]	6,056.5
LNG Centrifugal Compressors	7	compressors[f,g,3]	30,573	scfd/compressor[b]	1,547.5
LNG Compressor Exhaust					
LNG Engines	303	MMHPhr[f,g,3]	0.24	scf/HPhr[b]	1,401.7

Emissions are primarily from the production sector



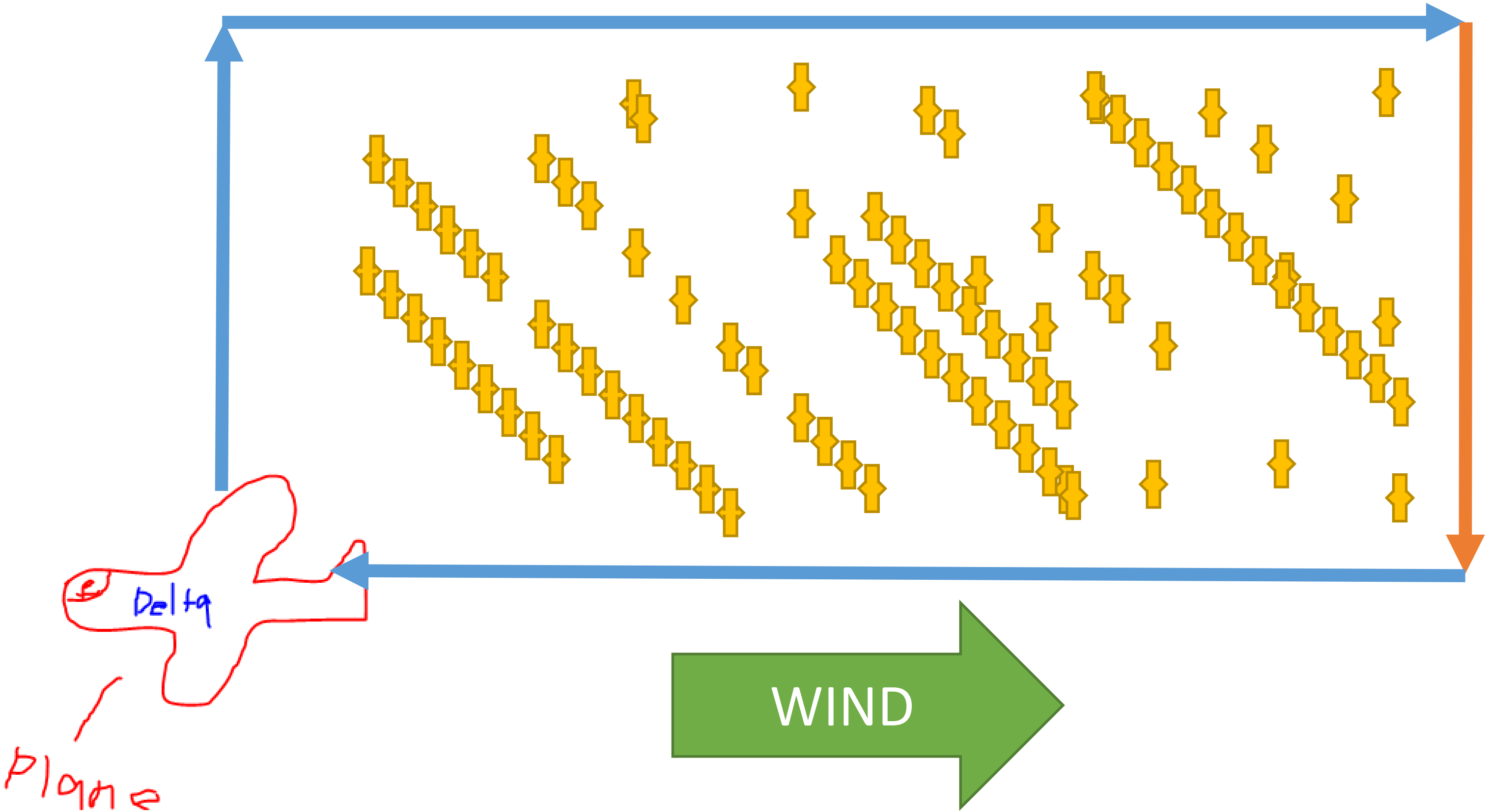
US inventory for 2014.

US inventory for 2014.



Method 2: Atmospheric mass-balance

$$FLUX = \bar{U}cos(\bar{\theta}) \int_{-b}^{b} \Delta X \int_{z=0}^{z_{top}} n_{air} dzdx$$



There are many ways to treat the data, but in the end all atmospheric methods boil down to an atmospheric mass balance problem.

Major studies reveal 60% more methane emissions

In Pennsylvania, Methane Emissions Higher Than EPA Estimates

EPA's Greenhouse Gas Inventory needs some fixing

U.S. Cities Might Release More Methane Than Previously Thought

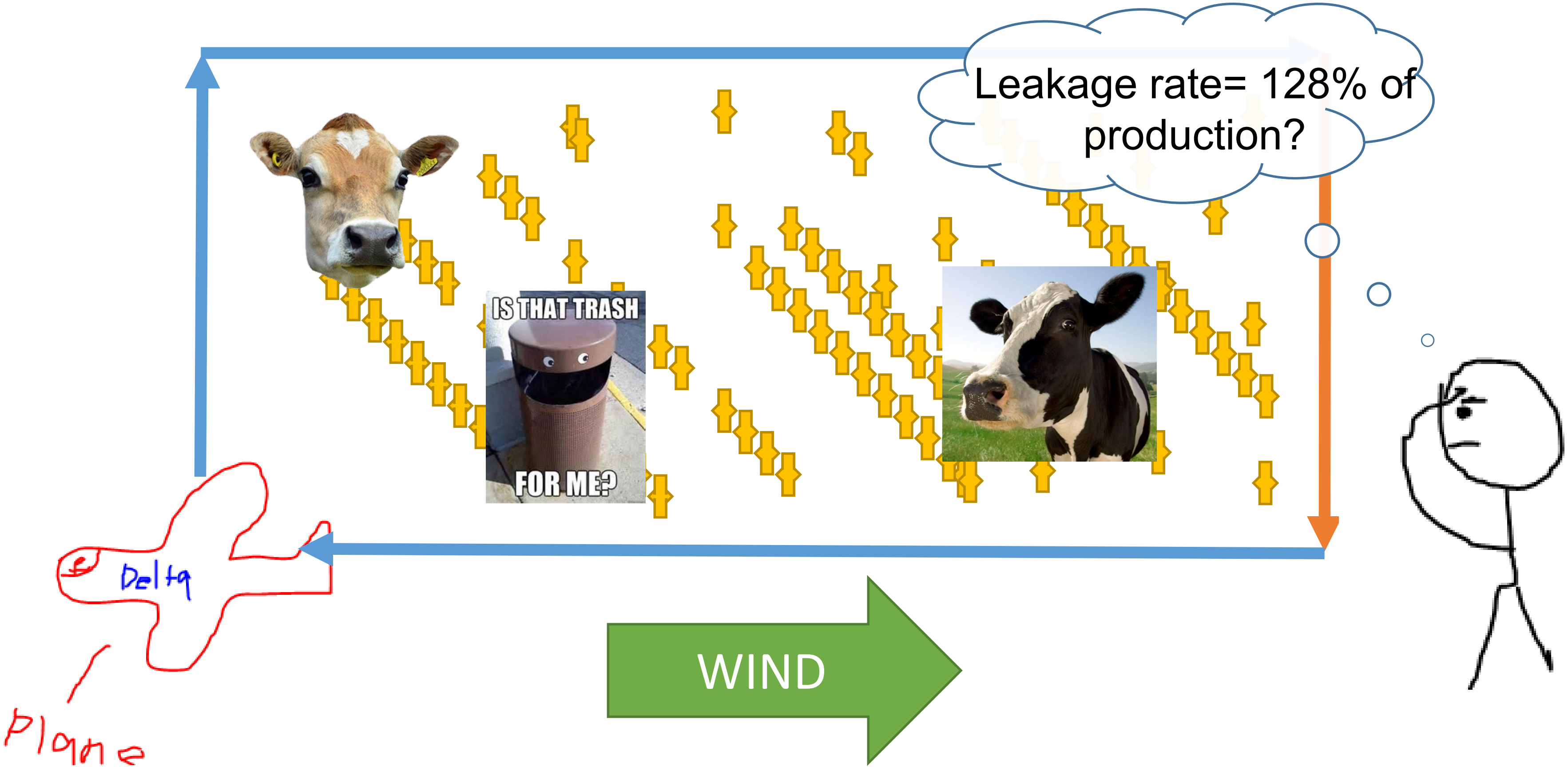
PennState

What's the issue?

Why use atmospheric methods?

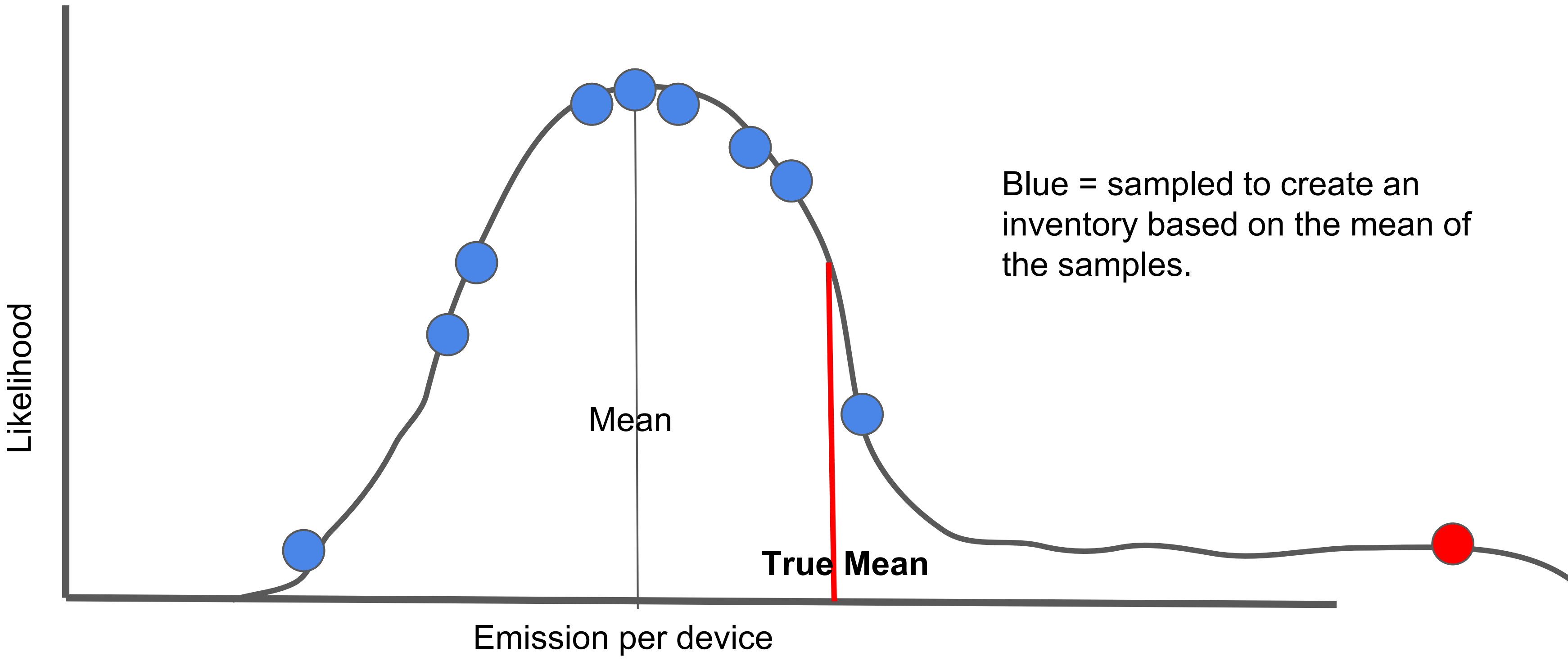
Why are there disagreements among methods?

What could be wrong with the top-down approach?



What could be wrong with the inventory approach?

What if one rare malfunction emits more than 100 working devices?



Blue = sampled to create an inventory based on the mean of the samples.


Top-down Approach
The CH_4 enhancement is 34ppb with a wind speed of 3m/s and an ABL depth of 1.3km. Total emissions in this region= **241kg/hr**
This well is emitting 25kg/hr
There's 5 wells in the basin
Total emissions in this region=5*35=**125kg/hr**
Bottom-Up Approach


Top-down Approach
That bottom-up estimate is too low! They probably didn't account for any extreme emissions!
That top-down estimate is too high! They probably forgot to account for the cows
Bottom-Up Approach

Other possible sources of differences

Source category missing from the inventory

Incomplete sampling of emissions over time

- Can be an issue with either approach

Imperfect knowledge of atmospheric flow

- Can also be a problem with either approach

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Extrapolation estimate: Pneumatic devices

Inventory: Allen et al (2013) sampled ~300 of them for about one hour each.
Total: 60,000 of them operating for 5 years.
Sample / Total = 300 device-hours / 60,000*365*24*5 device hours = 1×10^{-7}.

Extrapolation by a factor of 10,000,000.

Airborne work: Aircraft samples of 20,000 devices for 10 hours each (mixed in with many other devices, of course).
Sample / Total = 200,000 device-hours / large number above = 1×10^{-4}.

About 1,000 times more data coverage. (with associated complications of many colocated sources)

Outline

Introduction to the challenges of *complementary* methods.

My point of view:
It is very difficult to measure total emissions of methane from a complex national network of small leaks.

We have a stronger understanding when we search for consistency across methods that have complementary strengths.

Our current national methane emissions inventory is NOT consistent with atmospheric measurements.

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Review some recent atmospheric studies of oil/gas methane emissions:

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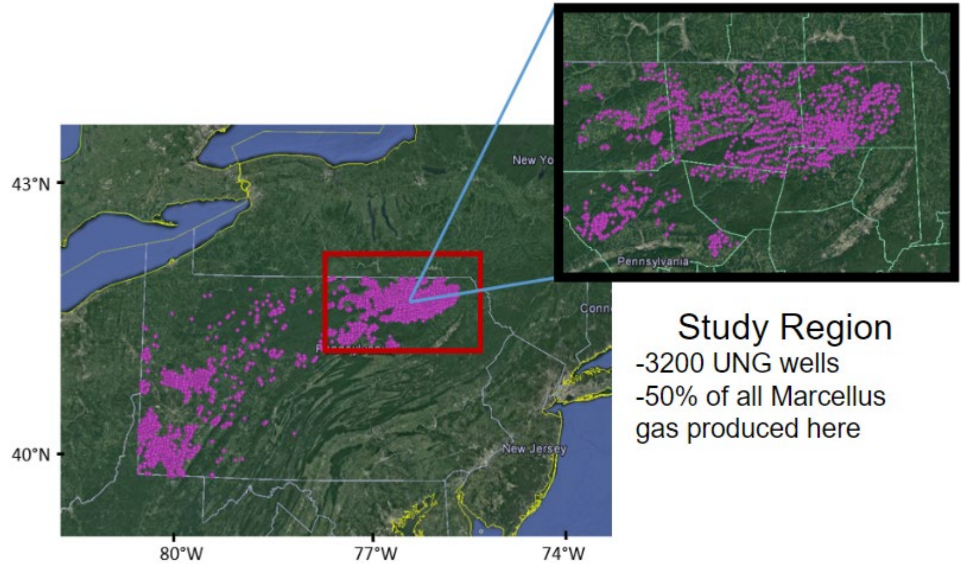
Outline research needs moving forward

Time to deploy the grad student

The Marcellus Study:



Objective: To quantify natural gas emissions from production in the northeastern Marcellus region

ADVANTAGES

1. Despite having only 3000 wells, 10% of all natural gas in the US is produced in northeast Pennsylvania (NEPA)

1. There's nothing else nearby, making it easy to interpret what we're measuring (or is it).

1. Dad lives in region and is a source of cheap labor to fix science instrumentation (i.e. restart router)

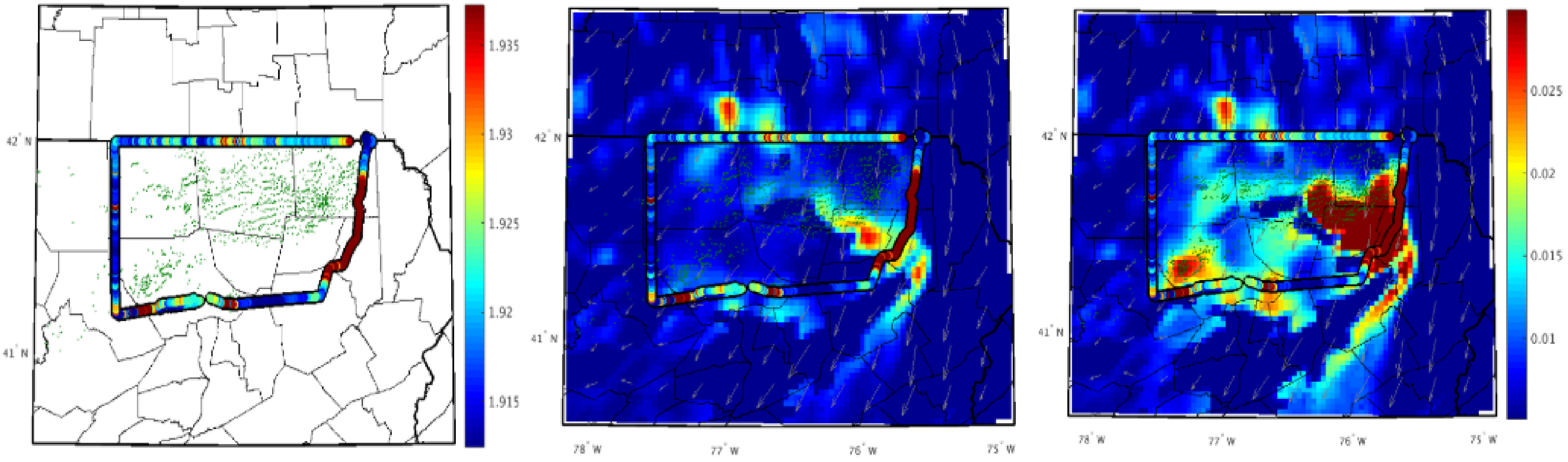
Barkley et al., ACP, 2017

Deriving Natural Gas Emissions: 3 Steps

Get methane observations

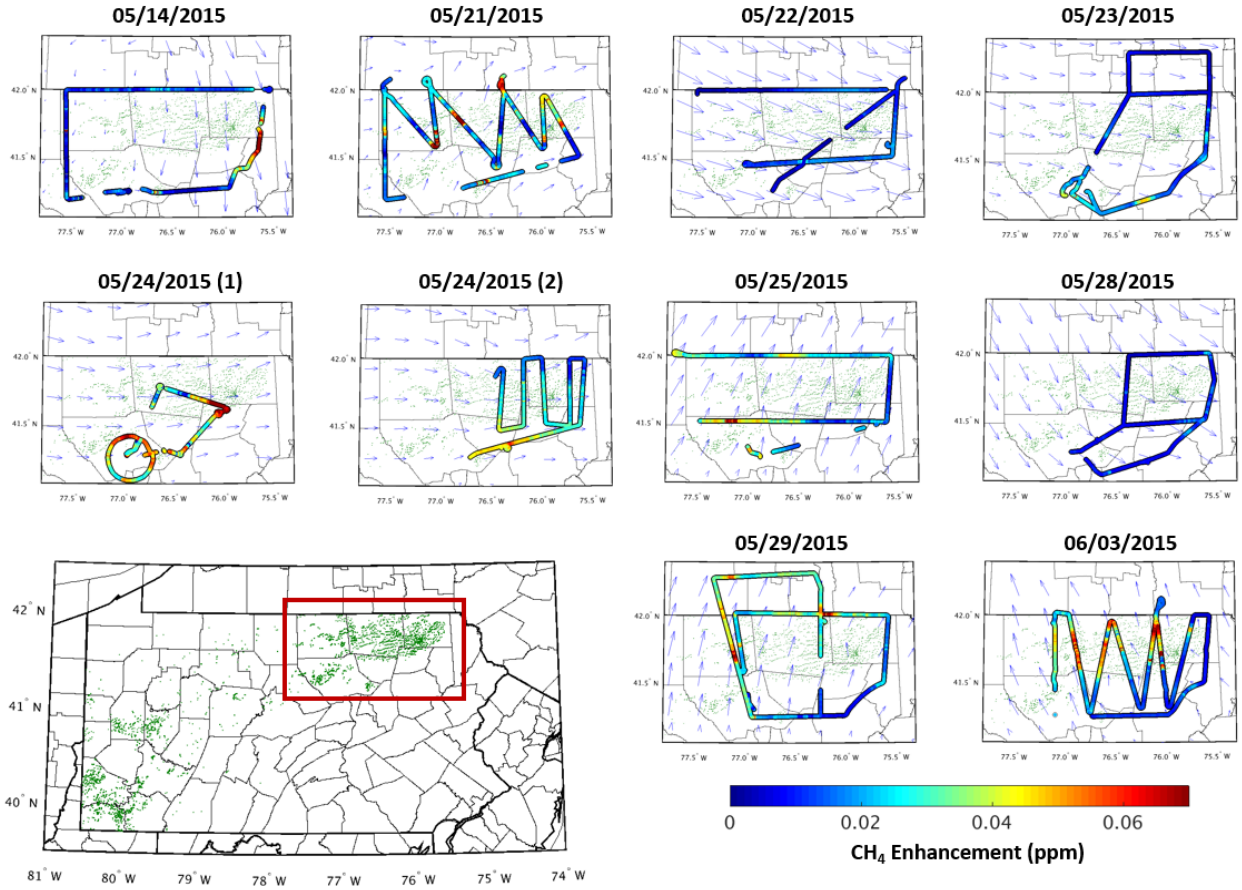
Model methane enhancements

Optimize natural gas emissions



Barkley et al., ACP, 2017

Step 1: Measure methane in Northeast PA

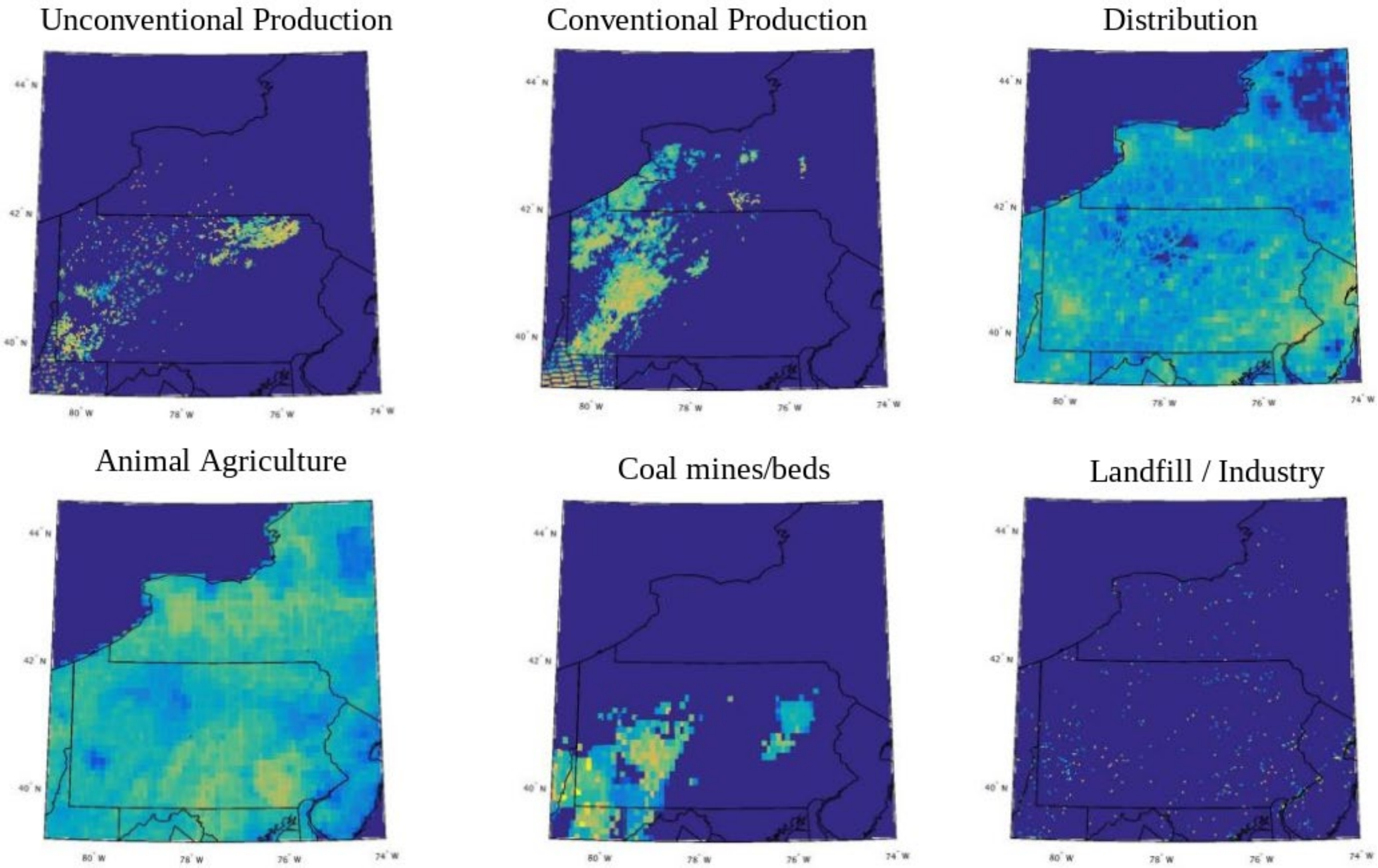


Barkley et al., ACP, 2017

10 flights

Step 2: Model Methane Enhancements

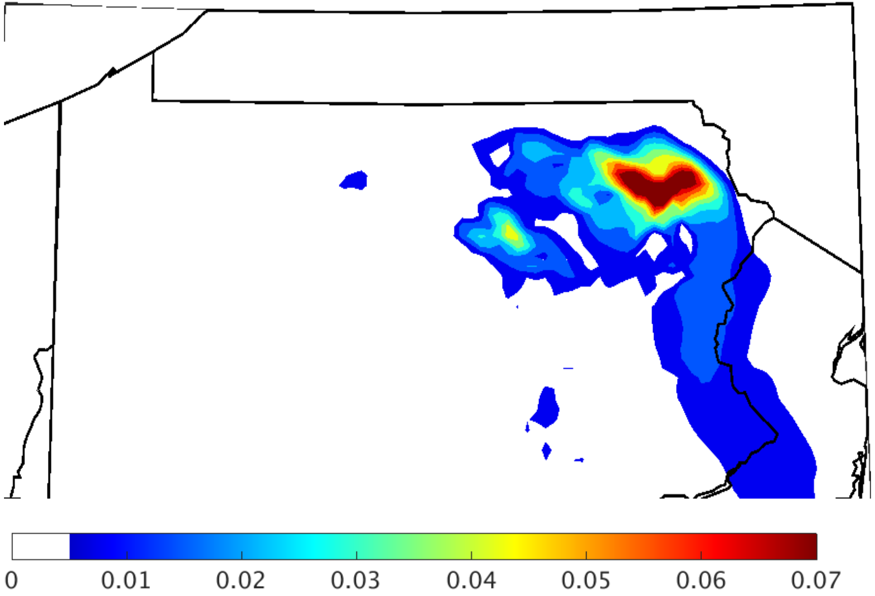
CH_4 Emissions Inventory



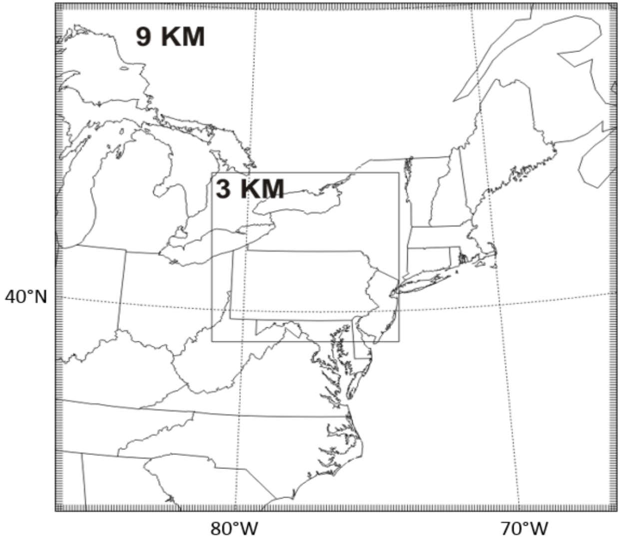
Barkley et al., ACP, 2017

Step 2: Model Methane Enhancements

-Use Weather Research and Forecasting Model (WRF-Chem) to model methane emissions throughout region at 3 km resolution

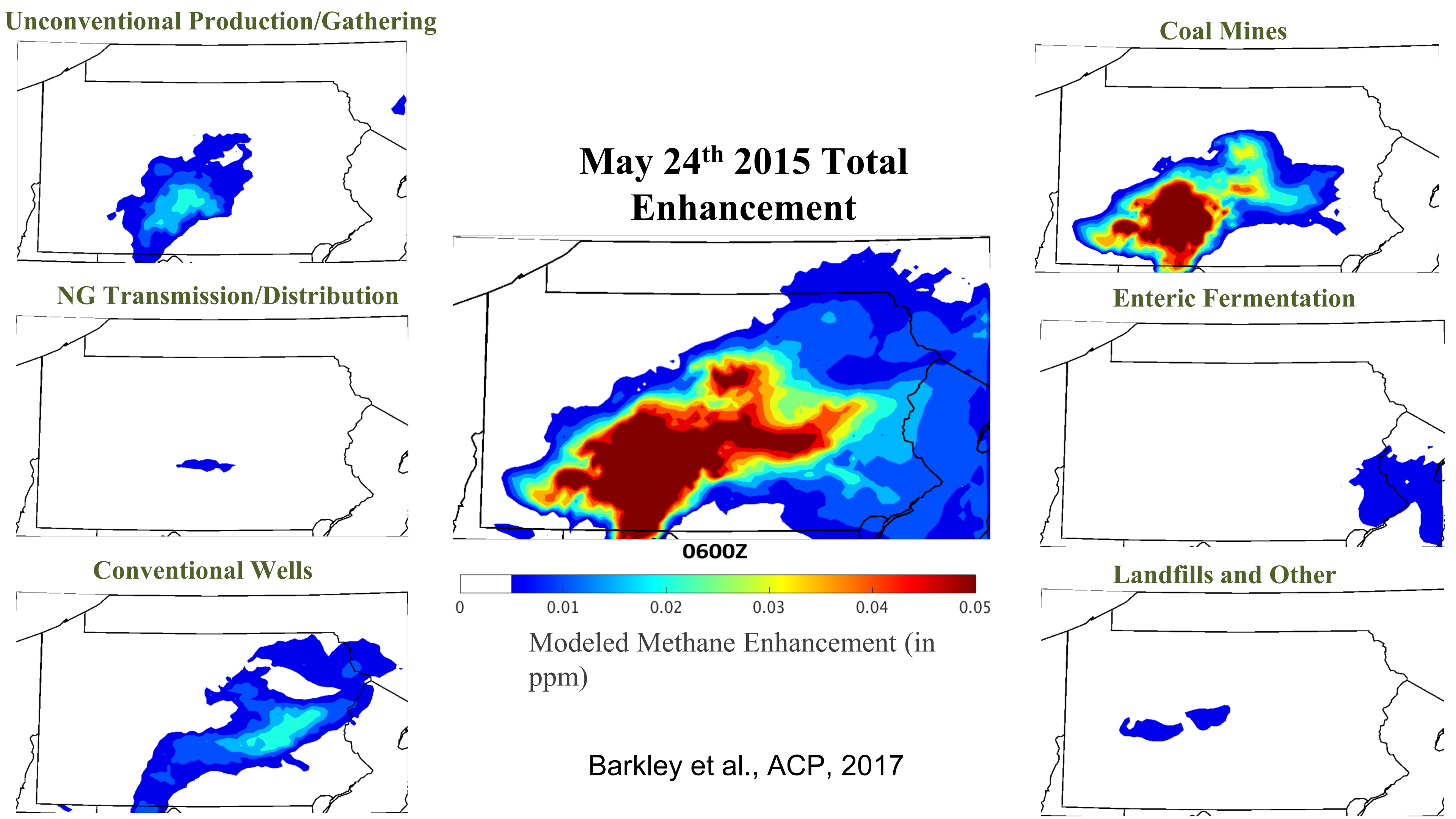


CH_4 Enhancement (ppb)



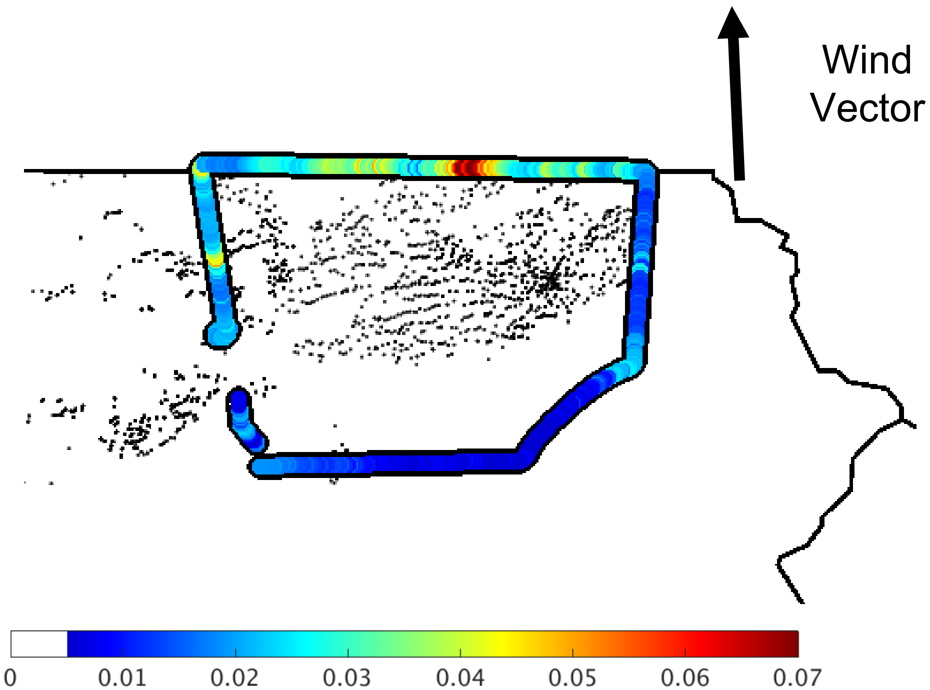
Modeling domain to simulate the atmospheric conditions during the deployment period (2015-2017) WRF

Barkley et al., ACP, 2017


Unconventional Production/Gathering
NG Transmission/Distribution
Conventional Wells
May 24th 2015 Total Enhancement
0600Z
0
0.01
0.02
0.03
0.04
0.05
Modeled Methane Enhancement (in ppm)
Barkley et al., ACP, 2017
Coal Mines
Enteric Fermentation
Landfills and Other

Step 3: Optimize Natural Gas Emissions

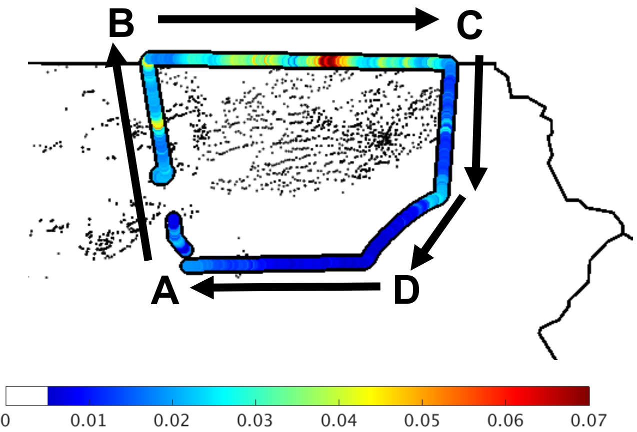
May 29th 2015:



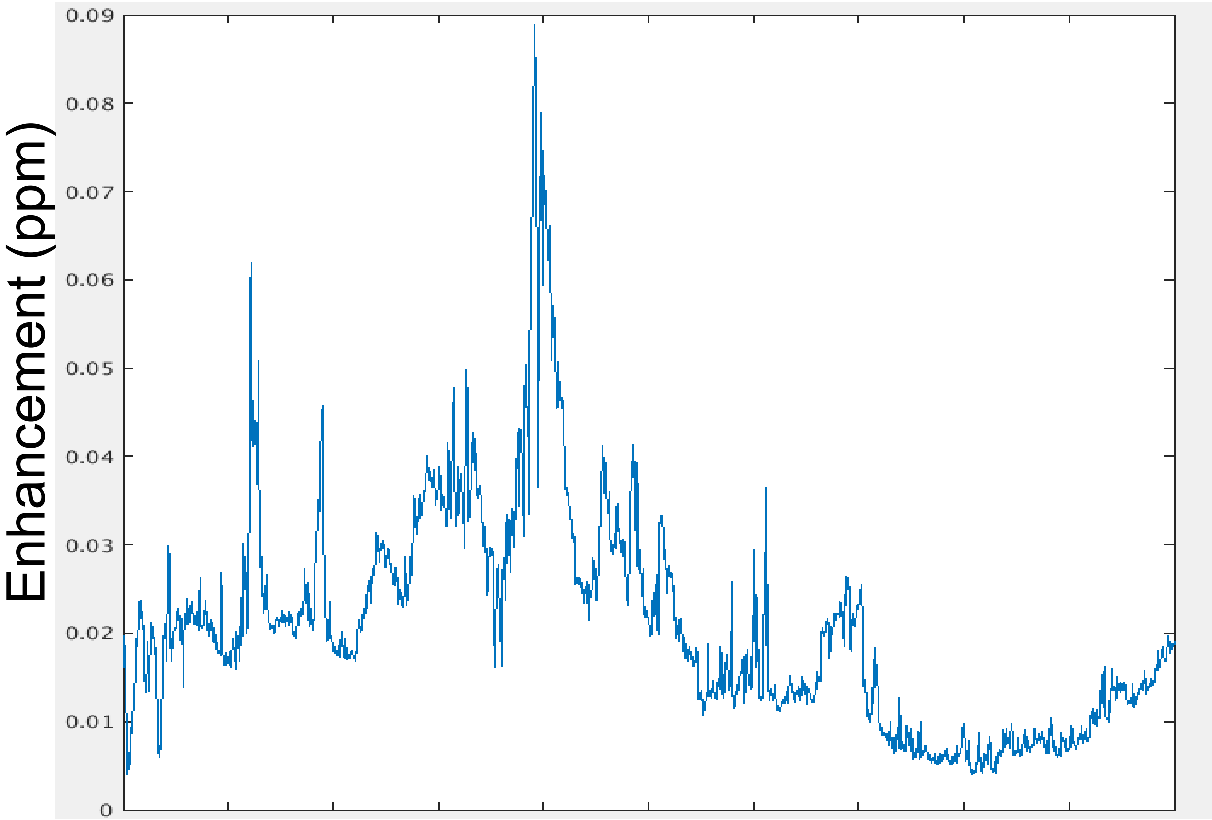
Atmospheric CH_4 enhancement (in ppm)

Barkley et al., ACP, 2017

Aircraft emissions estimate on May 29th 2015



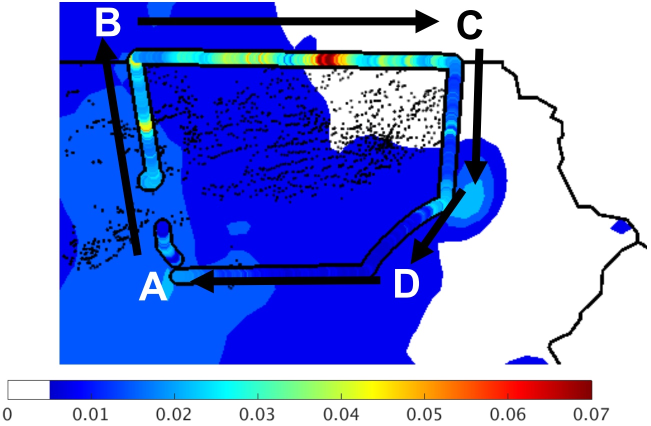
Observed CH_4 Enhancement (ppm)



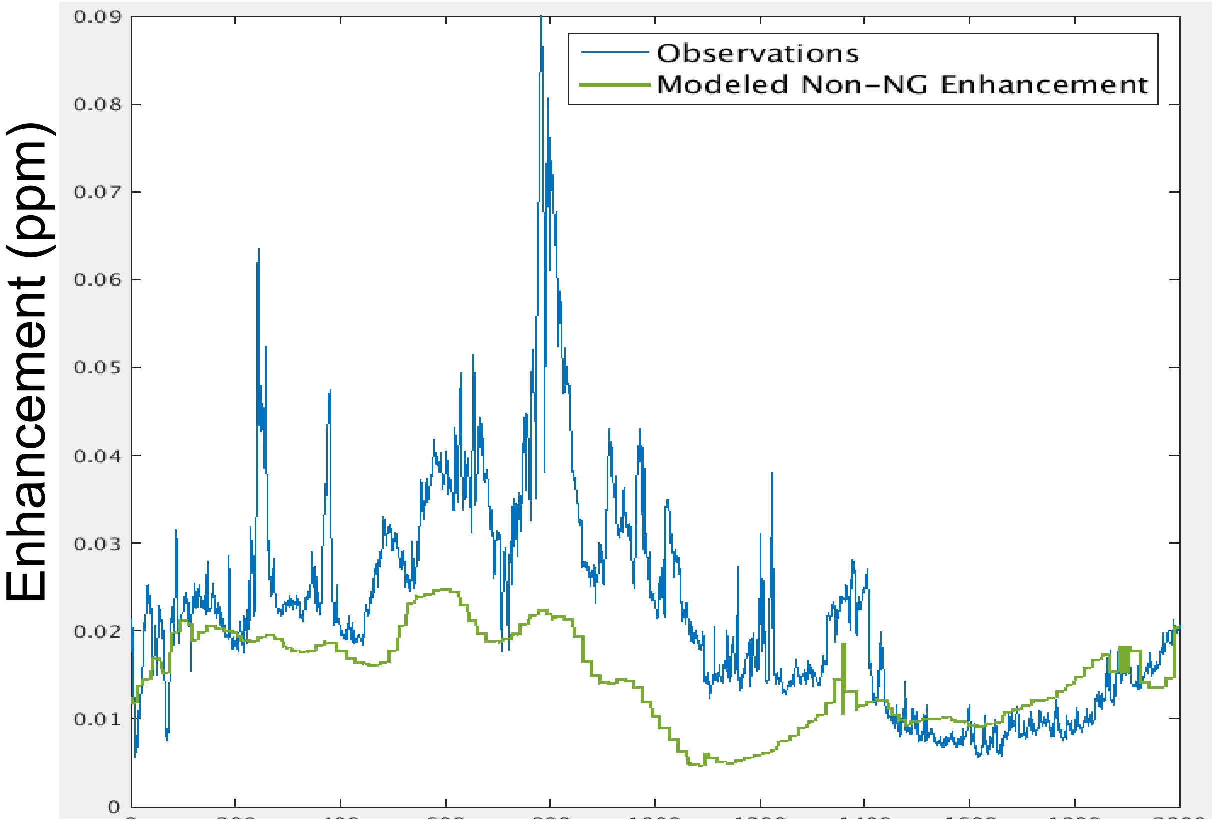
Barkley et al., ACP, 2017

Observed CH_4 Enhancement measured during the flight (in ppm)

Aircraft emissions estimate on May 29th 2015

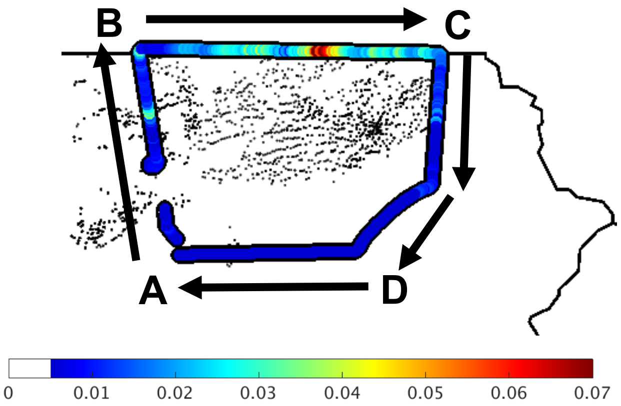


Barkley et al., ACP, 2017



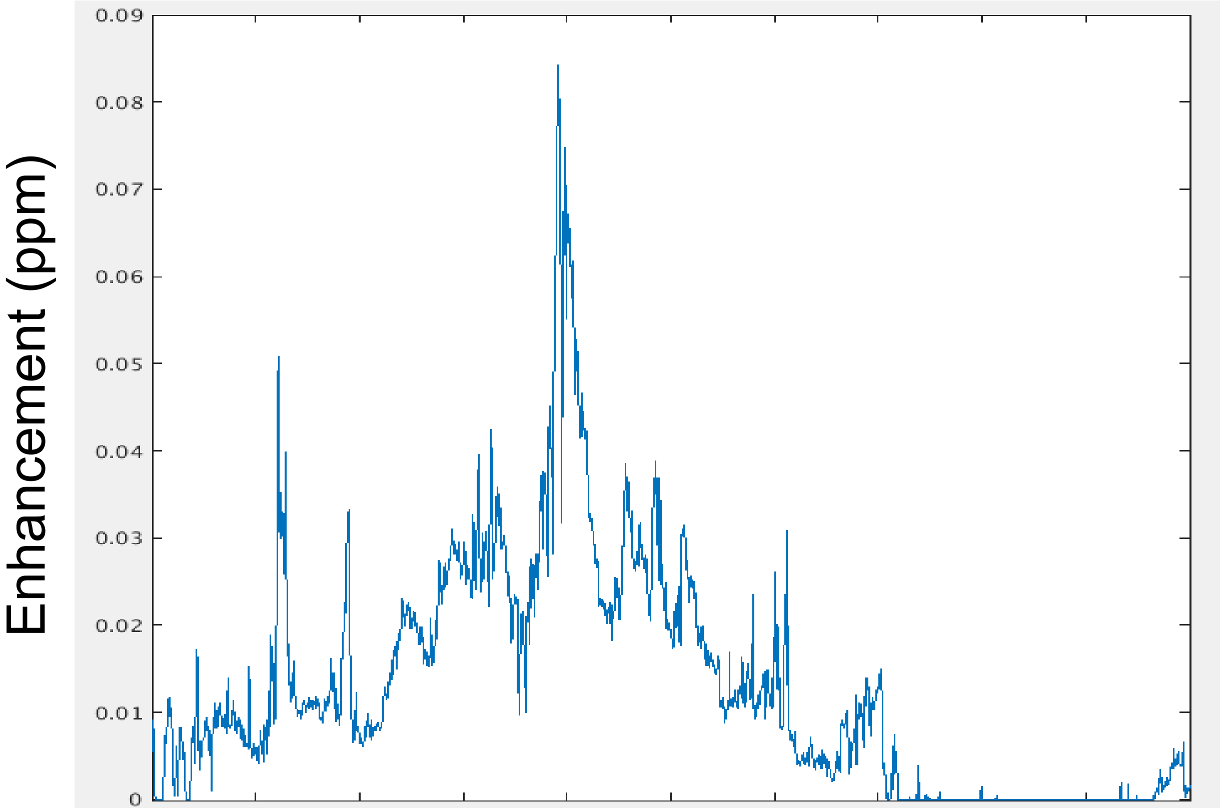
Observed and modeled Non-Natural Gas CH_4 enhancement for the May 29th flight (in ppm)

Aircraft emissions estimate on May 29th 2015



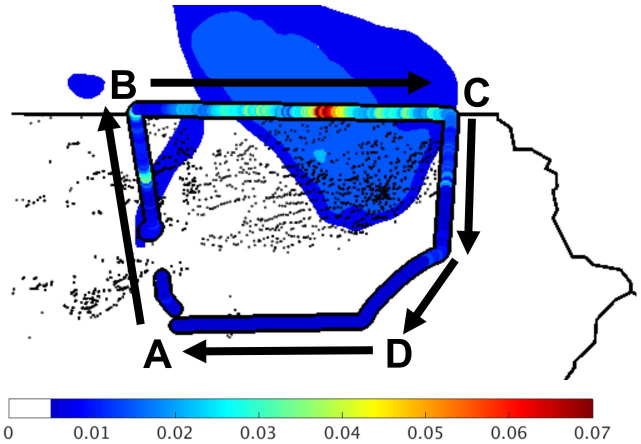
Natural Gas CH_4 Enhancement (ppm)

Barkley et al., ACP, 2017



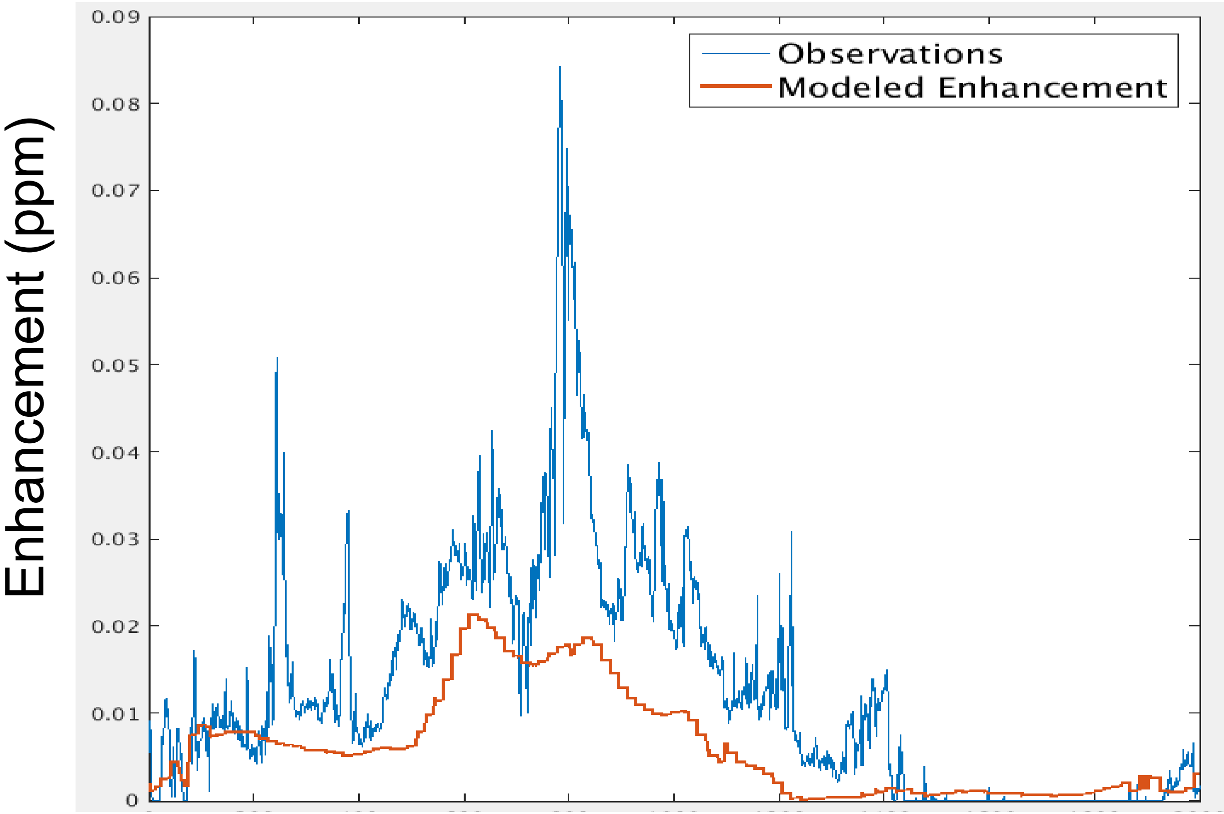
Observation-derived natural gas CH_4 enhancement for the May 29th flight (in ppm)

Aircraft emissions estimate on May 29th 2015



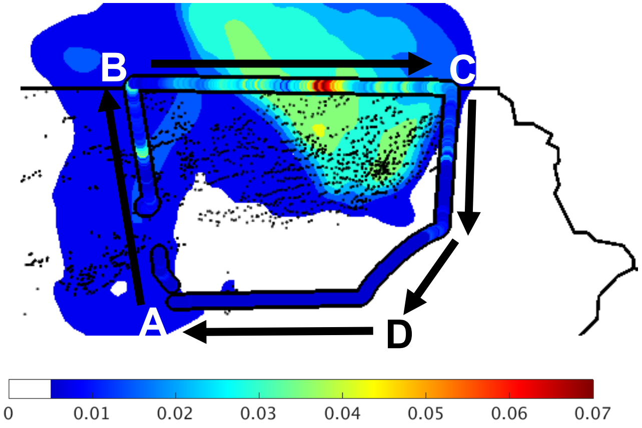
Natural Gas CH_4 Enhancement (ppm)
Emission Rate = **0.13%**

Barkley et al., ACP, 2017



Observed and modeled Natural Gas CH_4 Enhancement for the May 29th flight (in ppm)

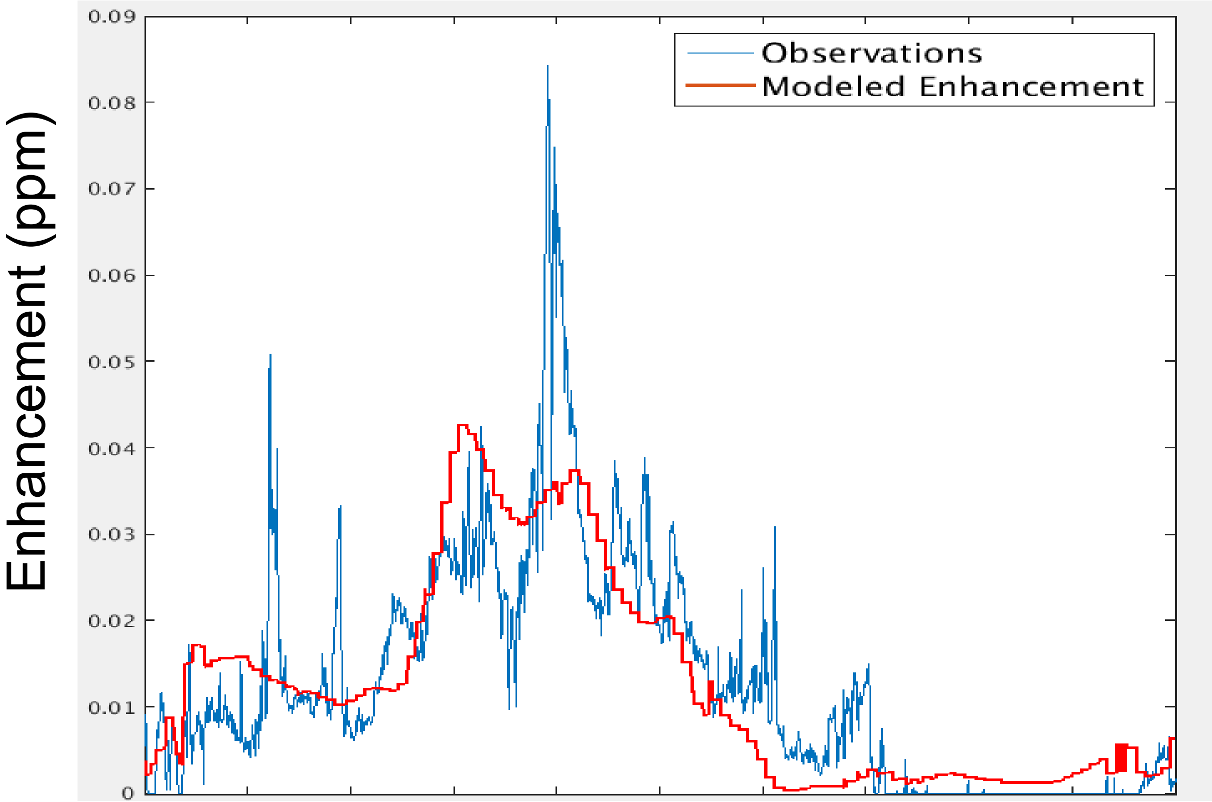
Aircraft emissions estimate on May 29th 2015



Natural Gas CH_4 Enhancement (ppm)

Emission Rate = **0.26%**

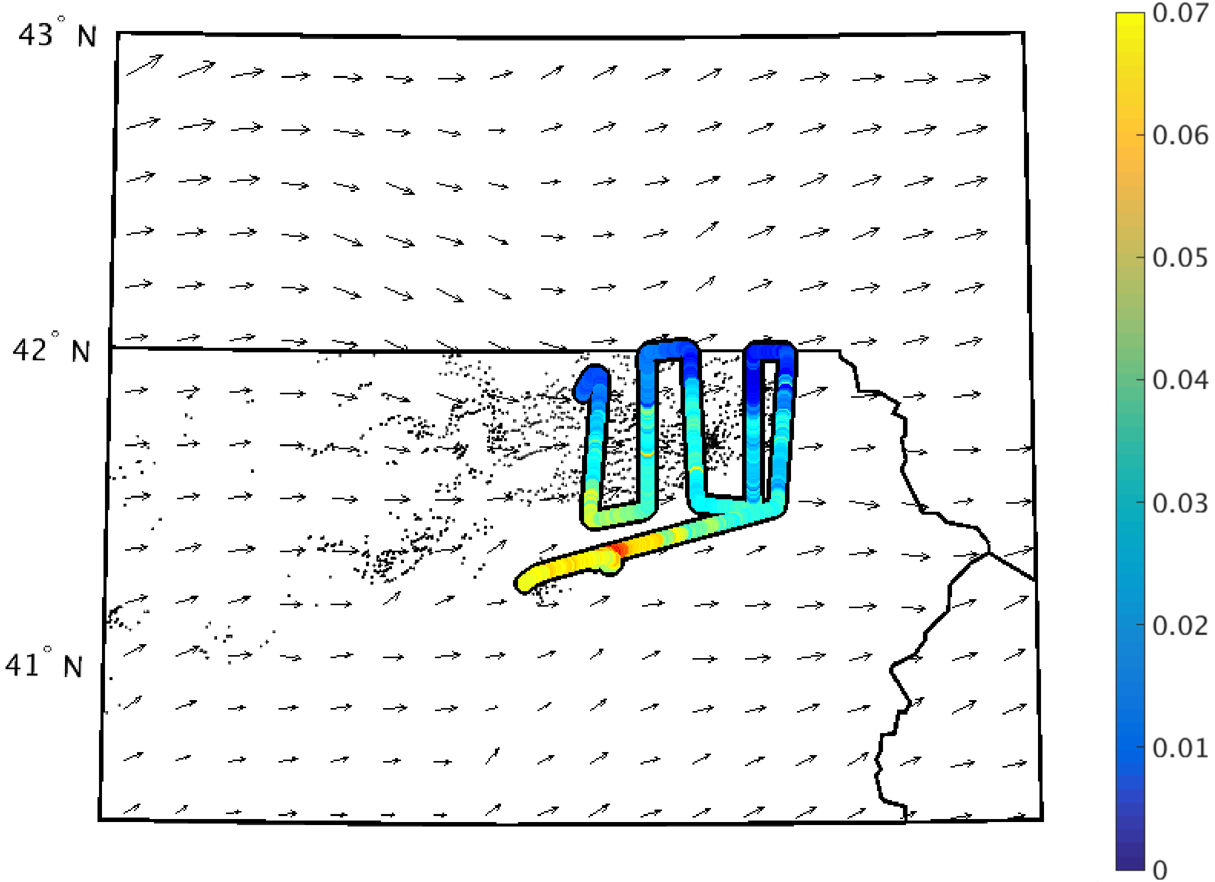
Barkley et al., ACP, 2017



Observed and optimized Natural Gas CH_4 enhancement for the May 29th flight (in ppm)

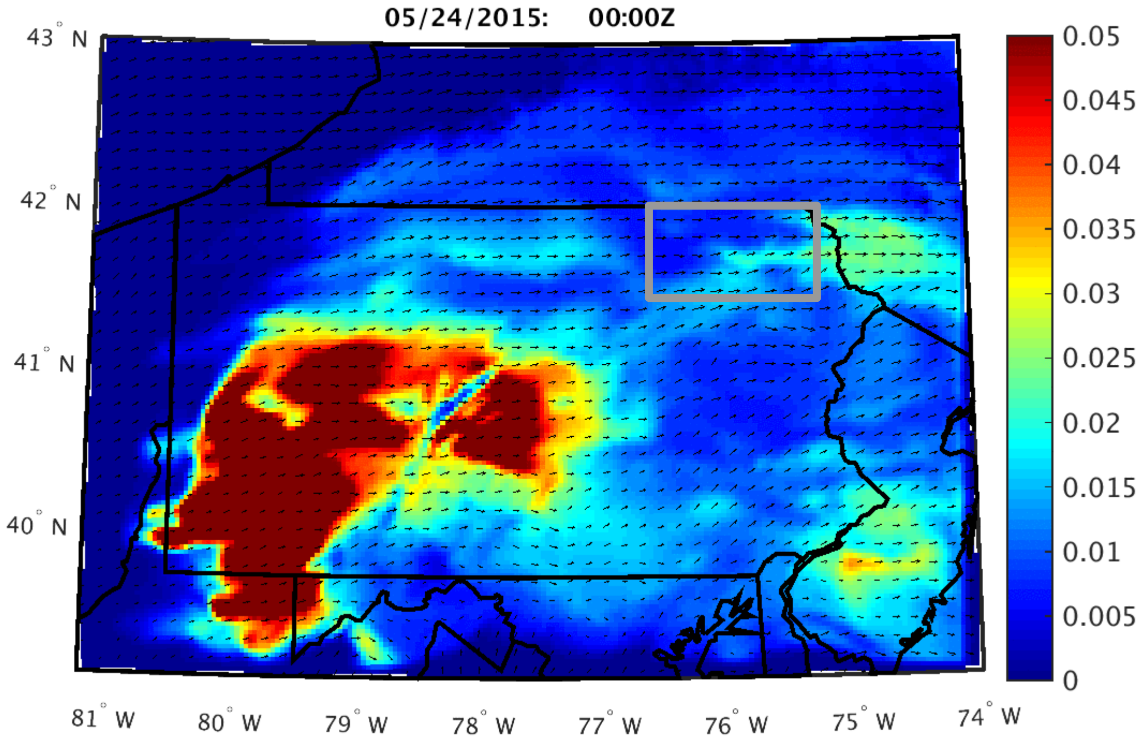
EXAMPLE 2: MAY 24^{th}, 2015
The utility of a model-based approach

Aircraft emissions estimate on May 24th 2015



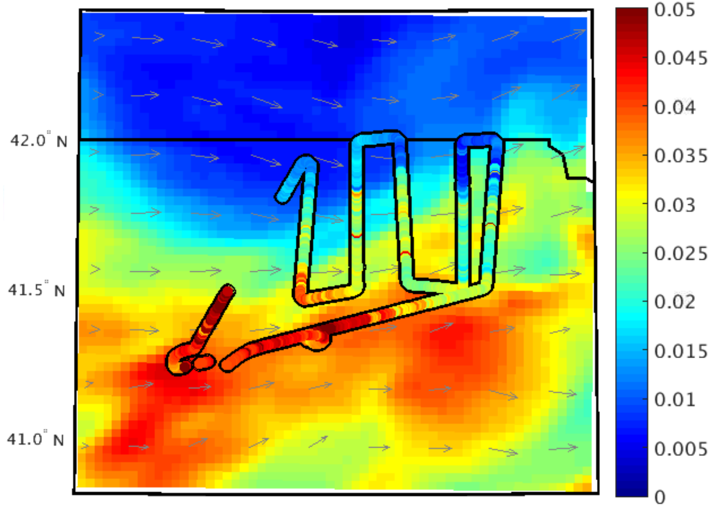
Observed CH_4 enhancement for the May 24th flight at 20z (in ppm)

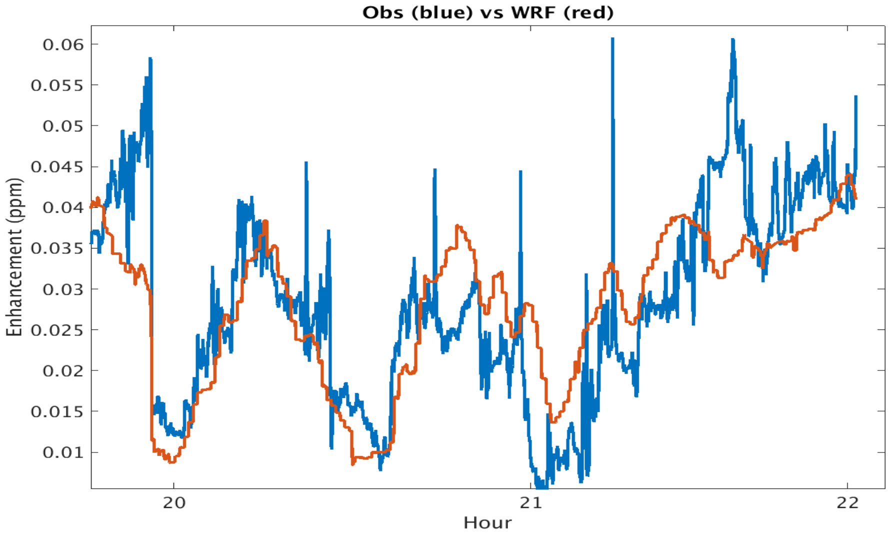
Modeled CH_4 Enhancement for May 24th, 2015



Coal plume has a significant impact on the regional measurements

May 24th 2015: WRF vs Obs All sources

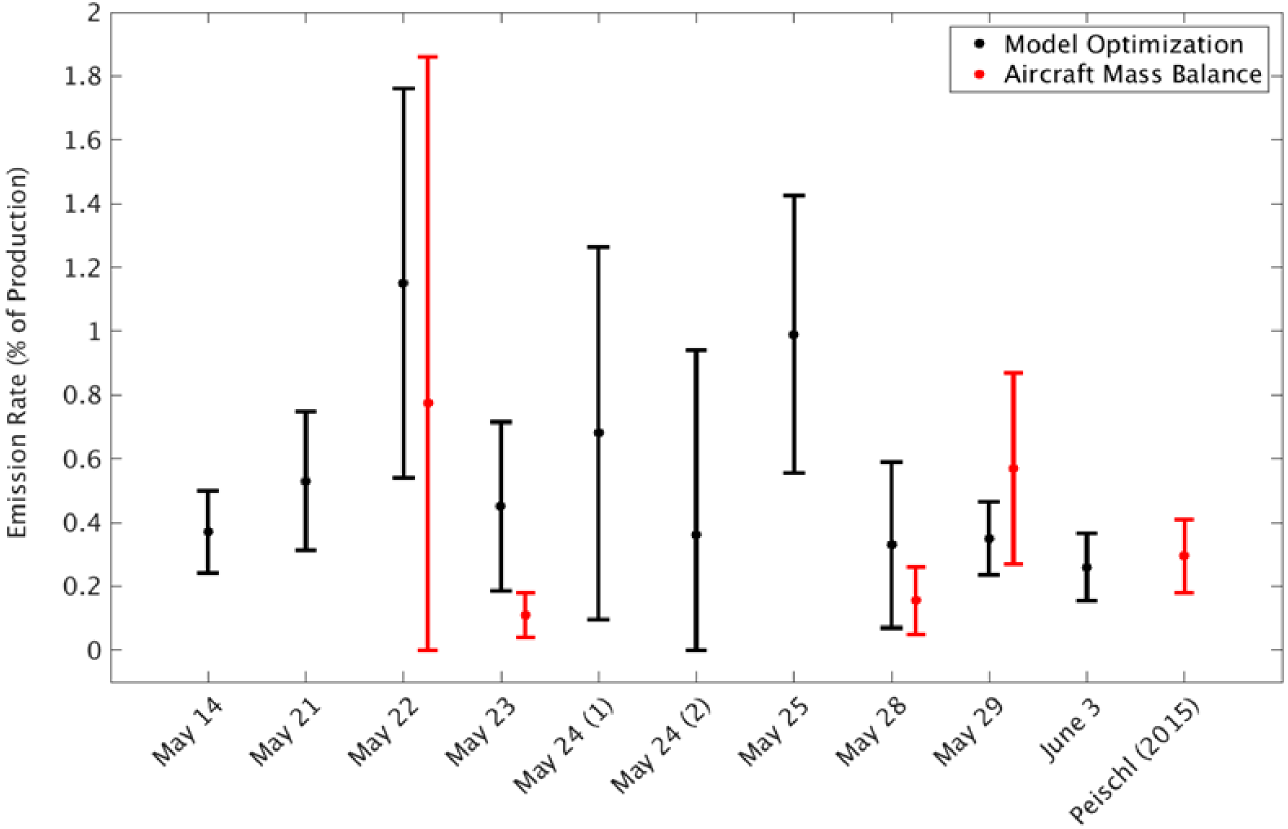




Optimized Natural Gas Emission Rate = 0.29%

Barkley et al., ACP, 2017

Best-guess upstream emission estimates

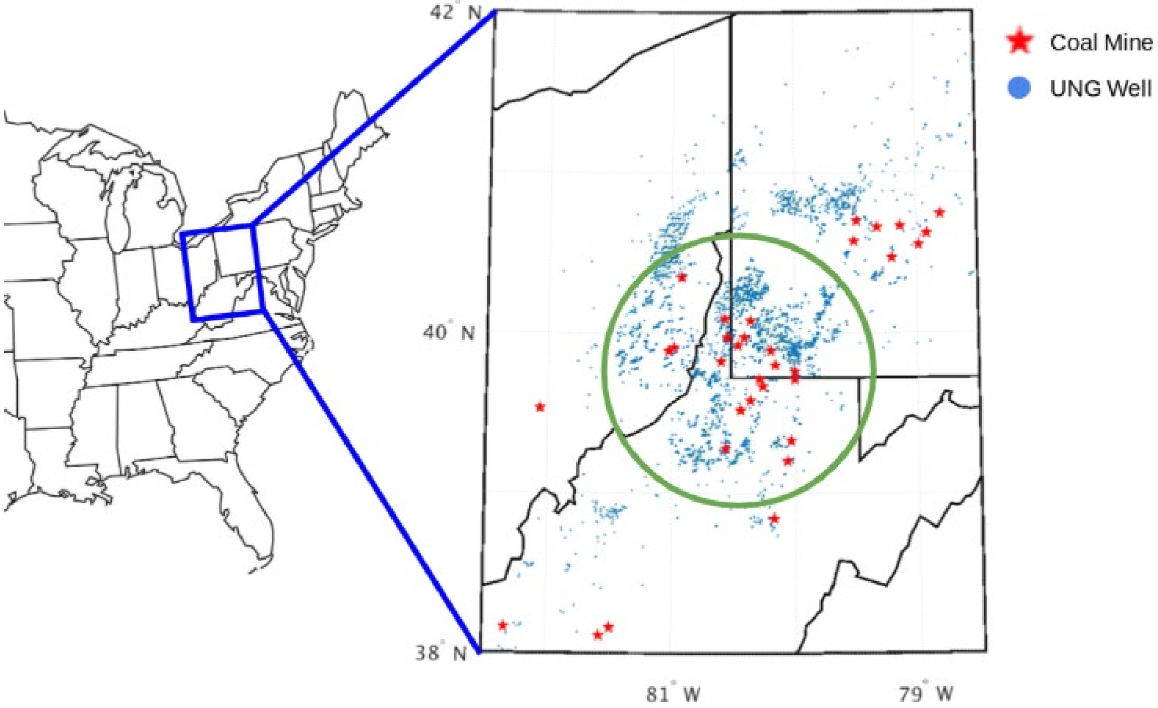


EPA inventory yields an emission rate of approximately 0.15% (?) of production.

Optimal mean leakage rate based on 10 flights in May 2015: **0.39% of production**

Barkley et al., ACP, 2017

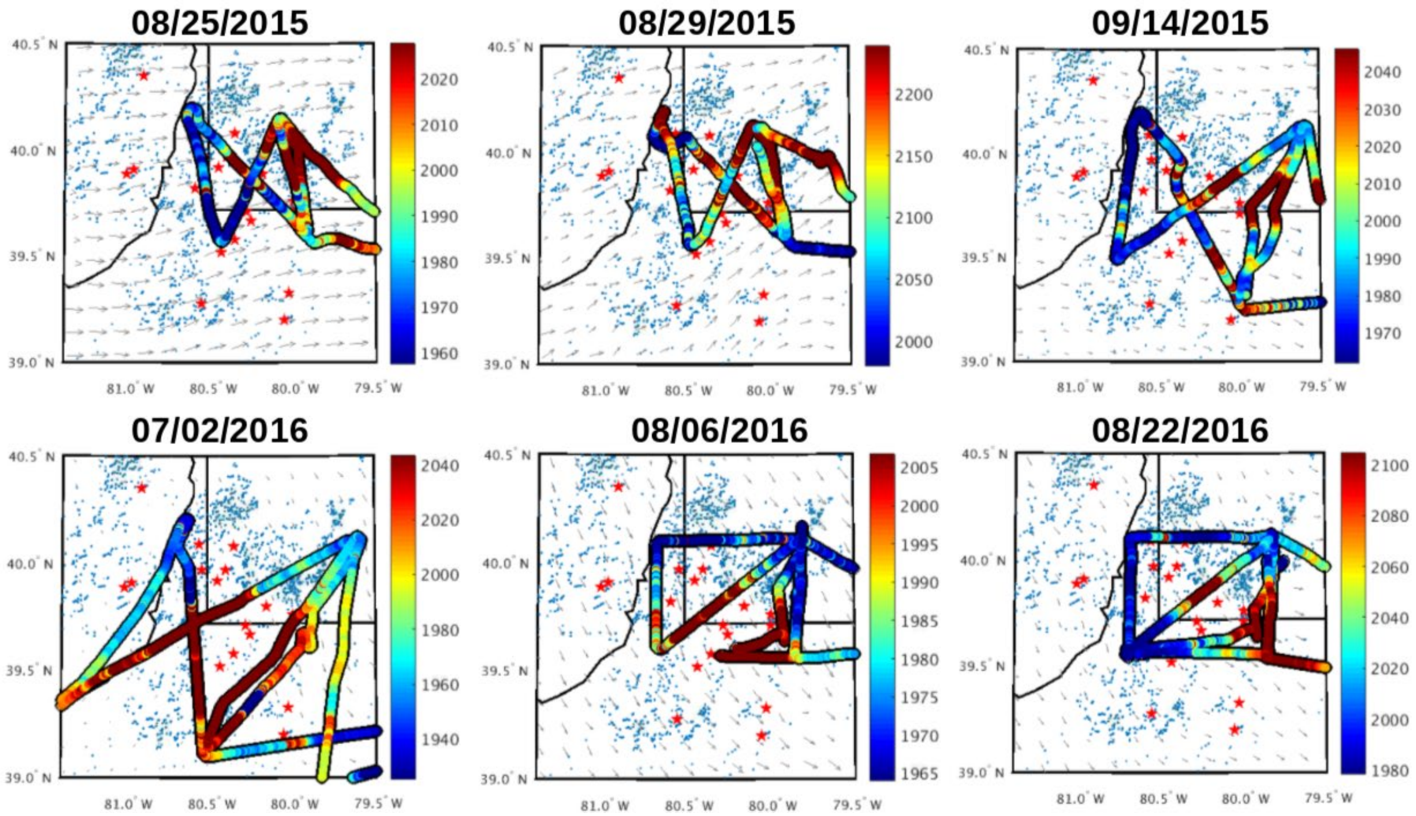
Let's quantify natural gas emissions in Southwest Pennsylvania



In this region, both coal and UNG wells are major sources of methane emissions

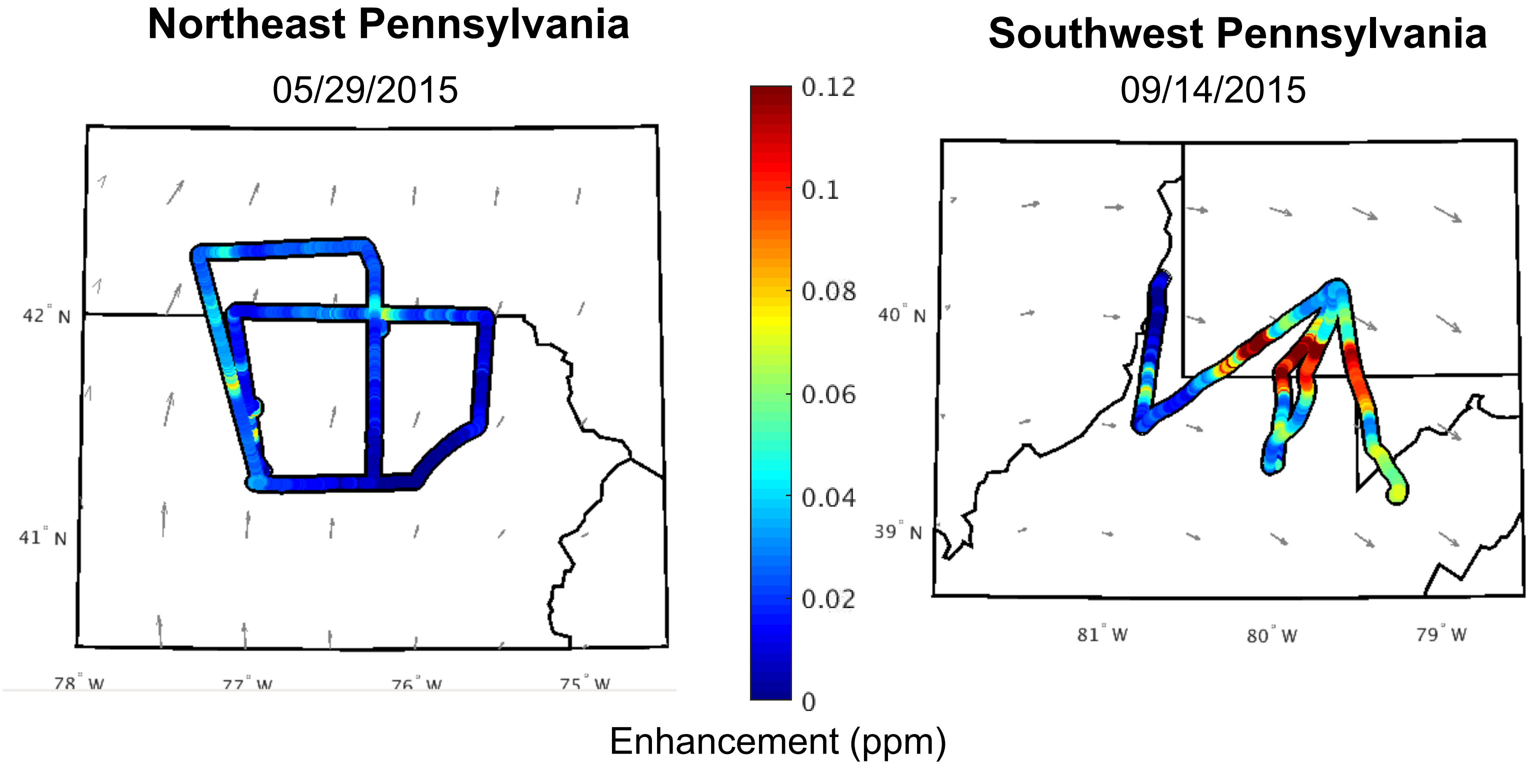
Barkley et al., GRL, 2019A

6 flights (19 transects) in 2015-2016 performed by the University of Maryland



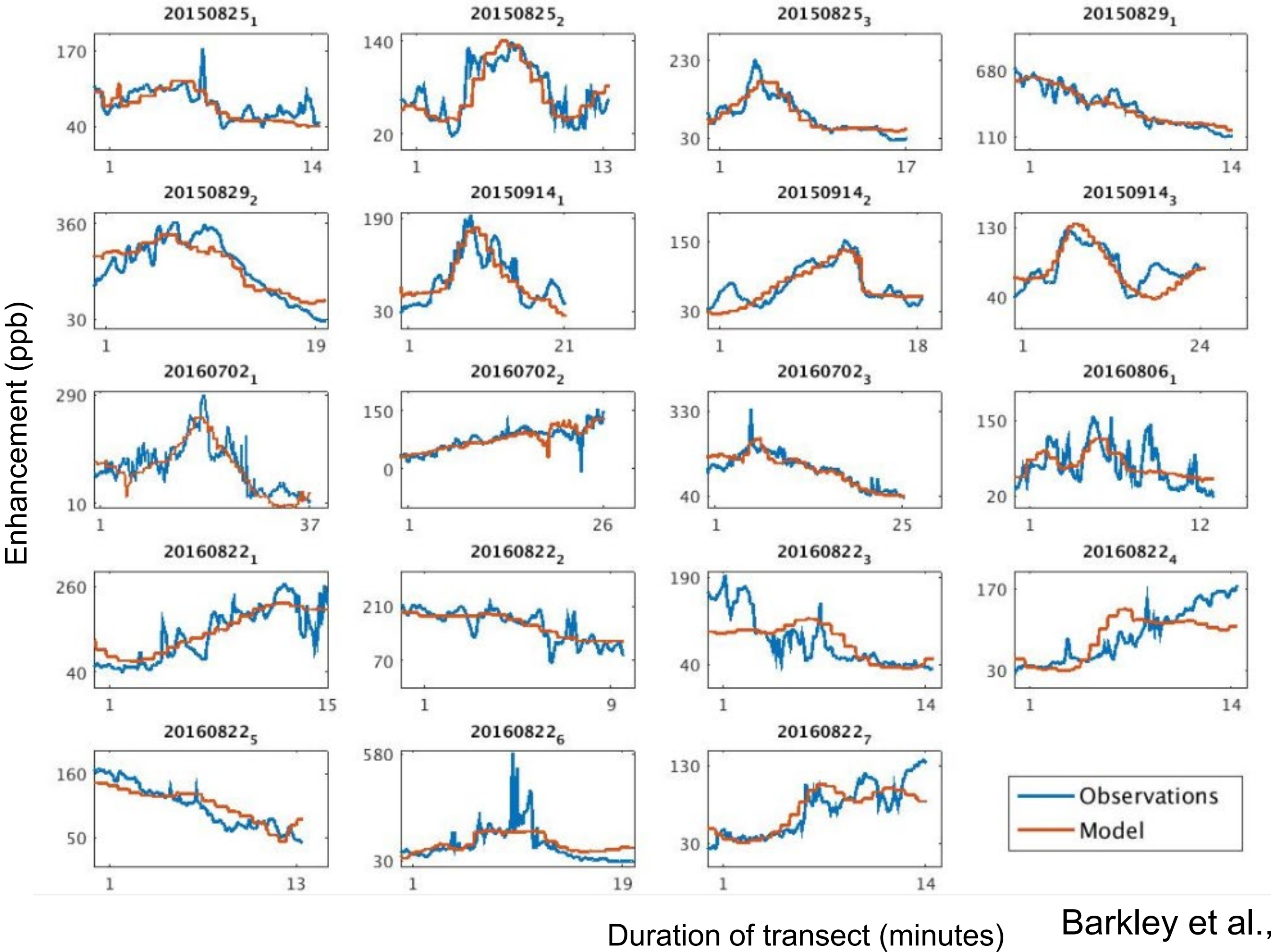
Barkley et al., GRL, 2019A

There's a lot more methane in SWPA



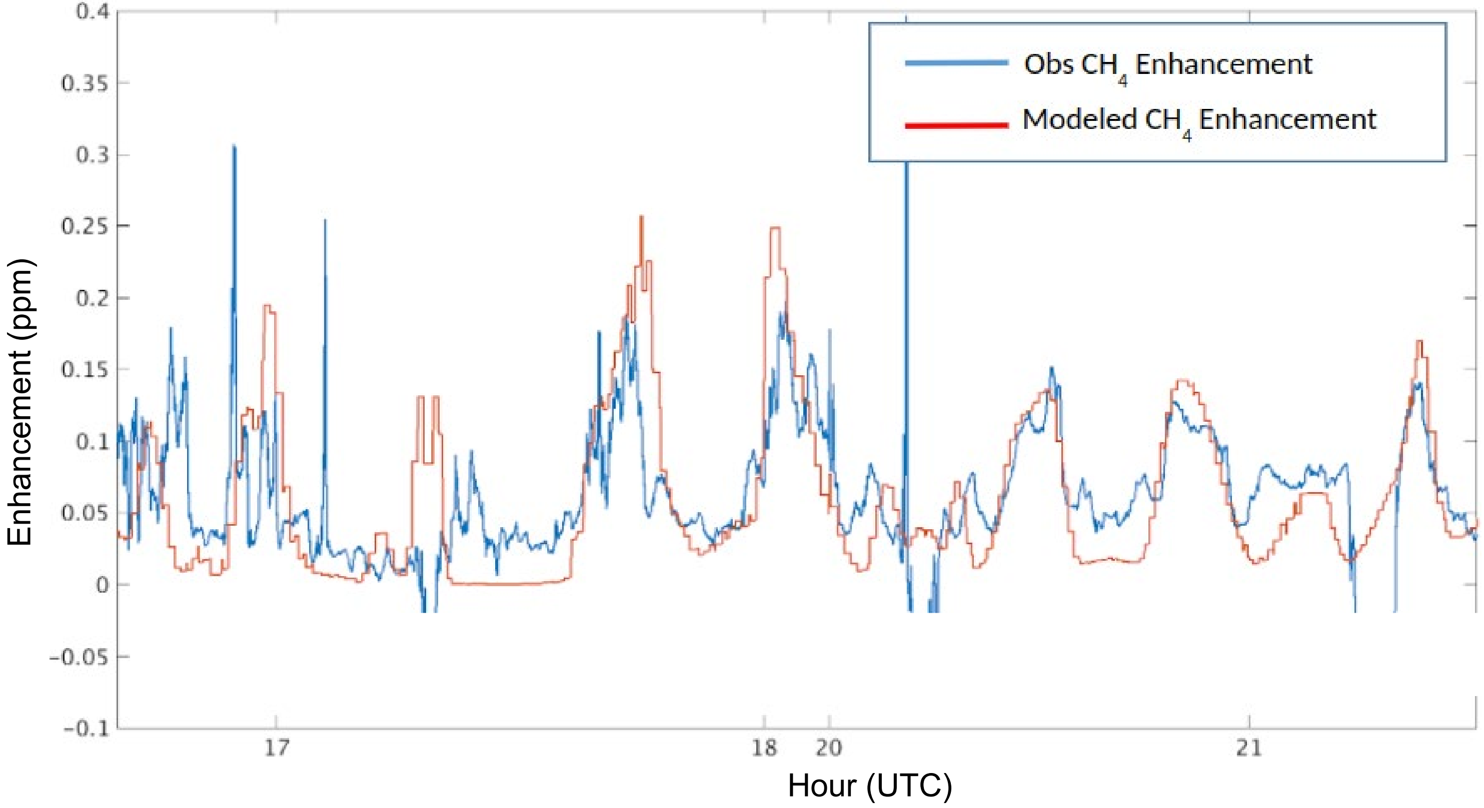
Barkley et al., GRL, 2019A

GOOD NEWS: Total flux is **easier to quantify**
BAD NEWS: Total flux is **harder to attribute**



Barkley et al., GRL, 2019A

September 14, 2015



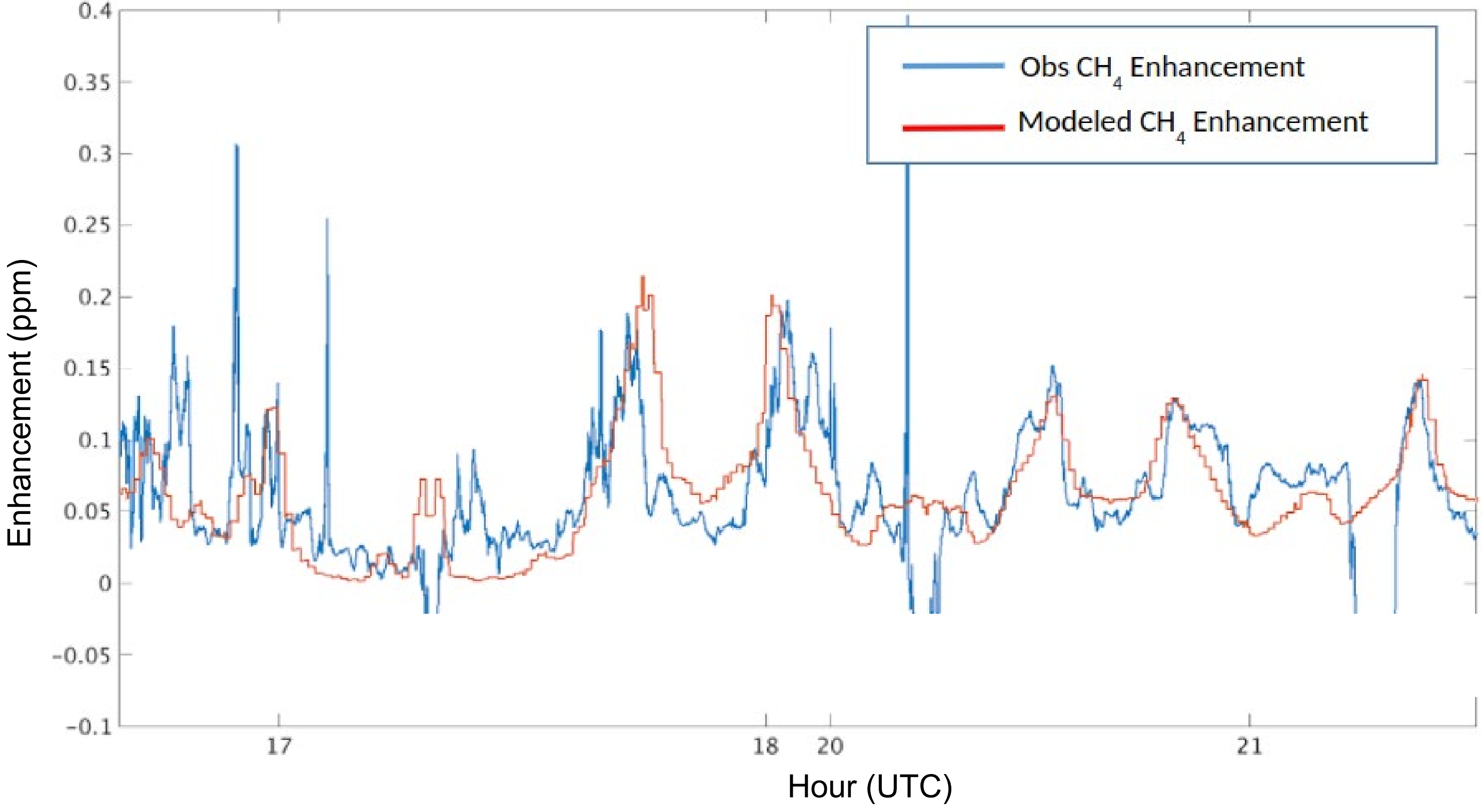
Barkley et al., GRL, 2019A

Optimized Model vs Obs solution using:

UNG Rate= 0%

Coal rate= 1.8 x EPA inventory

September 14, 2015



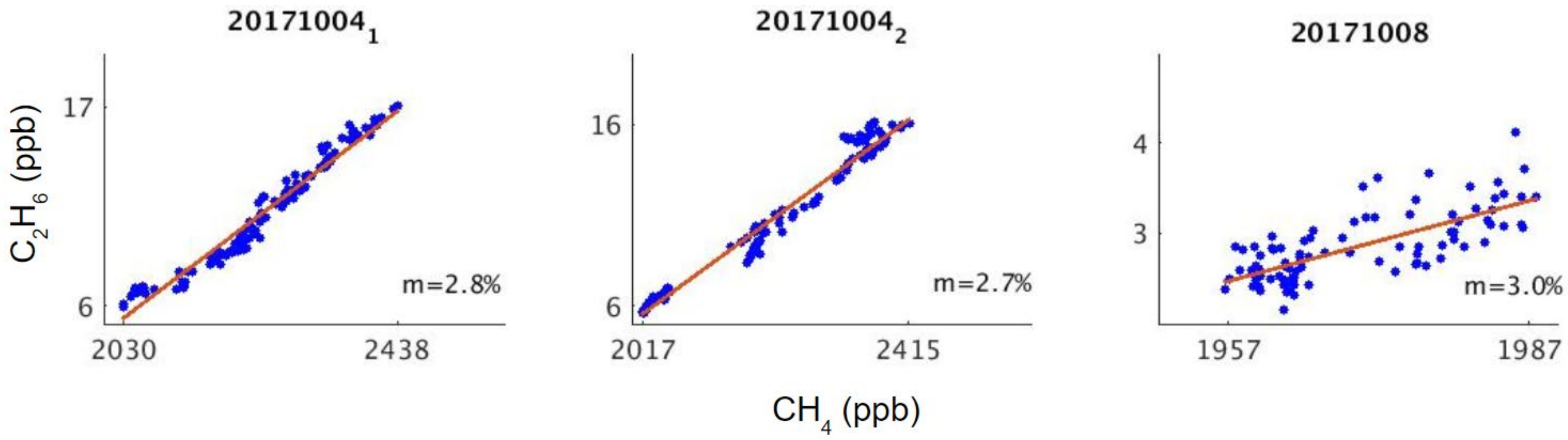
Barkley et al., GRL, 2019A

Optimized Model vs Obs solution using:

UNG Rate= 1.6%

Coal rate= 1.0 x EPA inventory

Continuous ethane measurements allow us to characterize the ethane/methane ratio of the mixed coal and gas plume



Ratios appear to be close to 3% ethane to methane.

Barkley et al., GRL, 2019A

Ratios of individual sources

SWPA Coal: 0.3% C_2H_6/CH_4

Kim 1973

SWPA Gas: 7.0% C_2H_6/CH_4

Colon-Roman 2016

Biogenic sources: 0% C_2H_6/CH_4

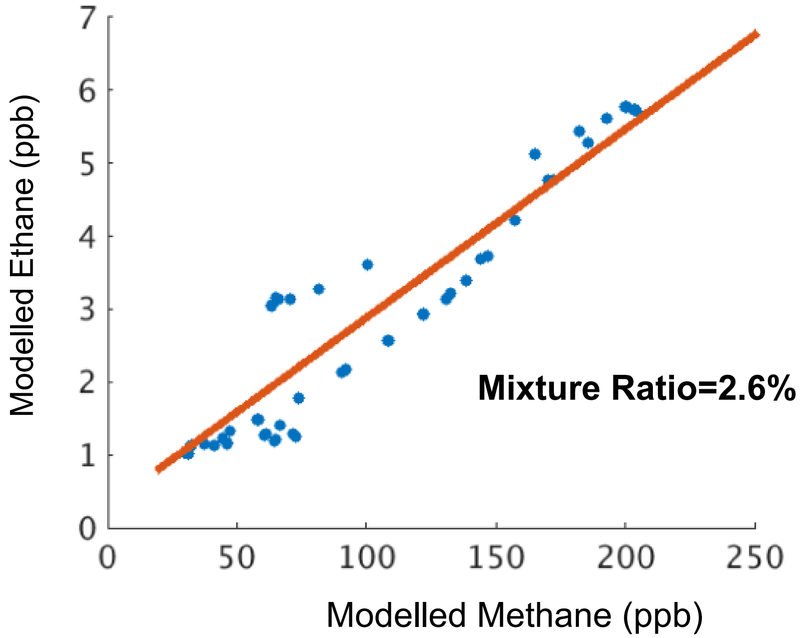
It is known

We can plug this information into the model to see what rates give us the observed ratio of the mixed plume

Barkley et al., GRL, 2019A

Replicating the ethane/methane signal

09/14/2017

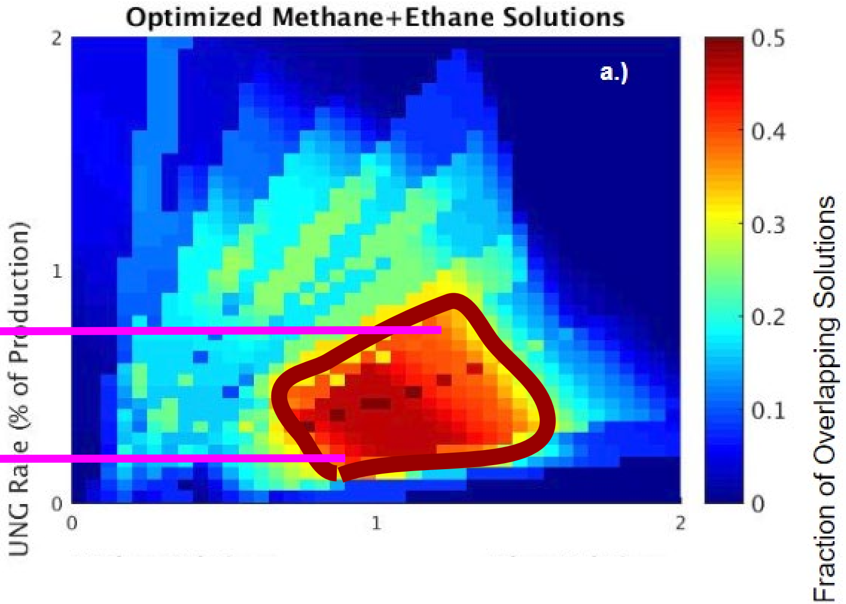


Barkley et al., GRL, 2019A

UNG = 0.9% of production

Coal Rate = 1.3 x EPA Inventory

Find where solutions overlap across the 19 transects

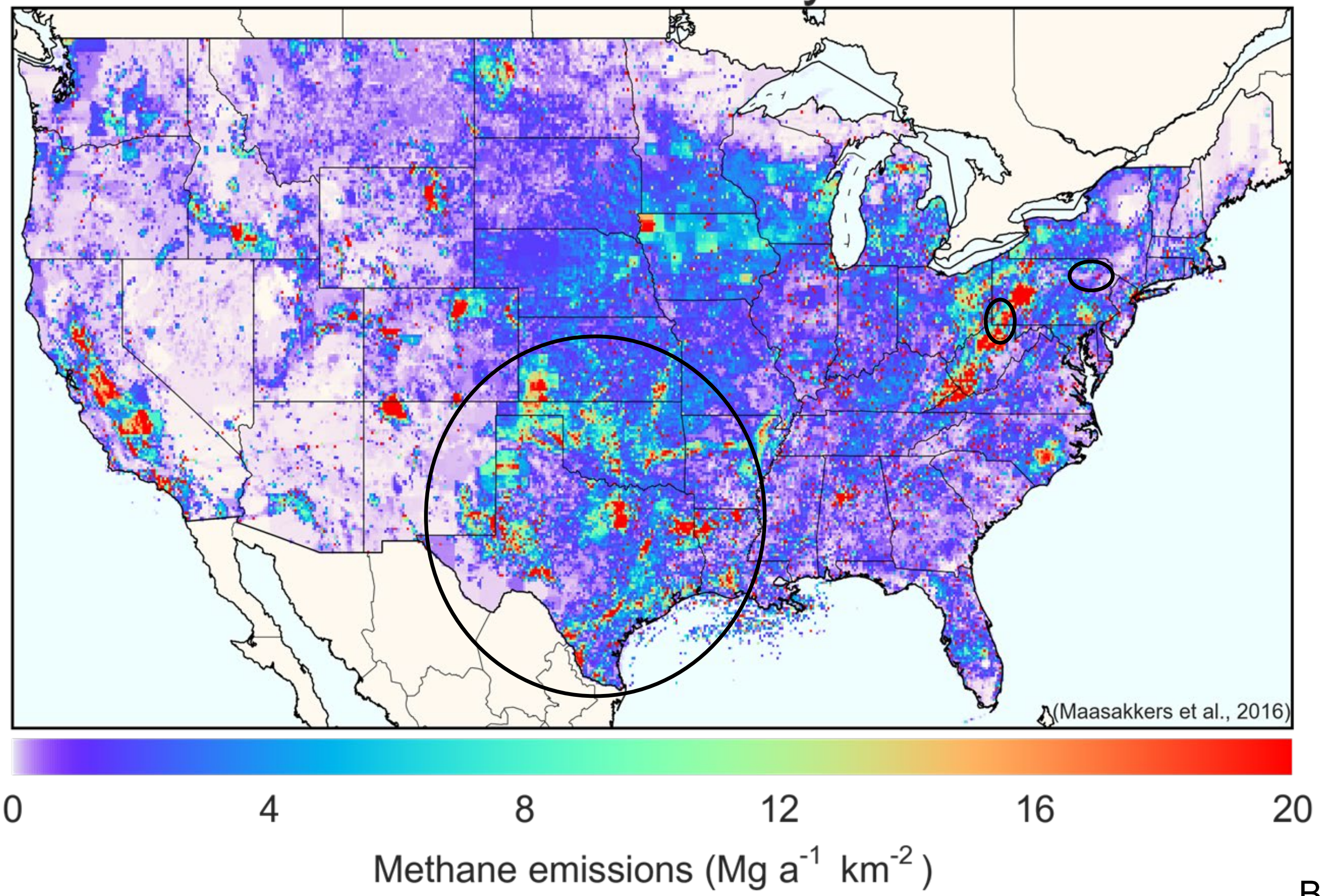


Gas leak rate between 0.2-0.8% of production

Bottom up inventory projects UNG emissions in SWPA to be 0.1% of production!!!

Barkley et al., GRL, 2019A

Gridded EPA Inventory for 2012

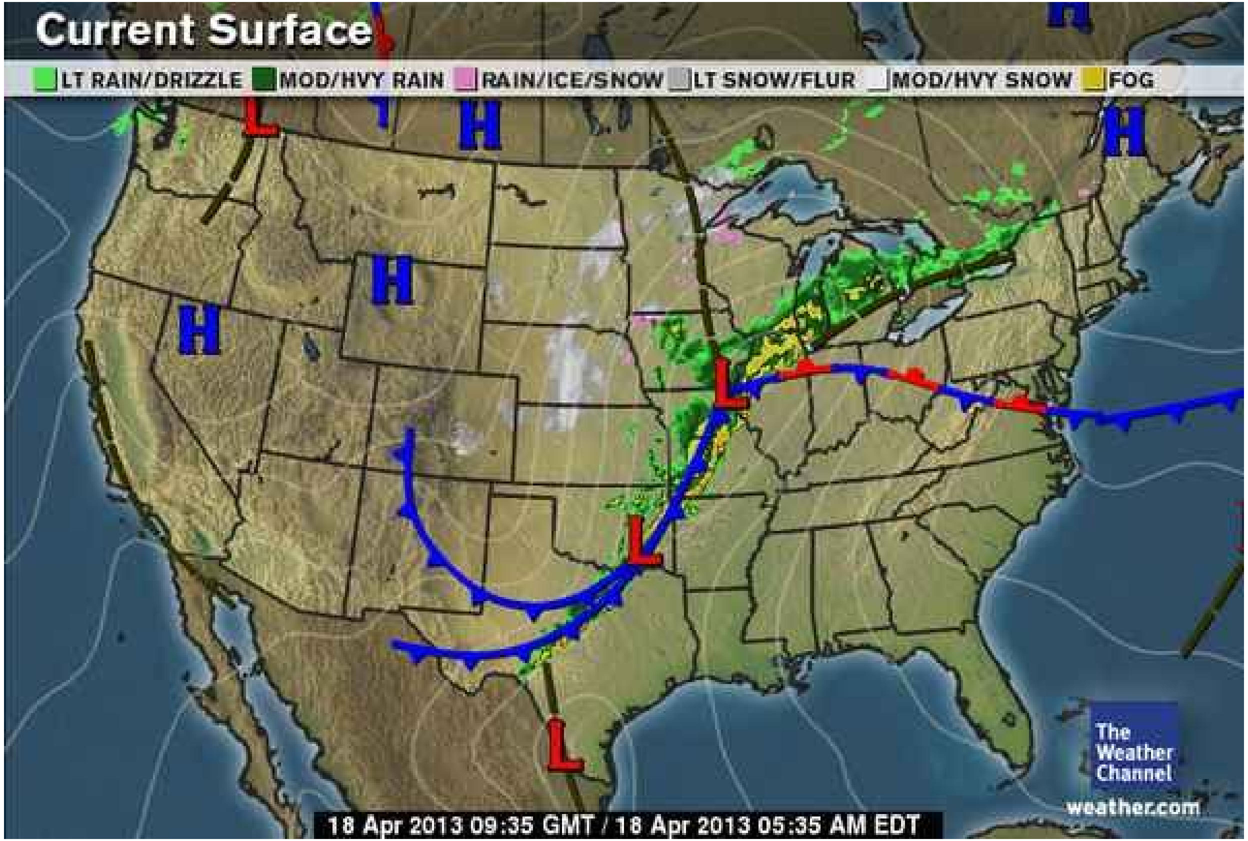


Includes all methane emissions included in the National Greenhouse Gas Inventory.

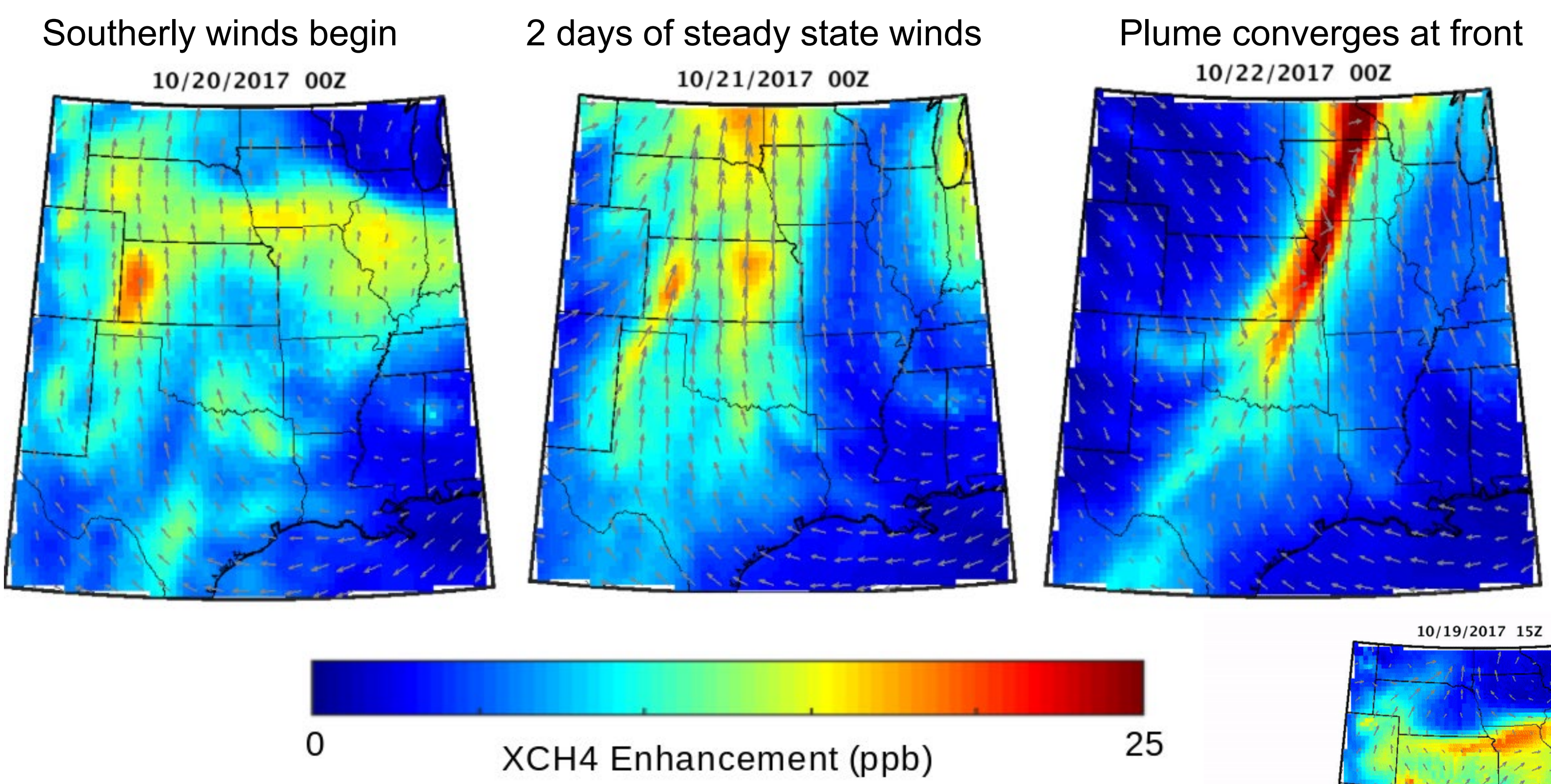
What if we estimate emissions from all of the south-central U.S. at once?

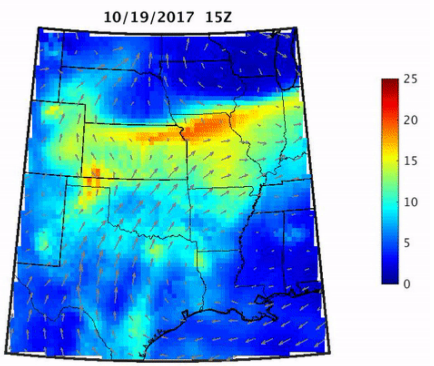
Can this be done? Does it match up with inventories?

Barkley et al., GRL, 2019B



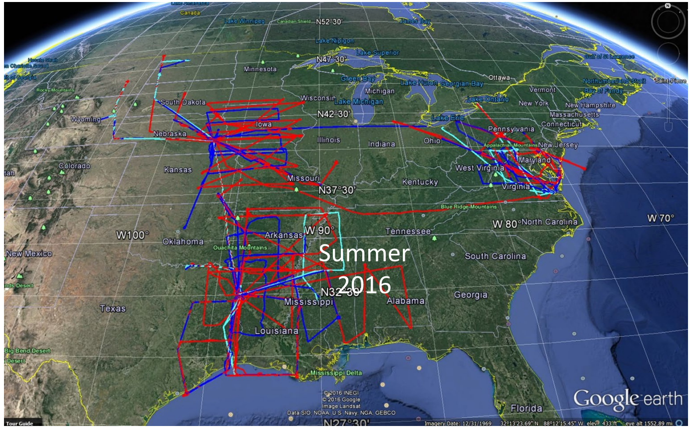
Fly downwind of gas production in southern US and use frontal transects to estimate emissions

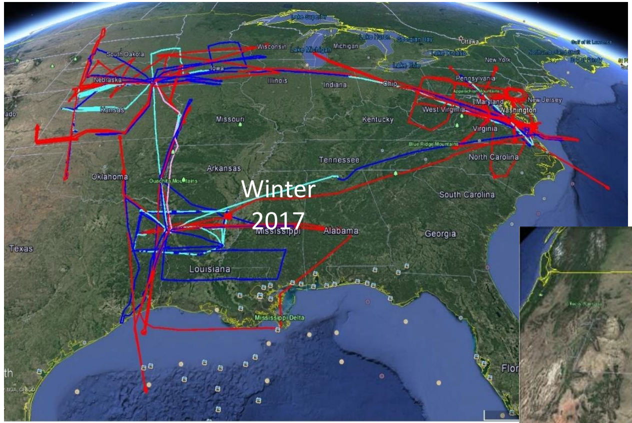


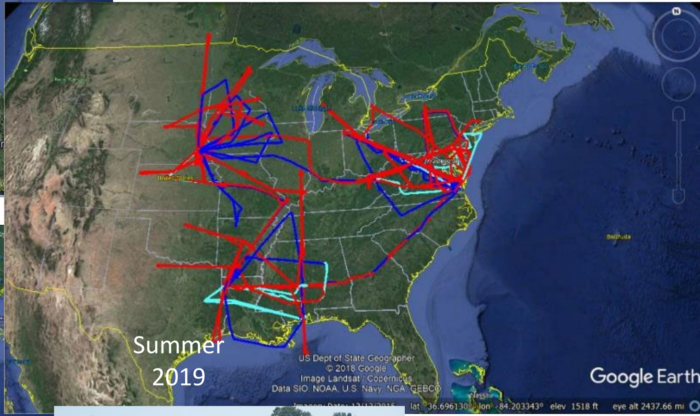


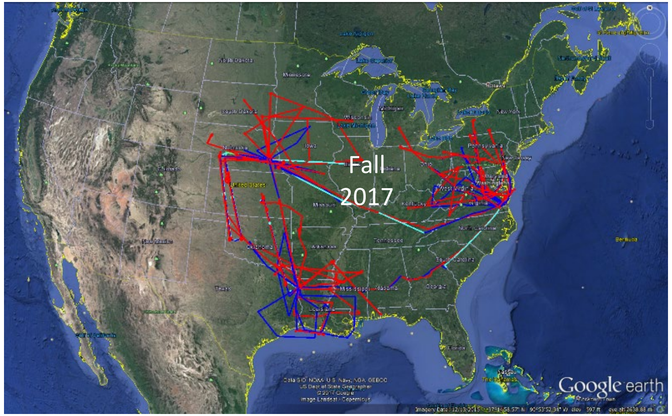
Barkley et al., GRL, 2019B

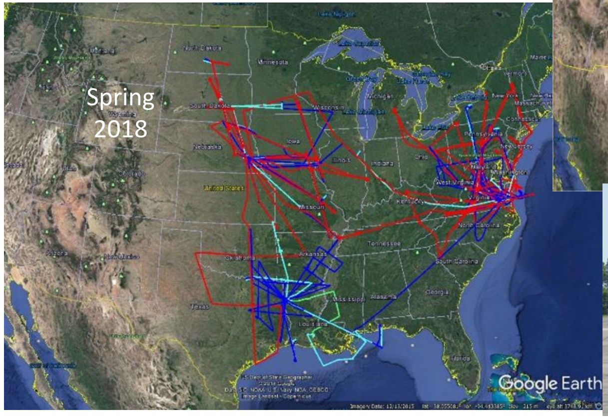
ACT-America flight campaign





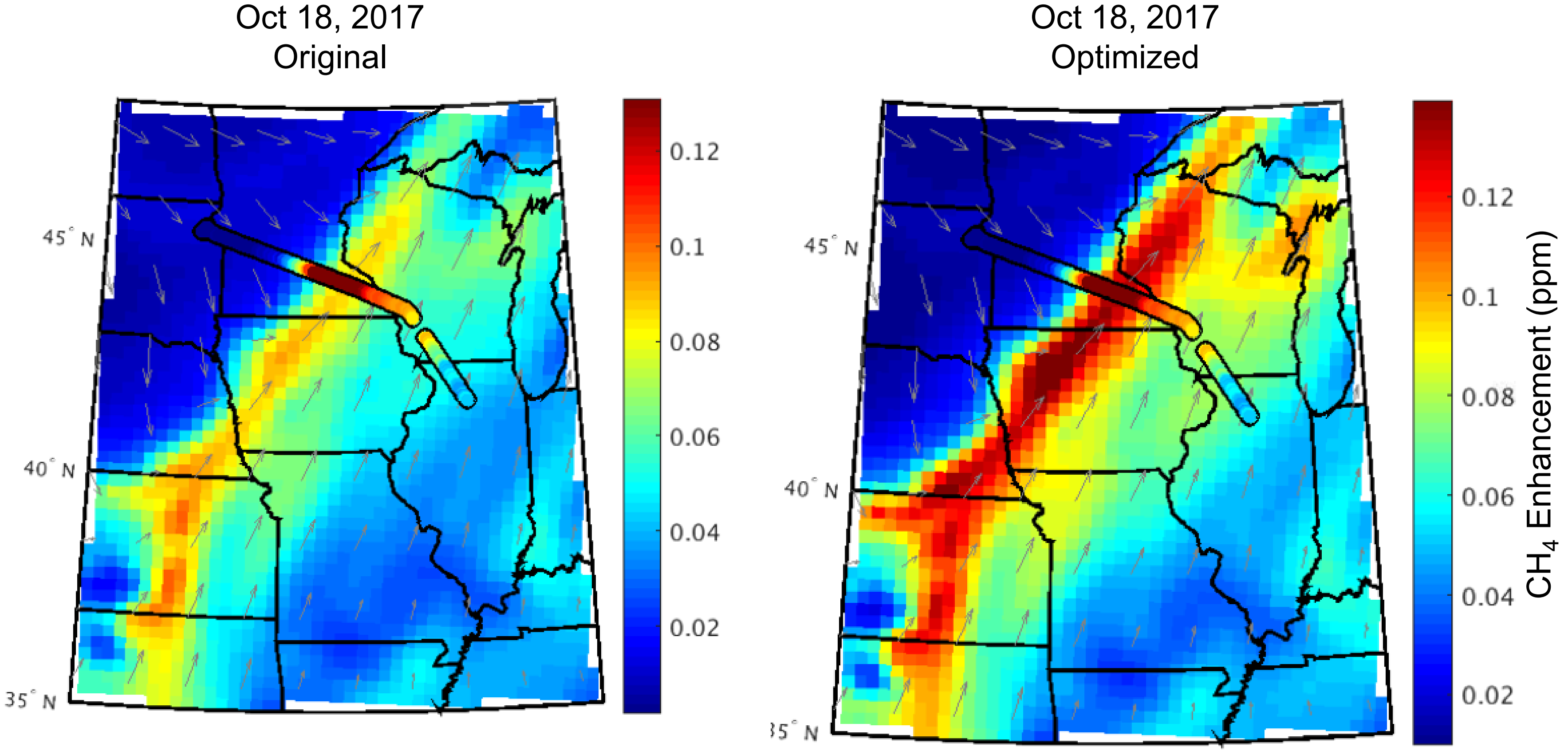




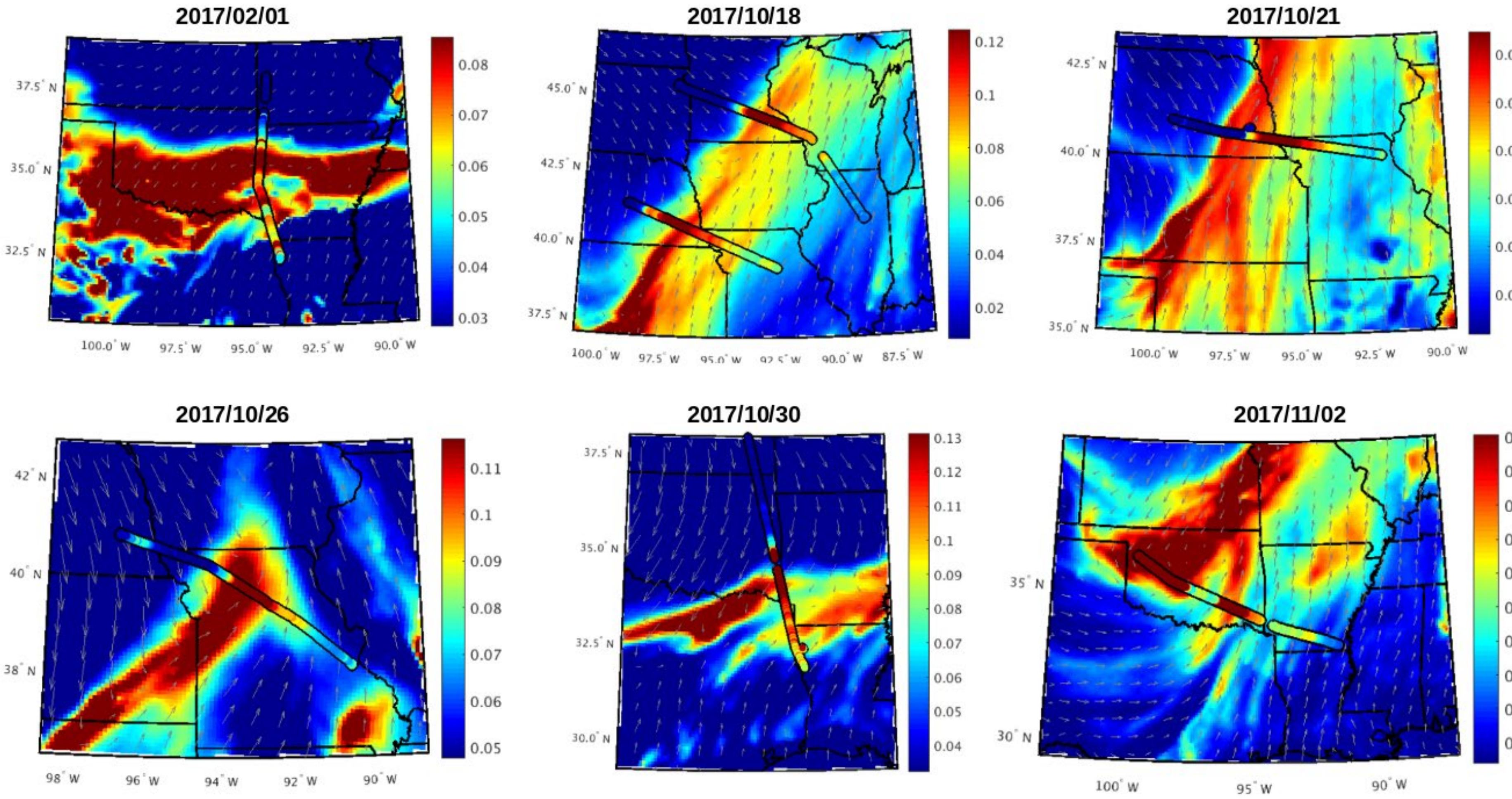


- Five, six-week campaigns over 3 years, covering each season and summer twice. ~25 flights / campaign.
- Each campaign: 2 weeks in each of 3 regions across US (MidAtlantic, MidWest, SouthCentral).
- About 50% of the data in the atmospheric boundary layer (ABL).
- 1140 total flight hours. About 1,500 flasks and 1,000 vertical profiles.

Optimization of Methane Sources: Oct 18th

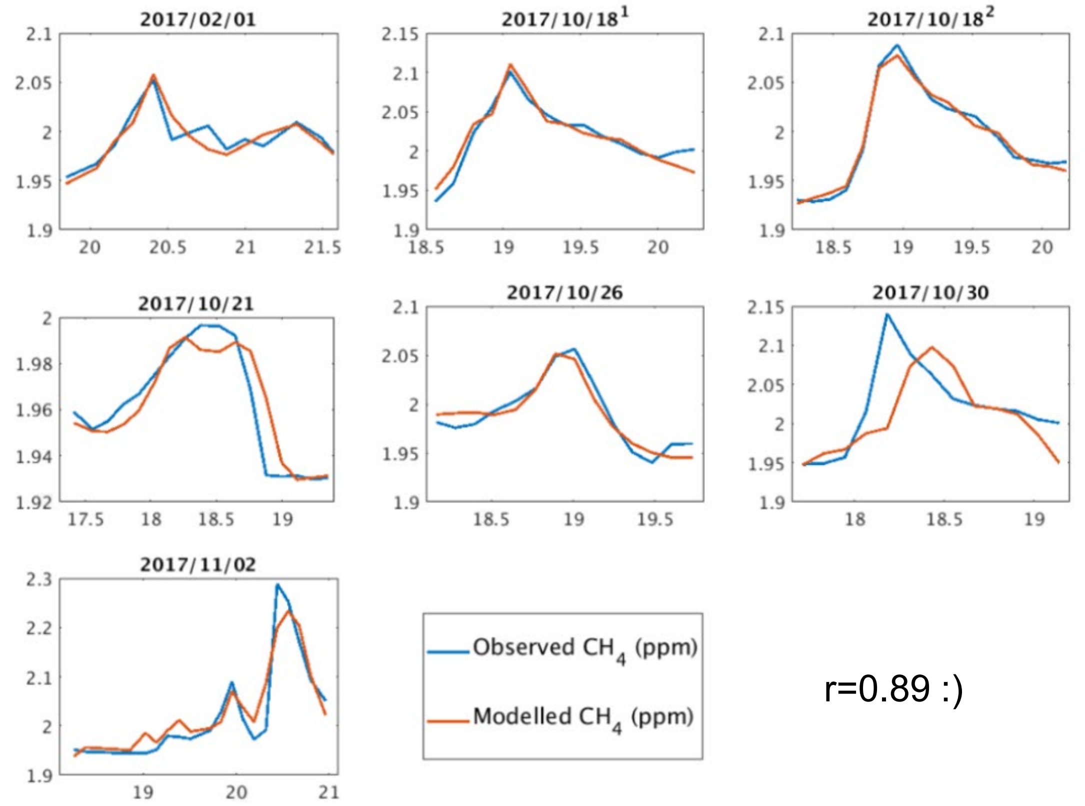


Barkley et al., GRL, 2019B



Barkley et al., GRL, 2019B

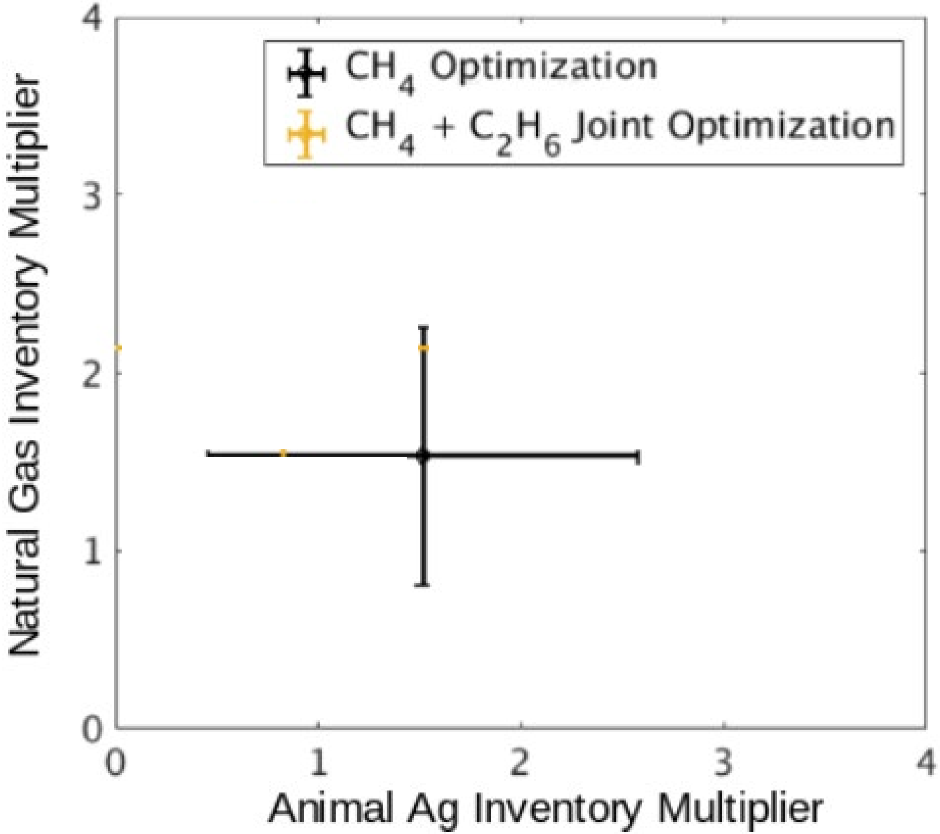
We’re really good at recreating the total methane plume



r=0.89 :)

Figure 2. Observed vs. modelled CH_4 for each of the 7 flights using the optimized gas and animal ag emission rates for each flight.

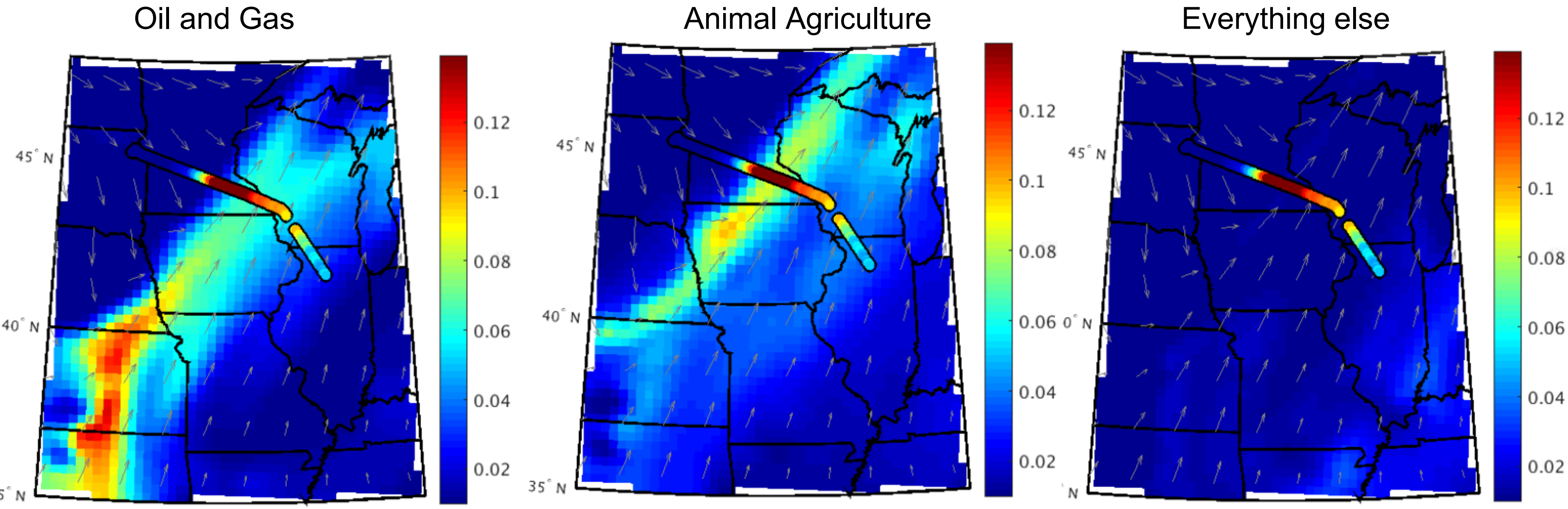
Barkley et al., GRL, 2019B



...but knowing which source to attribute it to will take more information.

Barkley et al., GRL, 2019B

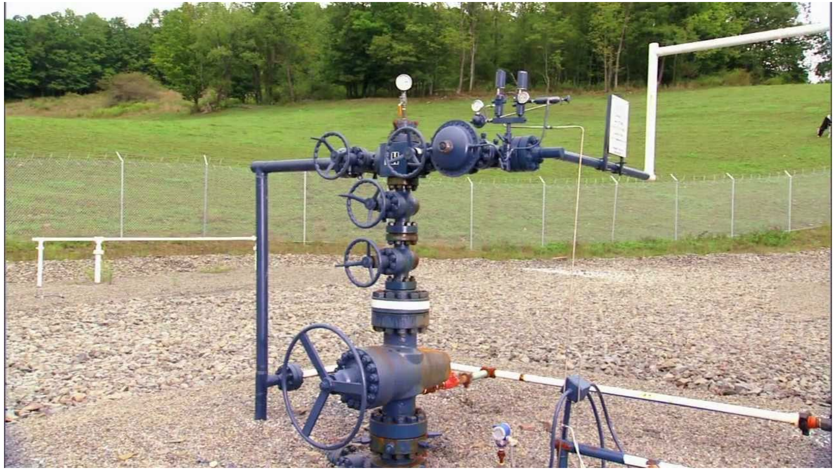
Optimization of Methane Sources: Oct 18th, 2017



CH_4 Enhancement (ppm)

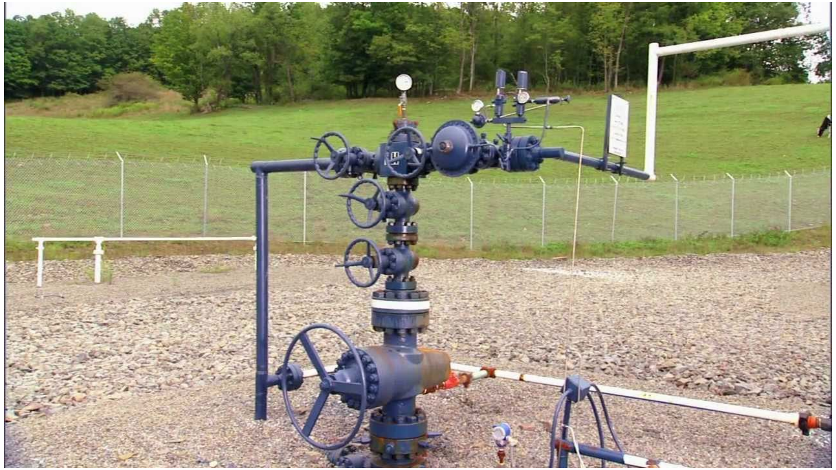
Barkley et al., GRL, 2019B

Major methane sources in the South

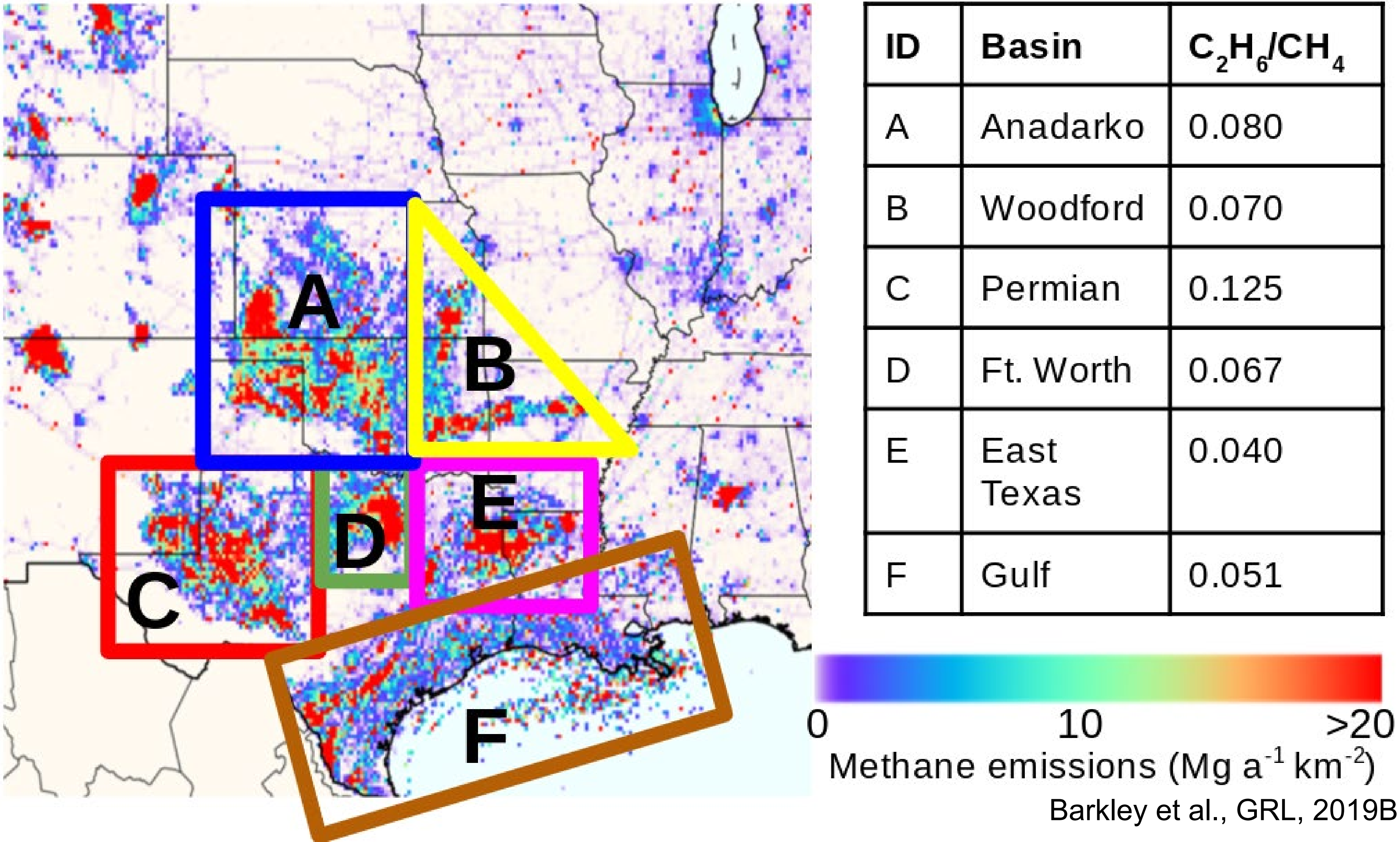


Barkley et al., GRL, 2019B

Major ethane sources in the South



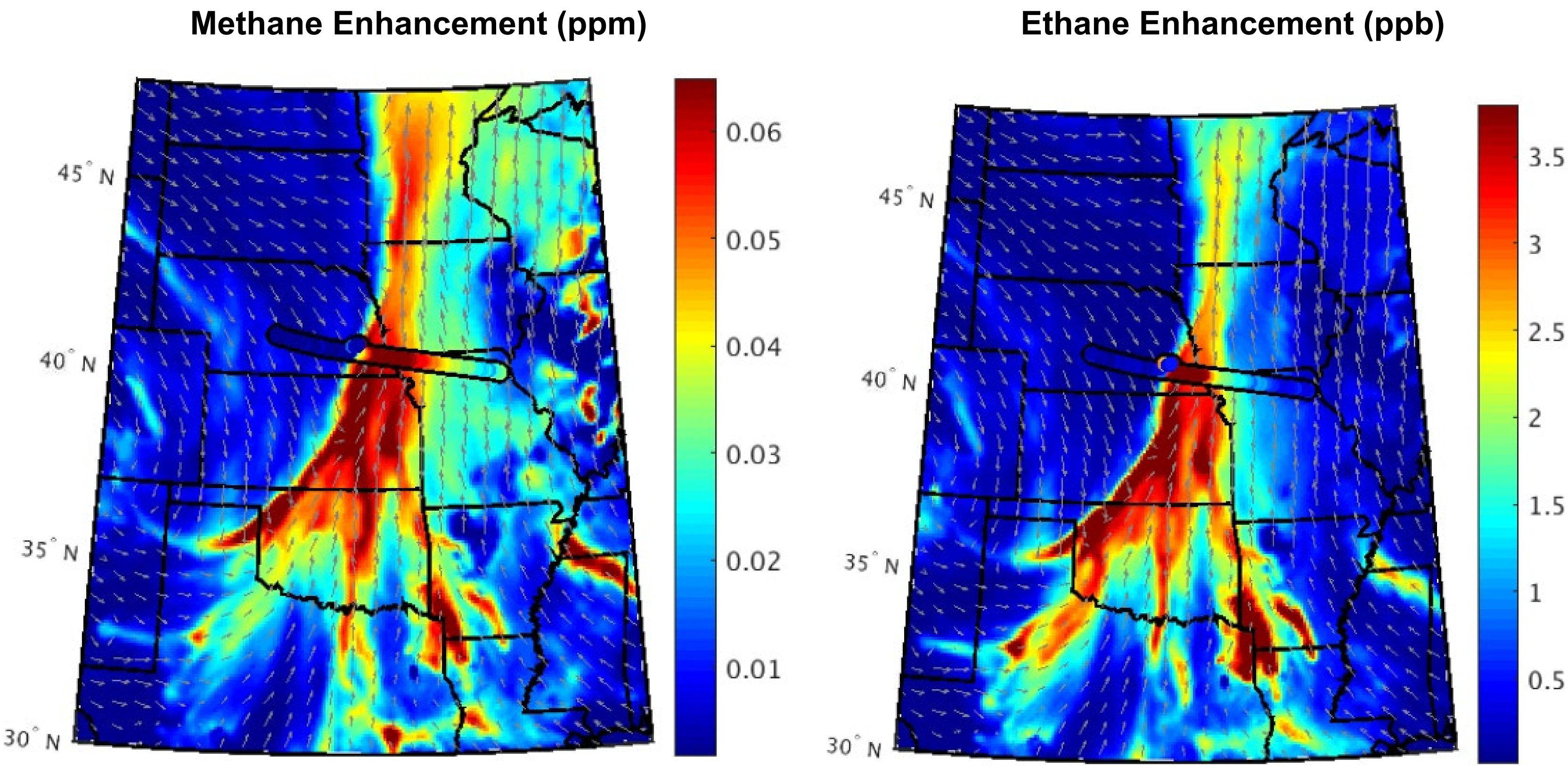
Barkley et al., GRL, 2019B



ID	Basin	C_2H_6/CH_4
A	Anadarko	0.080
B	Woodford	0.070
C	Permian	0.125
D	Ft. Worth	0.067
E	East Texas	0.040
F	Gulf	0.051

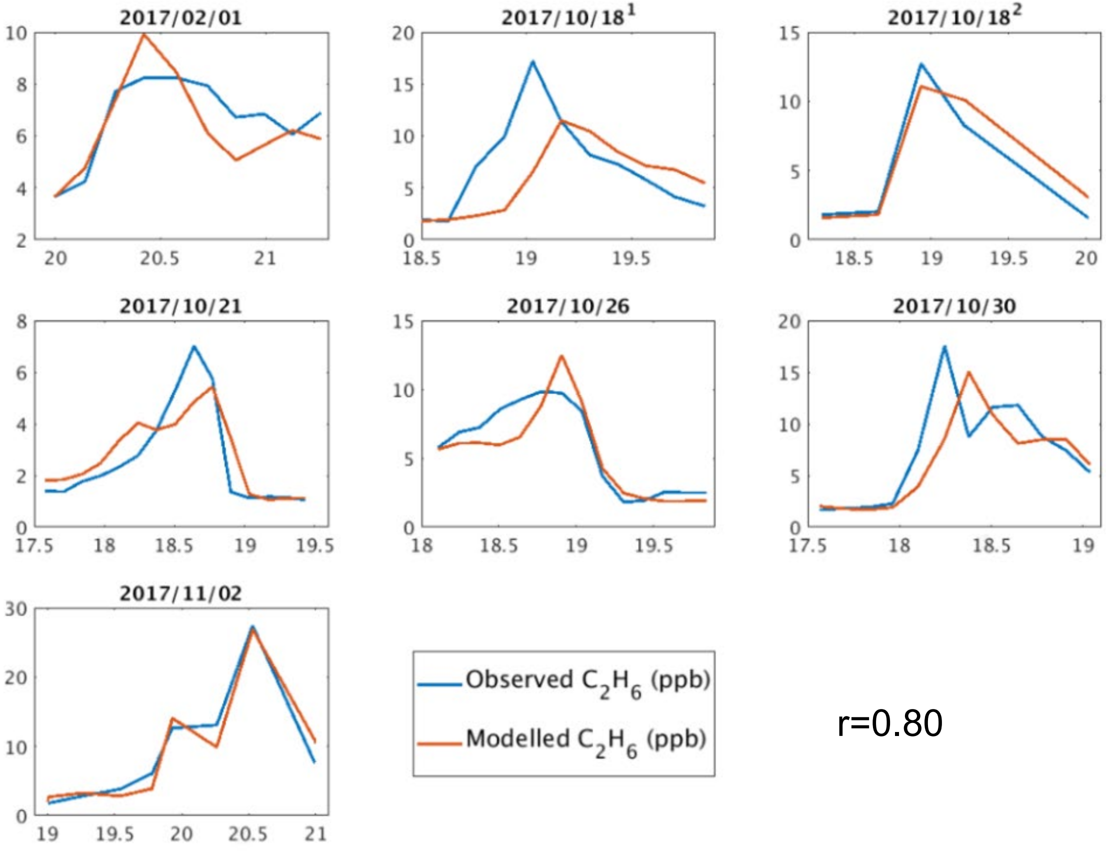
Barkley et al., GRL, 2019B

10/21/2017



Barkley et al., GRL, 2019B

Ethane Optimization



r=0.80

Figure 4. Observed vs. modelled C_2H_6 for each of the 7 flights using the optimized gas and animal ag emission rates for each flight.

Barkley et al., GRL, 2019B

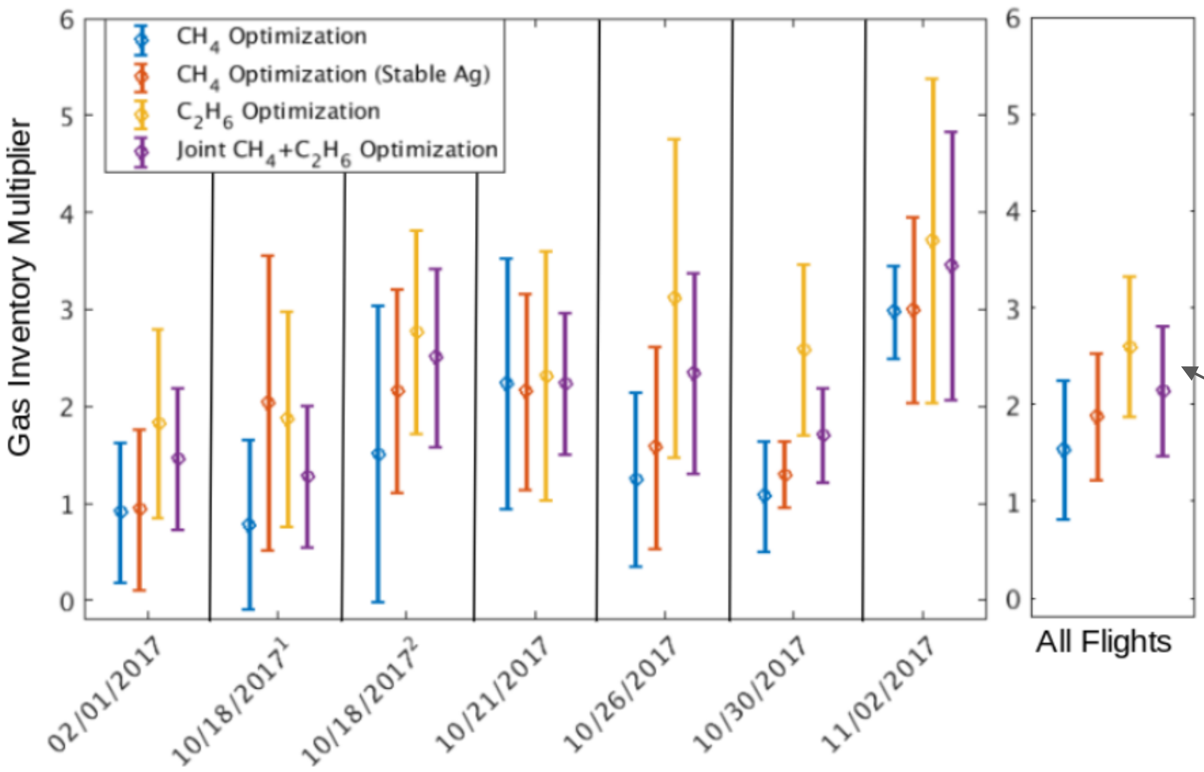


Figure 5. Optimized EPA gas inventory multipliers and their 95% confidence intervals for each flight. Each color represents a different strategy used in the optimization. (blue) Both gas and animal ag inventories were optimized using CH_4 data. (red) Only gas inventories were optimized, keeping animal ag values constrained by their inventory data. (yellow) Gas inventories were optimized using C_2H_6 data. (purple?) Both gas and animal ag inventories were optimized using the joint CH_4-C_2H_6 technique.

Best estimate of oil and gas emissions is roughly 2x inventory.

Animal agriculture emissions estimate is roughly equal to inventory.

Barkley et al., GRL, 2019B

Outline

Introduction to the challenges of complementary methods.

Describe atmospheric methods for deriving regional methane emissions. How we can account for:

- Multiple regional sources
- Day / night emissions
- Background contamination
- Variations in emission over time?

Review some recent atmospheric studies of oil/gas methane emissions:

- Airborne/ automobile site-based work synthesized by EDF
- Princeton study
- Penn State airborne work

Outline research needs moving forward

PennState

Synthesis

Describe atmospheric methods for deriving regional methane emissions. How we can account for:

Multiple regional sources

Trace gases (in this case, ethane). Spatial attribution (gridded inventory).

Day / night emissions

Flight data that integrates over a couple of days of emissions (south-central US).

Background contamination

Gridded inventory / spatial attribution and atmospheric transport reanalysis.

Variations in emission over time?

Repeated flights over a region. *Tower-deployments spanning months to years.*

Outline

Introduction to the challenges of complementary methods.

Describe atmospheric methods for deriving regional methane emissions. How we can account for:

- Multiple regional sources
- Day / night emissions
- Background contamination
- Variations in emission over time?

Review some recent atmospheric studies of oil/gas methane emissions:

- Airborne/ automobile site-based work synthesized by EDF
- Princeton study
- Penn State airborne work

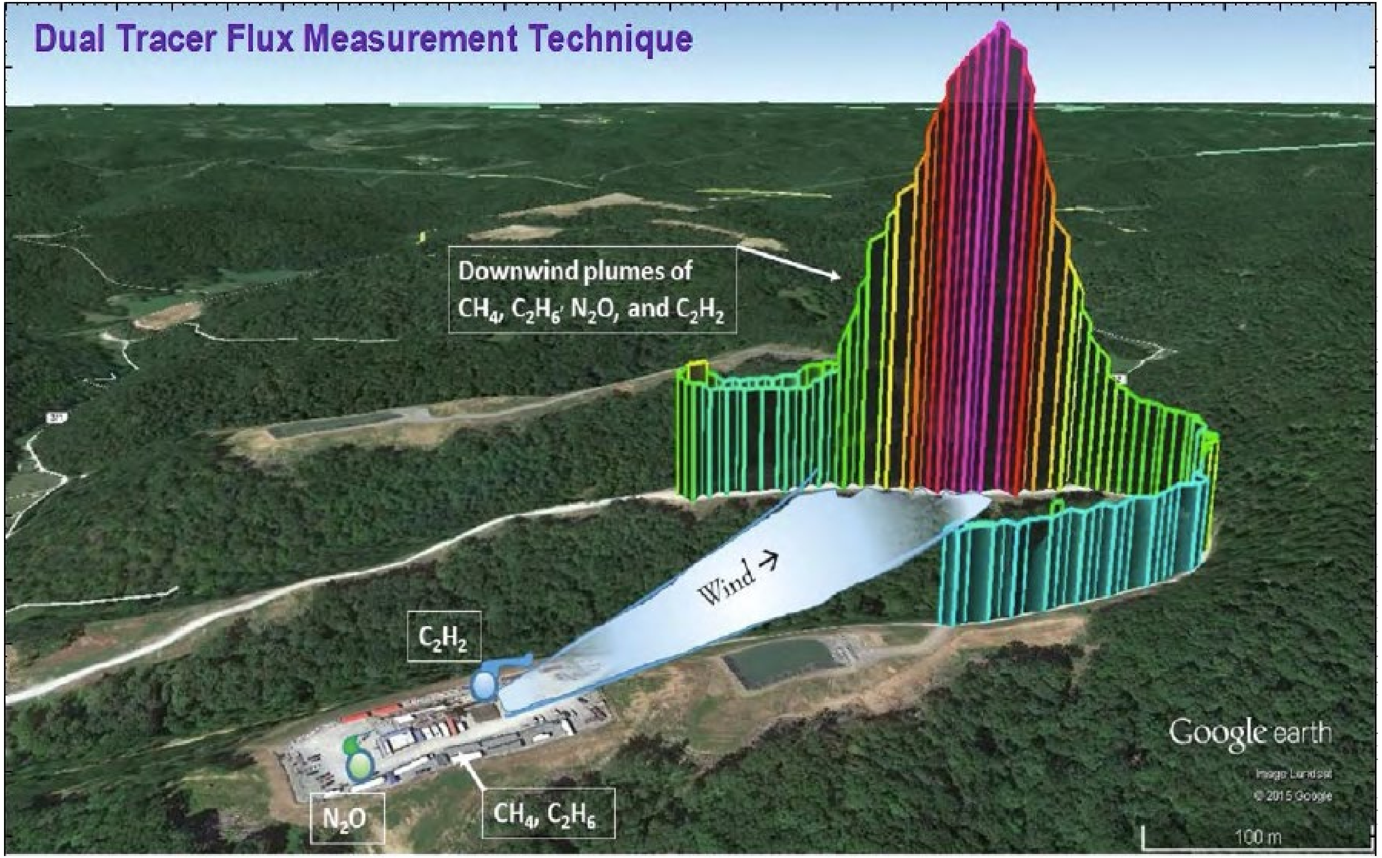
Outline research needs moving forward

How can we work towards greater confidence in and understanding of atmospheric emissions estimates?

- Make atmospheric measurements using multiple methods.
- Compare these to each other (and to inventories).
- If these disagree…study, iterate, interrogate…until the results converge.

ENVIRONMENTAL DEFENSE FUND
Finding the ways that work

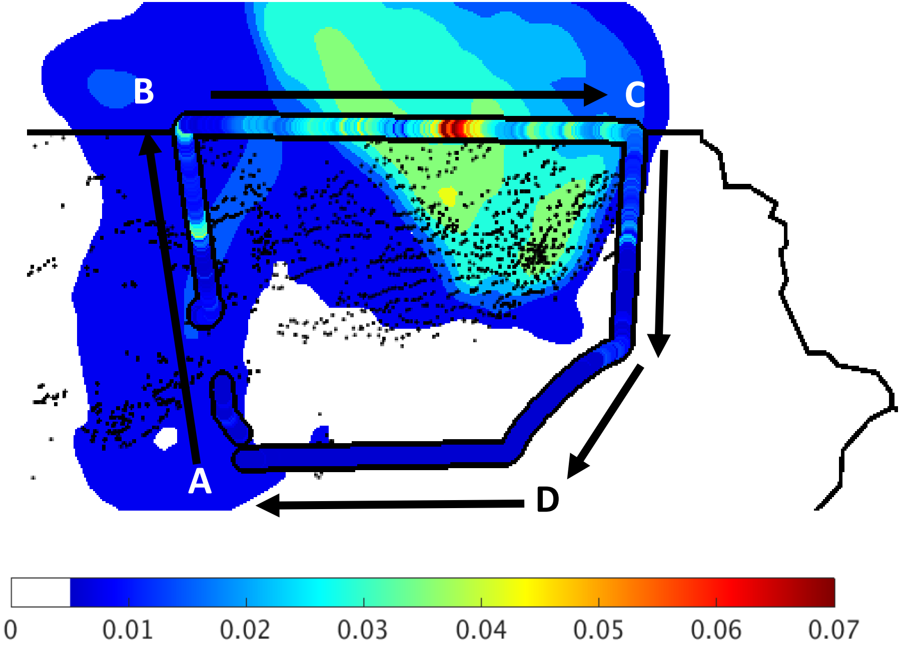
Atmospheric measurements: Site-level. Ground-based.



Omara et al., 2016; Caulton et al., 2019

Illustration by Omara and Presto, Carnegie Mellon University

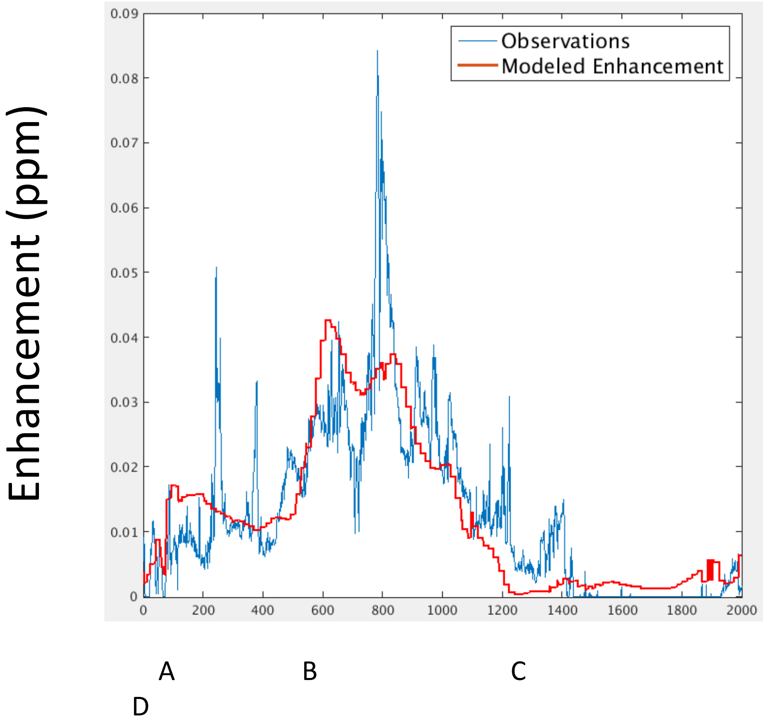
Airborne atmospheric methane observations: Entire gas-basin



Natural Gas CH_4 Enhancement (ppm)

Emission Rate = **0.26%**

Observed NG & Modeled NG (Rate=0.26%)



Barkley et al., 2017, Atmospheric Chemistry and Physics

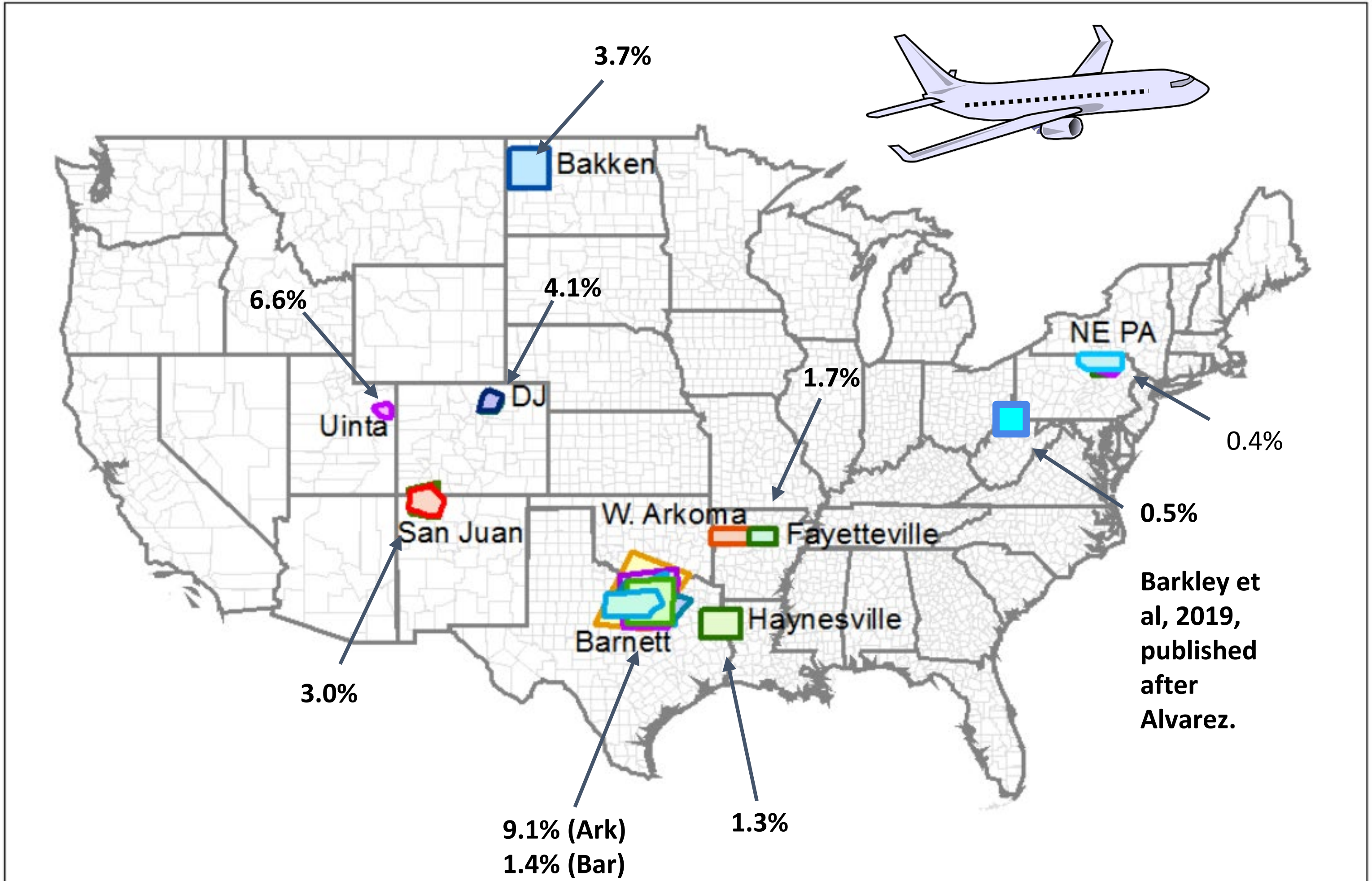
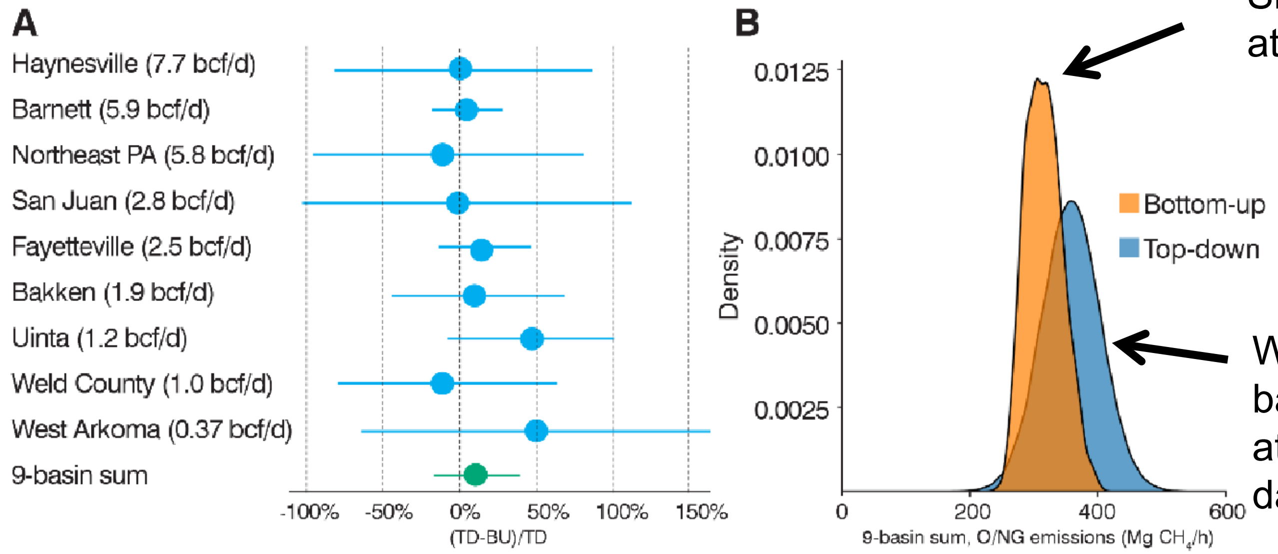


Figure from Alvarez et al, 2018. Rates from various studies (Barkley, Karion, Smith, Schwietzke, Petron, Peischl, Petron)

Pennsylvania gas wells, among the most productive in the nation, have very low emissions as a percentage of production.

But atmospheric data suggests the emissions in Pennsylvania are 2-5 times higher than EPA inventories would suggest.

Environmental Defense Fund-led, nation-wide re-assessment of natural gas methane emissions.



Site-by-site atmospheric data

Whole gas-basin atmospheric data

These agree!

Fig. 1. Comparison of this work's bottom-up (BU) estimates of methane emissions from oil and natural gas (O/ NG) sources to top-down (TD) estimates in nine U.S. O/ NG production areas. (A)

Alvarez et al., Science, 2018

Environmental Defense Fund-led, nation-wide re-assessment of natural gas methane emissions.

Table 1. Summary of this work's bottom-up estimates of CH_4 emissions from the U.S. oil and natural gas (O/NG) supply chain (95% confidence interval) and comparison to the EPA Greenhouse Gas Inventory (GHGI).

Industry segment	2015 CH_4 Emissions (Tg/y)	
	This work (bottom-up)	**EPA GHGI** (*17*)
Production	7.6 (+1.9/-1.6)	3.5
Gathering	2.6 (+0.59/-0.18)	2.3
Processing	0.72 (+0.20/-0.071)	0.44
Transmission and Storage	1.8 (+0.35/-0.22)	1.4
Local Distribution*	0.44 (+0.51/-0.22)	0.44
Oil Refining and Transportation*	0.034 (+0.050/-0.008)	0.034
U.S. O/NG total	13 (+2.1/-1.7)	8.1 (+2.1/-1.4)†

*This work's emission estimates for these sources are taken directly from the GHGI. The local distribution estimate is expected to be a lower bound on actual emissions and does not include losses downstream of customer meters due to leaks or incomplete combustion (Section S1.5).

†The GHGI only reports industry-wide uncertainties.

These do not agree!

Site-by-site atmospheric data

EPA inventory data

Alvarez et al., Science, 2018

Environmental Defense Fund-led, nation-wide re-assessment of natural gas methane emissions.

Methane emissions from the U.S. oil and natural gas supply chain were estimated using ground-based, facility-scale measurements and validated with aircraft observations in areas accounting for ~30% of U.S. gas production. When scaled up nationally, our facility-based estimate of 2015 supply chain emissions is 13 ± 2 Tg/y, equivalent to 2.3% of gross U.S. gas production. This value is ~60% higher than the U.S. EPA inventory estimate, likely because existing inventory methods miss emissions released during abnormal operating conditions. Methane emissions of this magnitude, per unit of natural gas consumed, produce radiative forcing over a 20-year time horizon comparable to the CO_2 from natural gas combustion. Significant emission reductions are feasible through rapid detection of the root causes of high emissions and deployment of less failure-prone systems.

Alvarez et al., Science, 2018

What's causing this discrepancy? A small number of large sources

higher than mean production site emissions estimated in this work). Emissions released from liquid storage tank hatches and vents represented 90% of these sightings. It appears that abnormal operating conditions must be largely responsible, because the observation frequency was too high to be attributed to routine operations like condensate flashing or liquid unloadings alone (24). All other observations were due to anomalous venting from dehydrators, separators, and flares. Notably, the two largest sources of aggregate emissions in the EPA GHGI—pneumatic controllers and equipment leaks—were never observed from these aerial surveys. Similarly, a national survey of gathering facilities found that emission rates were four times higher at the 20% of facilities where substantial tank venting emissions were observed, as compared to the 80% of facilities without such venting (25). In addition, very large emissions from leaking isolation valves

Alvarez *et* al. 2018

Princeton Marcellus study

-measures ~650 wellpads or 18% of all active unconventional wellpads in the state.

-Finds emission rate of 0.53%

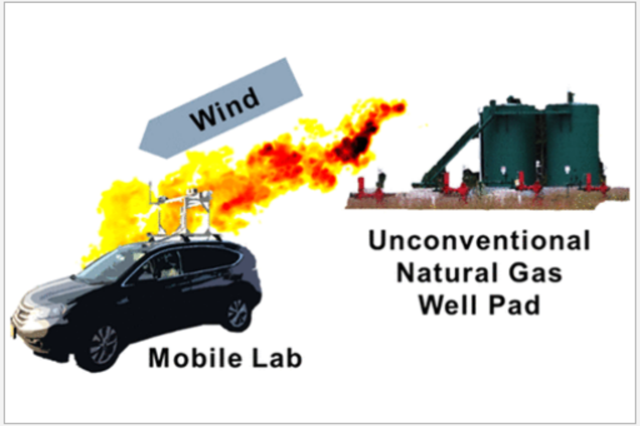
-PA DEP inventory (using EPA methods) estimates emission rate of ~0.1%

-Factor of 5 different!

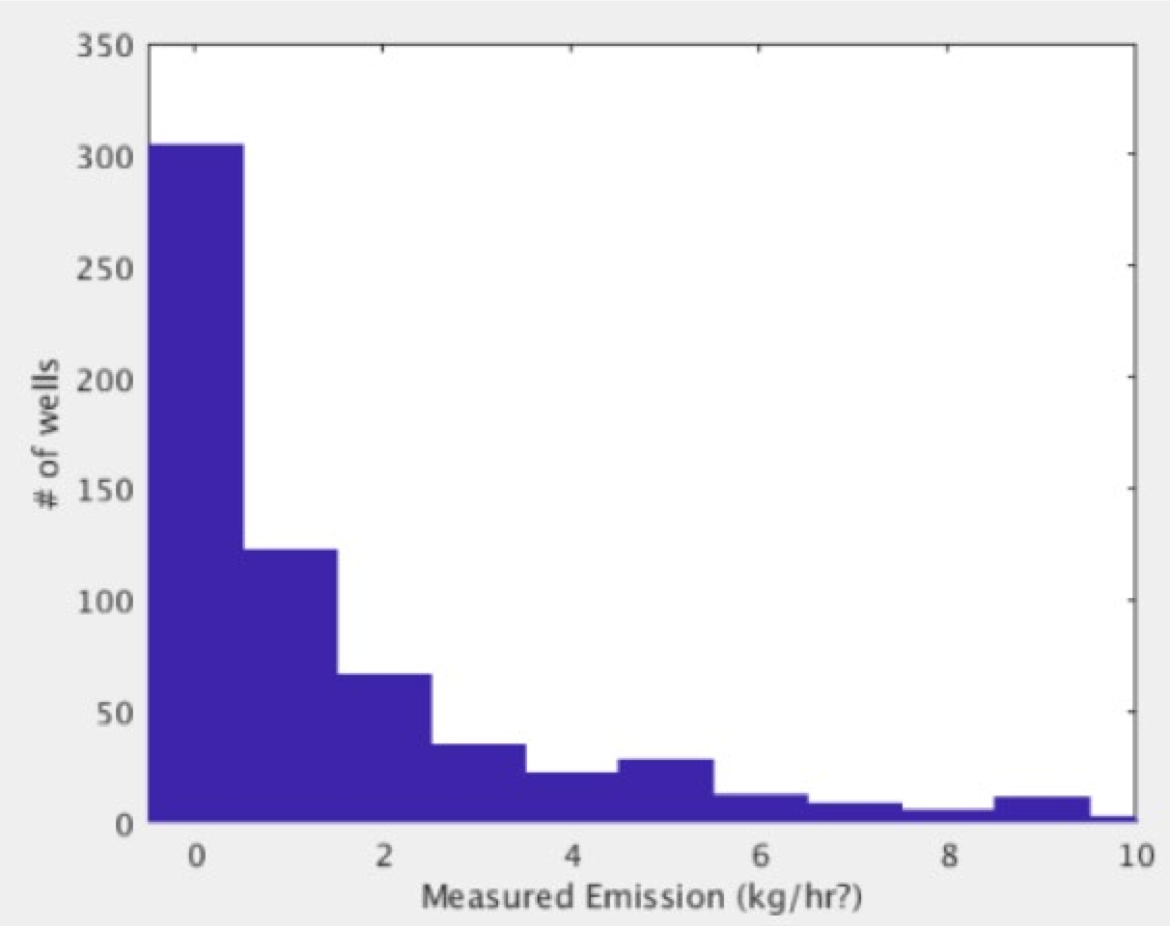
Caulton et al, Environmental Science and Technology, 2019

Abstract

A large-scale study of methane emissions from well pads was conducted in the Marcellus shale (Pennsylvania), the largest producing natural gas shale play in the United States, to better identify the prevalence and characteristics of superemitters. Roughly 2100 measurements were taken from 673 unique unconventional well pads corresponding to ~18% of the total population of active sites and ~32% of the total statewide unconventional natural gas production. A log-normal distribution with a geometric mean of 2.0 kg h^{-1} and arithmetic mean of 5.5 kg h^{-1} was observed, which agrees with other independent observations in this region. The geometric standard deviation (4.4 kg h^{-1}) compared well to other studies in the region, but the top 10% of emitters observed in this study contributed 77% of the total emissions, indicating an extremely skewed distribution. The integrated proportional loss of this representative sample was equal to 0.53% with a 95% confidence interval of 0.45–0.64% of the total production of the sites, which is greater than the U.S. Environmental Protection Agency inventory estimate (0.29%), but in the lower range of other mobile observations (0.09–3.3%). These results emphasize the need for a sufficiently large sample size when characterizing emissions distributions that contain superemitters.

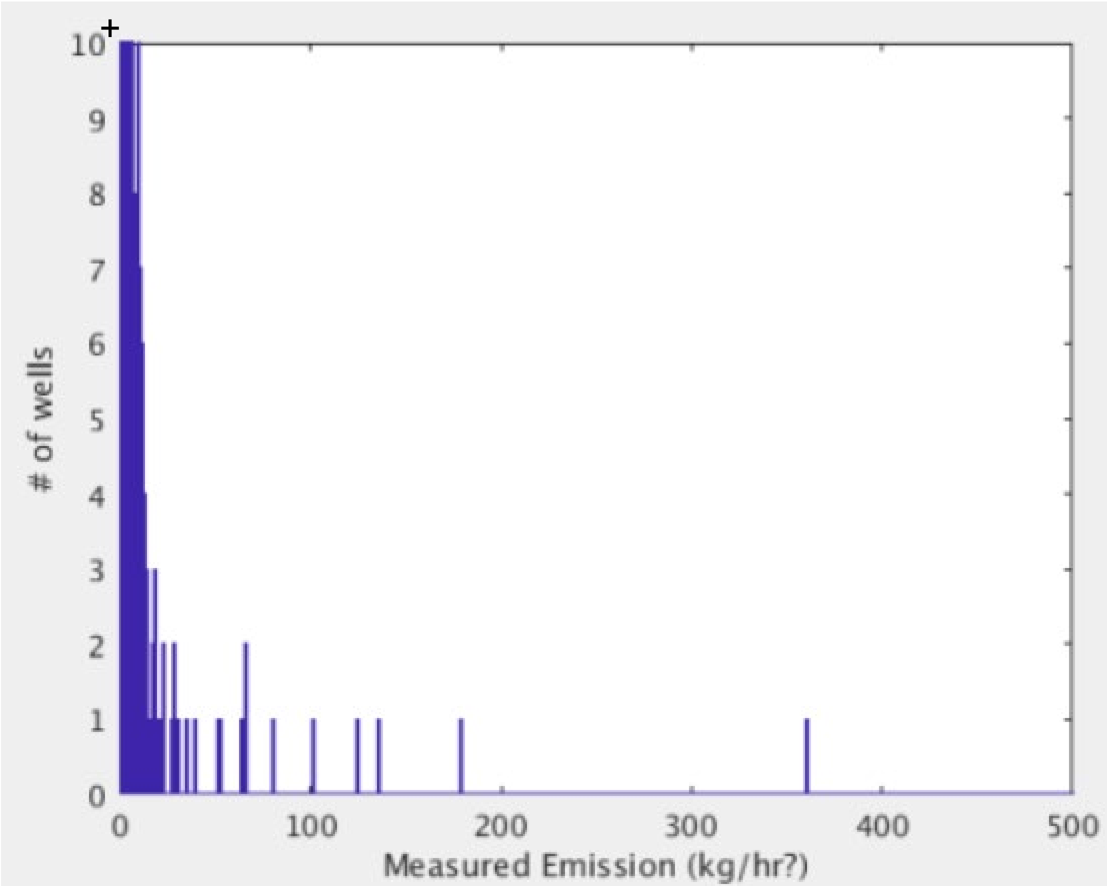


Distribution of emissions per well pad



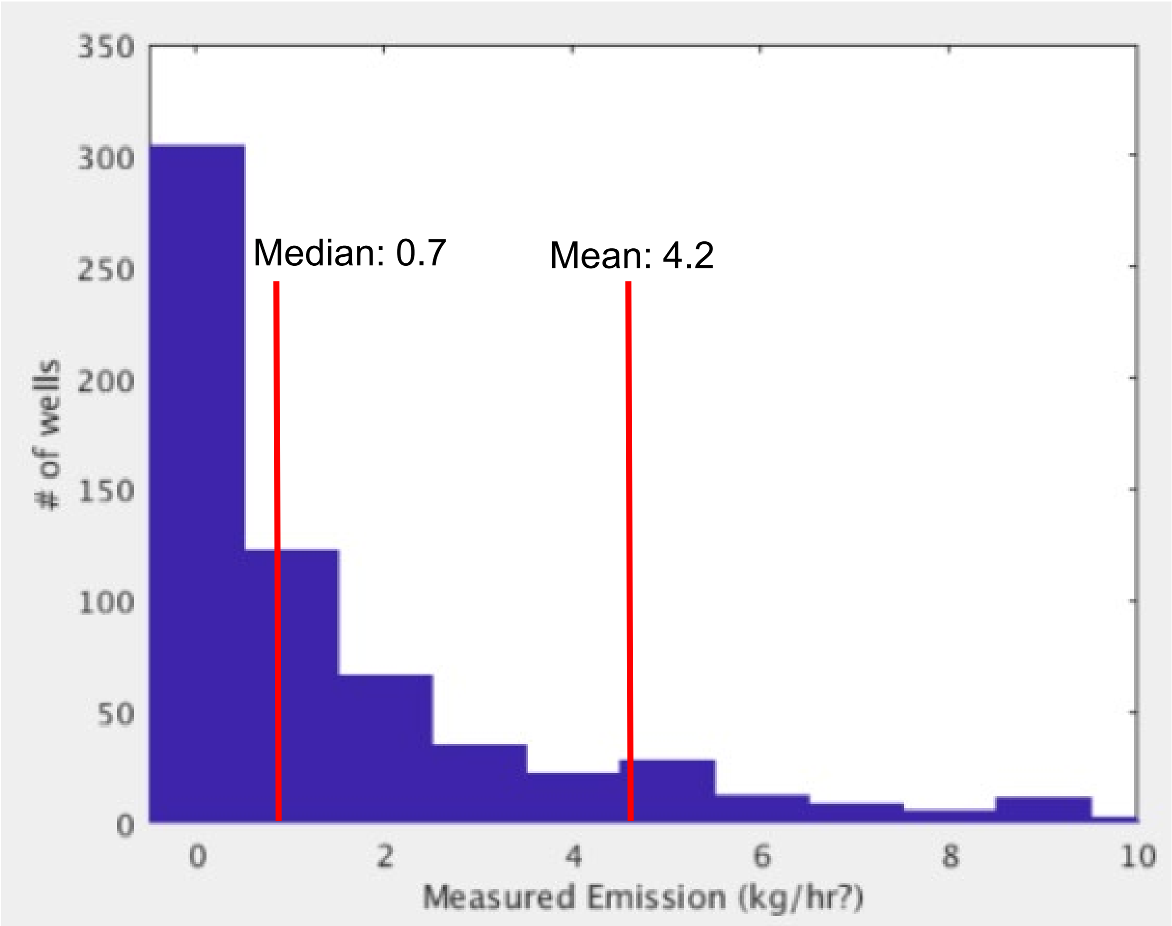
Caulton et al, Environmental Science and Technology, 2019

Oh wait, the x-axis extends further



Caulton et al, Environmental Science and Technology, 2019

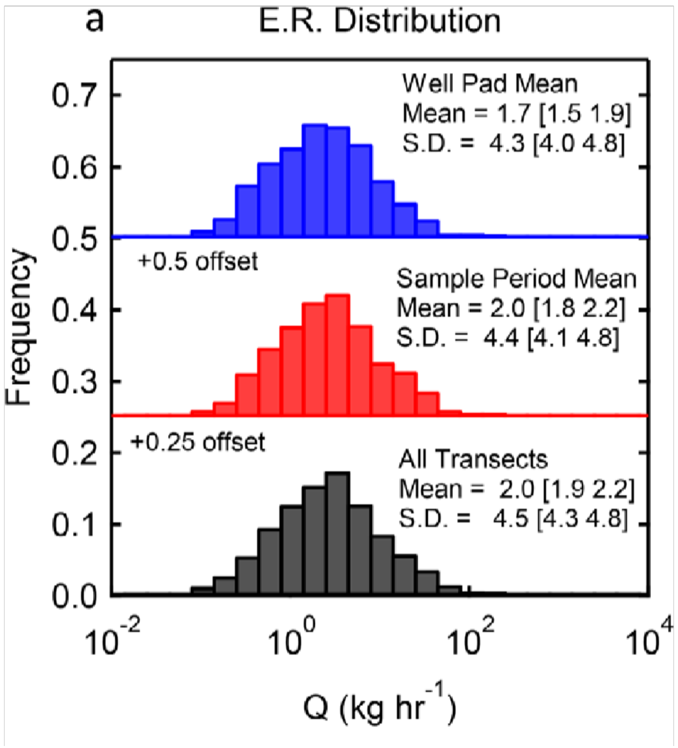
Median vs Mean are a factor of 6 different.

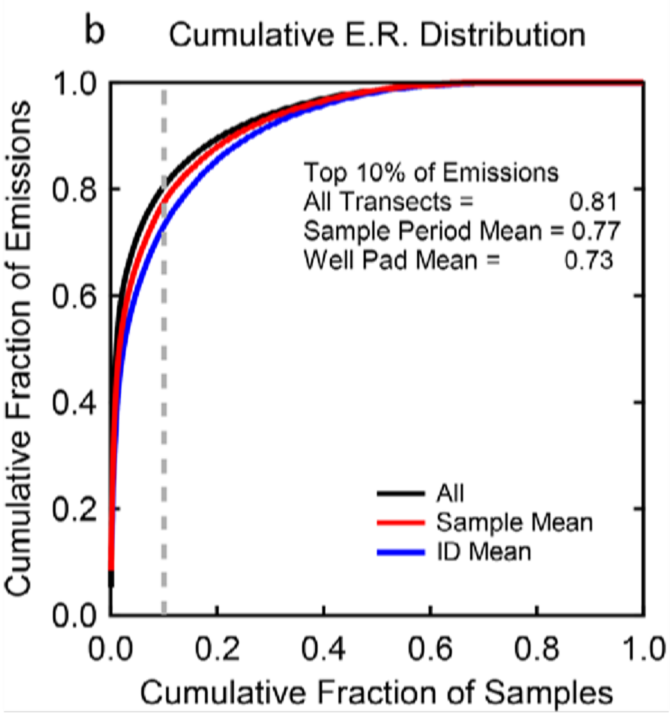


Caulton et al, Environmental Science and Technology, 2019

Median may characterize what to expect at a given wellpad, but doesn't represent the total GHG emissions from the system

Cumulative distribution of emissions, site-by-site





10% of production sites are responsible for nearly 80% of emissions.

Hypothesis: Some of these large sources are missing from EPA inventories.

Caulton et al, Environmental Science and Technology, 2019

Outline

Introduction to the challenges of complementary methods.

Describe atmospheric methods for deriving regional methane emissions. How we can account for:

- Multiple regional sources
- Day / night emissions
- Background contamination
- Variations in emission over time?

Review some recent atmospheric studies of oil/gas methane emissions:

- Airborne/ automobile site-based work synthesized by EDF
- Princeton study
- Penn State airborne work

Outline research needs moving forward

Synthesis

Review some recent atmospheric studies of oil/gas methane emissions:

Airborne/ automobile site-based work synthesized by EDF

Princeton study

Penn State airborne work

- All of these atmospheric data, spanning most of the unconventional gas production in the central and eastern United States, suggest that the EPA inventory currently underestimates emissions by roughly a factor of 2.
- Most of the emissions appear to be caused by a very small number of sites.
- What is missing within the inventory is not clear.
- Continuous monitoring of emissions is limited. Could we just be getting really unlucky with our time sampling?

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Outline research needs moving forward

Long-term, regional-scale atmospheric methane observations

Long-term data sets / analyses underway

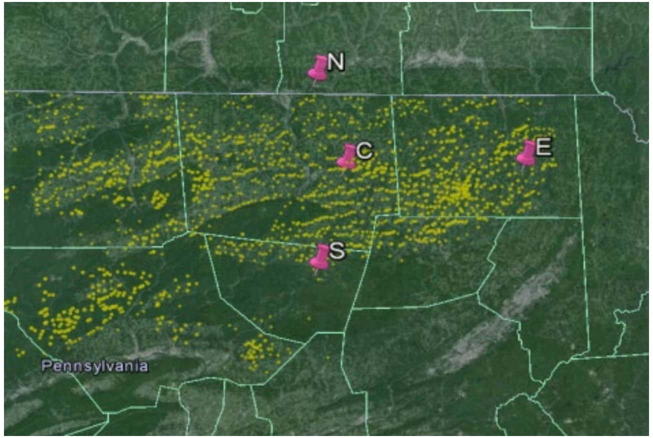
Indianapolis. > 5 year record. Complex background conditions, but capacity to simulate this / filter data. Analyses underway. Also > 40 aircraft flights over > 5 years. Synthetic analysis underway. Similar data sets emerging from Boston, Salt Lake City, Los Angeles. Some published results.

Marcellus. 2 year record. Manuscript ready to be drafted. Results could be presented.

N. America - half(?) decade with reasonable CH4 coverage. PSU/NOAA project to perform continental inversions. NIST - 37 tower inversion for the NE US - 2016-2017 underway.

TROPOMI - experimental
GEOCARB - to be launched

Deployment of calibrated CRDS instruments at the four identified tower locations



Barkley et al, in prep

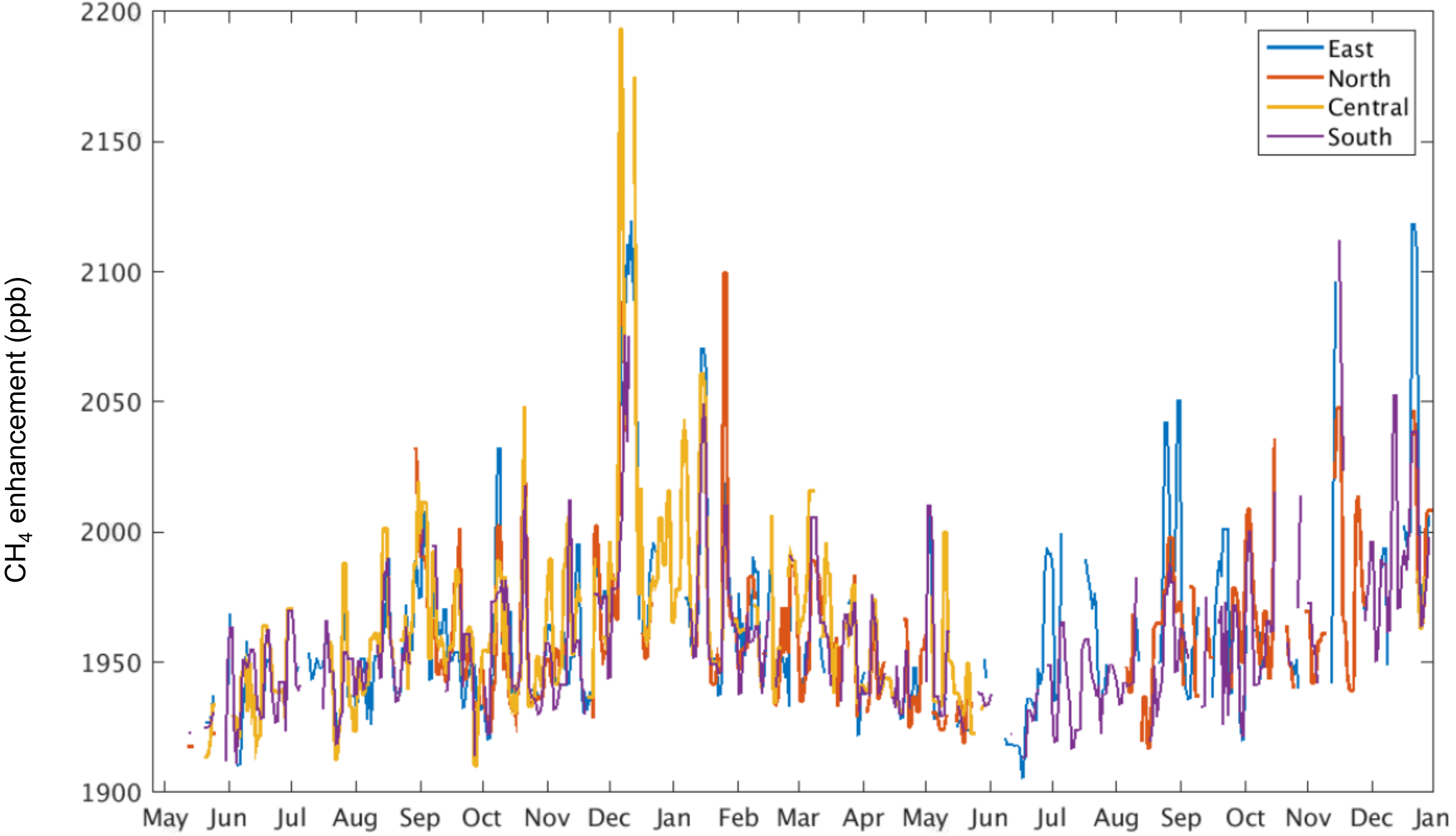
Definitive tower locations of the 4 towers called North (N), East (E), South (S), and Central (C). Unconventional wells are plotted in the background.

	Latitude	Longitude	Installation Date	Elevation (mASL)	Sampling height (mAGL)
Tower N-North	42.0159	-76.4333	05/08/15	476	46
Tower S-South	41.4662	-76.4188	05/07/15	591	61
Tower C-Central	41.7568	-76.3265	05/05/15	341	59
Tower E-East	41.7685	-75.6807	05/13/15	450	59

Coordinates, elevations, and sampling heights of the 4 towers

Photo of temporary shed (upper) and tube inlet at tower N, 46m AGL (lower)

Afternoon Towers CH4: What we actually see.



NOTES

-Seasonal cycle present

-East tower goes rogue after an event in late June

-Something happens meteorologically in early December 2015

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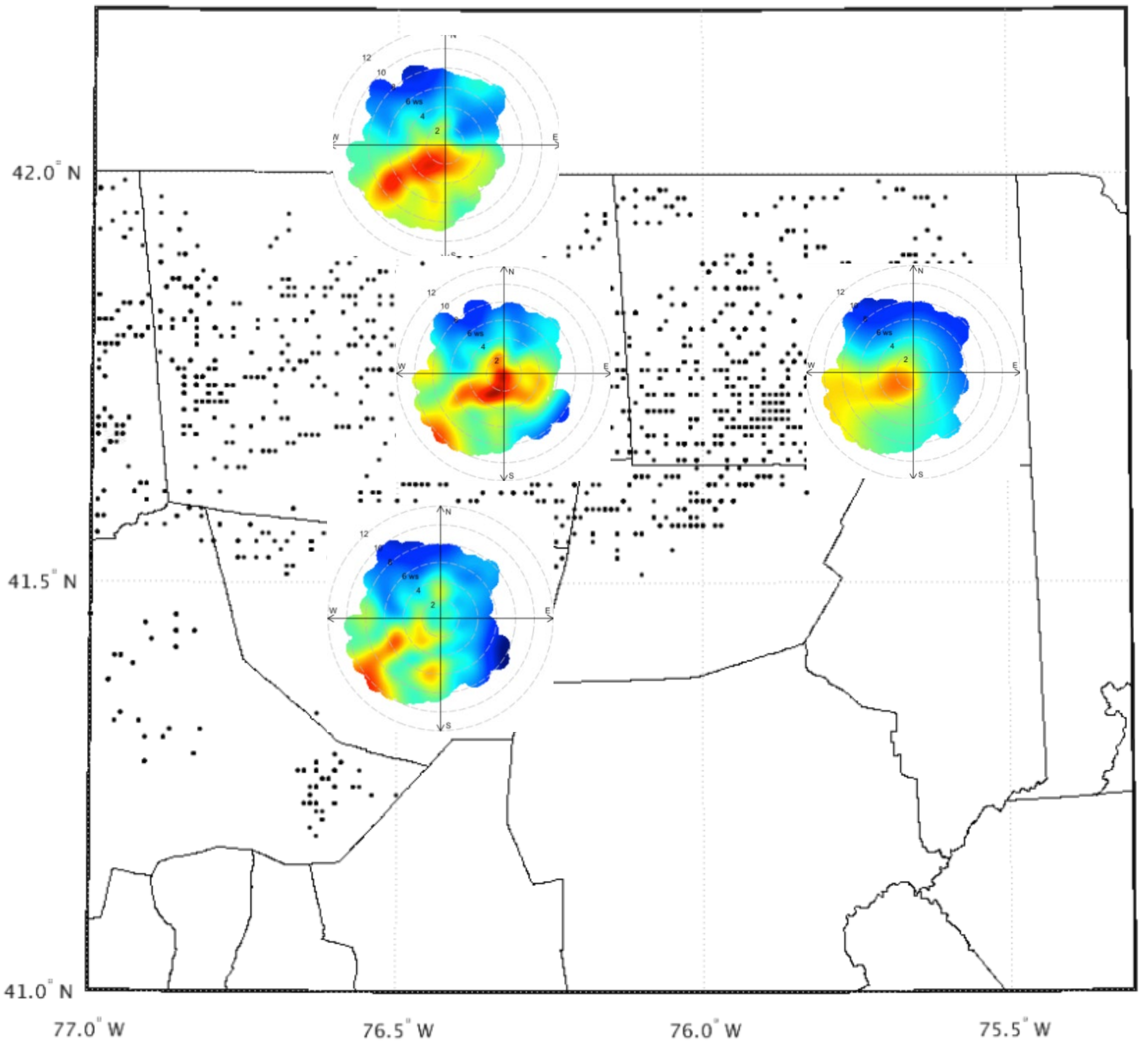

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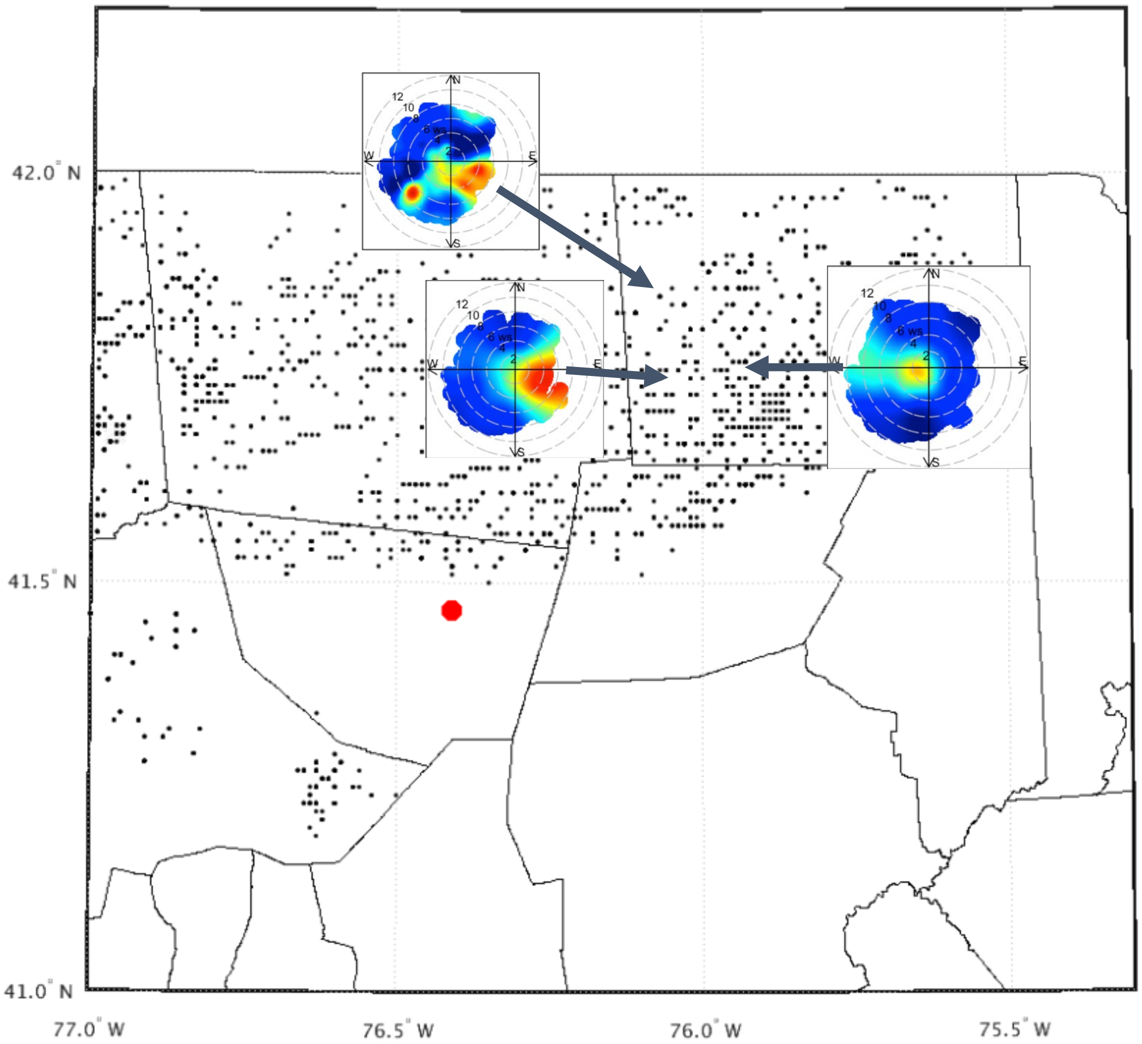

South as background

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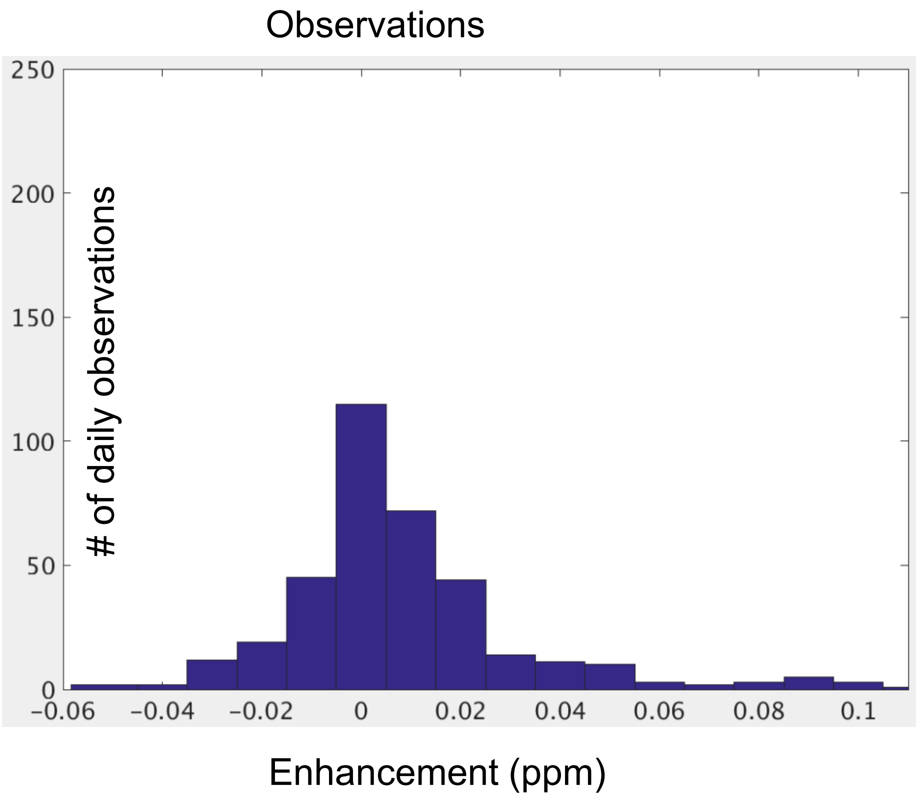
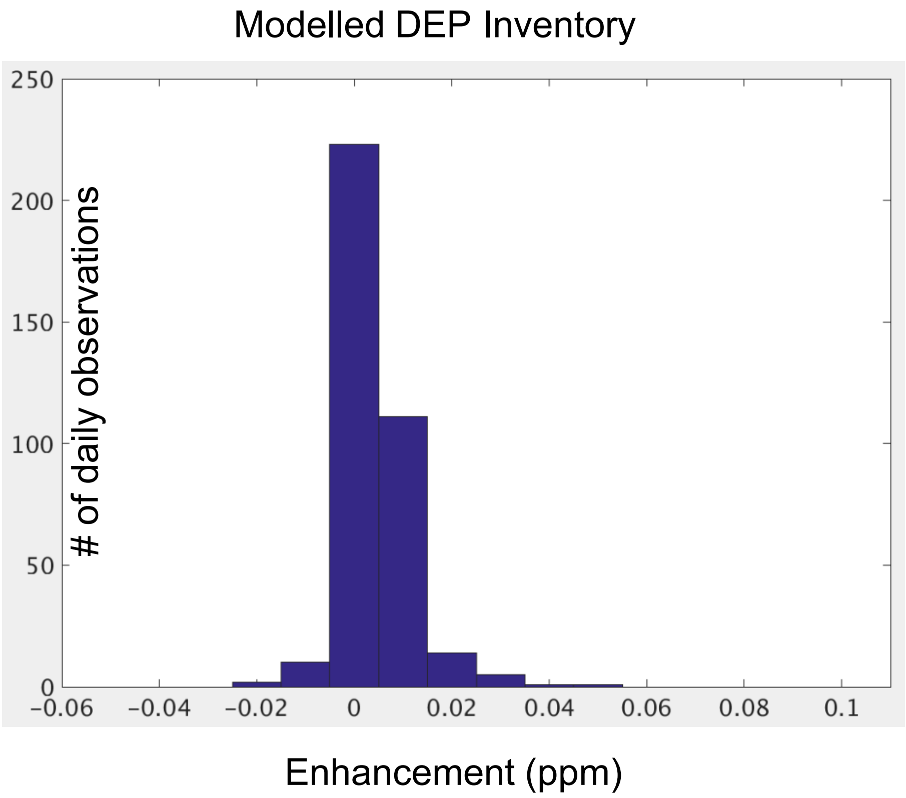
Recreate pdf of enhancements





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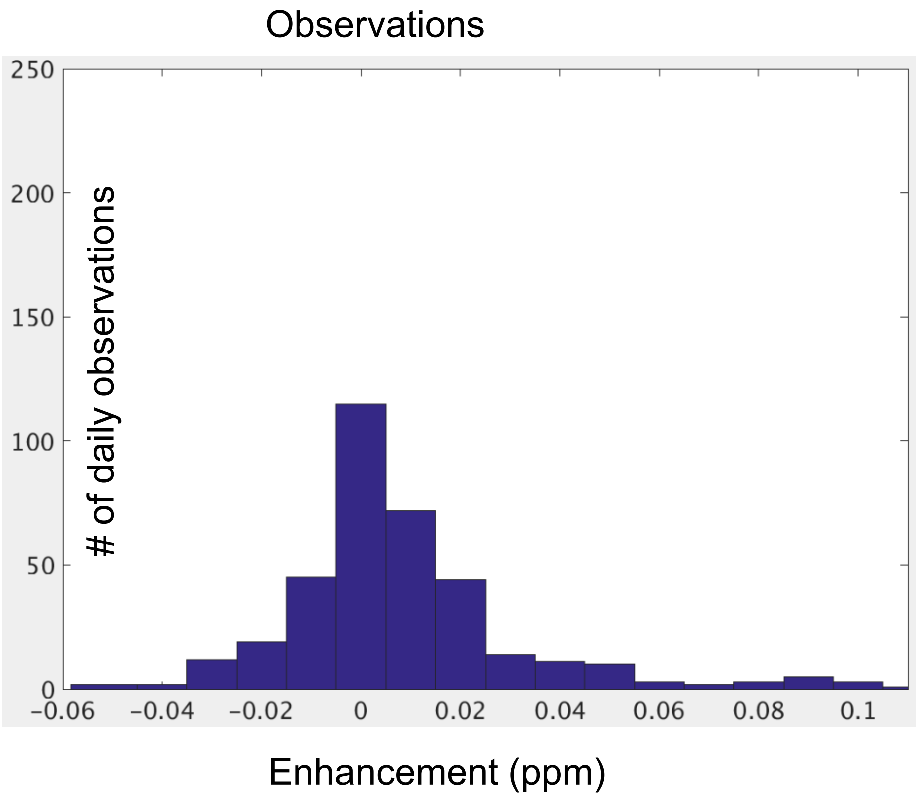

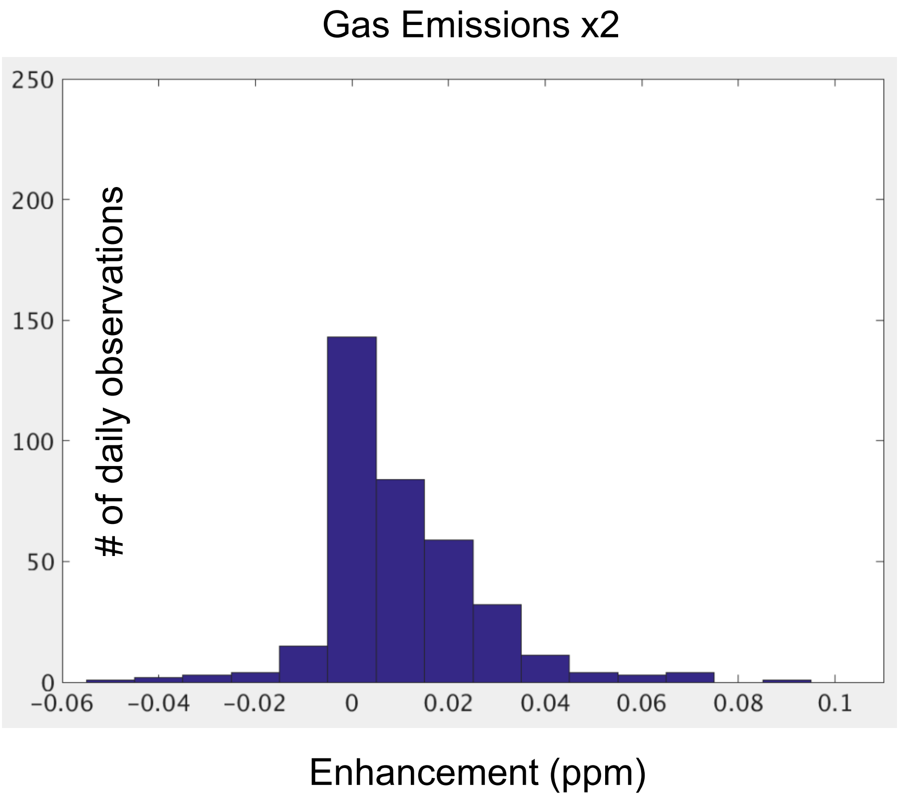

Barkley et al, in prep

Synthesis

Outline research needs moving forward

Continuous monitoring of emissions is happening. These results will be emerging in the data, and the results (to date) appear to be broadly consistent with the airborne studies.

What else is needed?

A call for collaborative research.

Need:

Field measurements designed to understand the difference between inventory and atmospheric methods at the level that allows the inventory to be updated.

Hypothesis: Inventory data are reasonably accurate *for what they include*. Abnormal operating conditions at a small number of sites are not included.

Hard problem. Once we have found sites with anomalously large emissions, how can we clearly identify the discrepancy with inventory, in a way that enables a more accurate inventory?

If we want an accurate national oil and gas methane emissions inventory, we need to solve this problem.

thanks for your attention

Barkley et al, in prep.

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