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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Outline research needs moving forward
What’s the issue?
Why use atmospheric methods?
Why are there disagreements among methods?
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.

This is why we know total global methane emissions.

The atmospheric is a powerful and valuable integrator of emissions.
What’s the issue?
Why use atmospheric methods?
Why are there disagreements among methods?
Method 1: Bottom-up Approach

Total Emissions

<table>
<thead>
<tr>
<th>Activity</th>
<th>Activity Data</th>
<th>Emission Factor (Potential)</th>
<th>Calculated Potential Emissions (Mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fugitives</td>
<td>301,748 miles</td>
<td>1.55 scfd/mile</td>
<td>3,296.3</td>
</tr>
<tr>
<td>Pipeline Leaks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activity</td>
<td>National Activity Data</td>
<td>National Emission Factor or Range of Regional Values (Potential)</td>
<td>Calculated Potential (Mg)*</td>
</tr>
<tr>
<td>----------</td>
<td>------------------------</td>
<td>---------------------------------------------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td><strong>Gas Wells</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Associated Gas Wells</strong></td>
<td>205,407 dewatered*</td>
<td>7,43-42.6</td>
<td>365,748</td>
</tr>
<tr>
<td><strong>Non-associated Gas Wells (less fracked wells)</strong></td>
<td>205,407 dewatered*</td>
<td>7,43-42.6</td>
<td>365,748</td>
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<tr>
<td><strong>Gas Wells with Hydraulic Fracturing</strong></td>
<td>250,777 dewatered*</td>
<td>7,55-42.49</td>
<td>308,851</td>
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<tr>
<td><strong>Well Pad Equipment</strong></td>
<td>11,136 ft</td>
<td>9,1-7,19</td>
<td>9,936,261</td>
</tr>
<tr>
<td><strong>Injectors</strong></td>
<td>308,377 ft</td>
<td>0,09-1,42</td>
<td>0,73</td>
</tr>
<tr>
<td><strong>Hydraulically Fracturing Completions and Workovers</strong></td>
<td>523,885 (2010)</td>
<td>9,43-6,01</td>
<td>9,936,261</td>
</tr>
<tr>
<td><strong>Compressors</strong></td>
<td>4,518 compressors</td>
<td>2,63-8,12</td>
<td>9,936,261</td>
</tr>
<tr>
<td><strong>Gathering and Boosting Stations</strong></td>
<td>4,999 stations*</td>
<td>5,00-8,00</td>
<td>2,63</td>
</tr>
<tr>
<td><strong>Pipeline Leaks</strong></td>
<td>431,051 miles</td>
<td>32,36-63,1</td>
<td>2,63</td>
</tr>
<tr>
<td><strong>Natural Gas Well Completion, and Well Workover</strong></td>
<td>761 completions/year</td>
<td>703,23-848,65</td>
<td>11,3</td>
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<tr>
<td><strong>Gas Well Workovers without Hydraulic Fracturing</strong></td>
<td>8,932 completions/year</td>
<td>3,97-7,26</td>
<td>44,306</td>
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<tr>
<td><strong>Hydraulically Fracturing Completions and Workovers</strong></td>
<td>1,791 completions/year</td>
<td>36,38</td>
<td>63,8</td>
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<tr>
<td><strong>Fracked Hydraulically Fracturing Completions and Workovers</strong></td>
<td>546 completions/year</td>
<td>2,81</td>
<td>2,096</td>
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<tr>
<td><strong>Hydraulically Fracturing Completions and Workovers with REC</strong></td>
<td>1,043 completions/year</td>
<td>3,2</td>
<td>3,378</td>
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<tr>
<td><strong>Well Workovers that are not</strong></td>
<td>1,076 completions/year</td>
<td>2,86</td>
<td>9,65</td>
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<tr>
<td><strong>Well Workovers that are not</strong></td>
<td>153,067 col/yr</td>
<td>2,95-3,95</td>
<td>971</td>
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<tr>
<td><strong>Normal Operations</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Pneumatic Device Vehicles</strong></td>
<td>83,4,919 (2010)</td>
<td>1,76-14,20</td>
<td>1,105,119</td>
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<tr>
<td><strong>Pneumatic Device–Vehicles–Low Blow (Lil)</strong></td>
<td>220,283 (2010)</td>
<td>22,52-26,64</td>
<td>220,283</td>
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<tr>
<td><strong>Pneumatic Device–High Blow (Hi)</strong></td>
<td>25,086 (2010)</td>
<td>612,96-74,91</td>
<td>25,086</td>
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<tr>
<td><strong>Pneumatic Device–Compressed Air Blower (BC)</strong></td>
<td>479,933 (2010)</td>
<td>21,36-4,36</td>
<td>479,933</td>
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<tr>
<td><strong>Chemical Injection Pumps</strong></td>
<td>83,4,919 (2010)</td>
<td>1,76-14,20</td>
<td>83,4,919</td>
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<tr>
<td><strong>Kerney Pumps</strong></td>
<td>5,012,733 (2010)</td>
<td>977,7-1,560</td>
<td>100,057</td>
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<tr>
<td><strong>Dewatering Plants</strong></td>
<td>5,026,983 (2010)</td>
<td>271,58-2,341</td>
<td>31,483</td>
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<tr>
<td><strong>Condensate Tanks Without Control Devices</strong></td>
<td>139,4,919 (2010)</td>
<td>21,87-35,27</td>
<td>253,092</td>
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<tr>
<td><strong>Condensate Tanks with Control Devices</strong></td>
<td>139,4,919 (2010)</td>
<td>4,2-35,90</td>
<td>253,092</td>
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<tr>
<td><strong>Compressor Exhaust Vent</strong></td>
<td></td>
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<tr>
<td><strong>Gas Engines</strong></td>
<td>61,648 MWh/yr</td>
<td>62,37-2,95</td>
<td>749,785</td>
</tr>
<tr>
<td><strong>Well pad equipment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Liquid Unloading with Plunger Loks</strong></td>
<td>22,477 MWh/yr</td>
<td>2,95-11,34</td>
<td>59,289</td>
</tr>
<tr>
<td><strong>Liquid Unloading without Plunger Loks</strong></td>
<td>37,912 MWh/yr</td>
<td>2,95-11,34</td>
<td>59,289</td>
</tr>
<tr>
<td><strong>Blowdowns</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Vented Blowdowns</strong></td>
<td>422,542 hours</td>
<td>7,86-8,74</td>
<td>688</td>
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<tr>
<td><strong>Piped Blowdowns</strong></td>
<td>431,051 miles (gathering)</td>
<td>304-491-20,36</td>
<td>2,740</td>
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<td><strong>Drainage Blowdowns</strong></td>
<td>48,518 compressors</td>
<td>9,18-4,49</td>
<td>48,518</td>
</tr>
<tr>
<td><strong>Drainge Blowdowns</strong></td>
<td>48,518 compressors</td>
<td>9,18-4,49</td>
<td>48,518</td>
</tr>
<tr>
<td><strong>Power Safetys Valves</strong></td>
<td>1,015,140 (2010)</td>
<td>35,56-36,26</td>
<td>700</td>
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<tr>
<td><strong>Mileage</strong></td>
<td>107,783 col</td>
<td>68,74-78,04</td>
<td>1,463</td>
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<tr>
<td><strong>Produced Water from Coal Bed Methane Wells (black water)</strong></td>
<td>5,000 gallons</td>
<td>0,35-0,62</td>
<td>12,790</td>
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<tr>
<td><strong>Driller Sites</strong></td>
<td>20,596,130 (2010)</td>
<td>21,15-21,97</td>
<td>47,032</td>
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<tr>
<td><strong>Offshore Platforms</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Shallow Water Gas Platforms (Gulf of Mexico and Pacific)</strong></td>
<td>1,972 platform</td>
<td>0,896-3,914</td>
<td>1,972</td>
</tr>
</tbody>
</table>

**Table 8-134: 2014 Data and Calculated GHG Emissions (Mg) for the Natural Gas Production Stage**
Emissions are primarily from the production sector.

- Production: 63.5%
- T&S: 18.8%
- Processing: 7.1%
- Distribution: 7.1%
- Abandoned: 3.5%

US inventory for 2014.
US inventory for 2014.

- Pneumatic Devices: 53%
- Everything else: 47%
Method 2: Atmospheric mass-balance

\[ FLUX = \bar{U} \cos(\bar{\theta}) \int_{-b}^{b} \Delta X \int_{z=0}^{z_{\text{top}}} n_{\text{air}} \, dz \, dx \]

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
What’s the issue?
Why use atmospheric methods?
Why are there disagreements among methods?
What could be wrong with the top-down approach?

Leakage rate = 128% of production?
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.
This well is emitting 25kg/hr.

There are 5 wells in the basin.

Total emissions in this region = 5 * 25 = 125kg/hr.

The CH\textsubscript{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.
That top-down estimate is too high! They probably forgot to account for the cows.

That bottom-up estimate is too low! They probably didn’t account for any extreme emissions!
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
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
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 = 1x10^{-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 = 1x10^{-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.
Outline

Introduction to the challenges of complementary methods. Describe atmospheric methods for deriving regional methane emissions. How we can account for:

- Multiple regional sources
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- Variations in emission over time?

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

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- Princeton study
- Penn State airborne work

Outline research needs moving forward
Time to deploy the grad student
The Marcellus Study:

**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

Unconventional Production

Conventional Production

Distribution

Animal Agriculture

Coal mines/beds

Landfill / Industry
Step 2: Model Methane Enhancements

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

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

Barkley et al., ACP, 2017
Unconventional Production/Gathering

Coal Mines

NG Transmission/Distribution

Enteric Fermentation

Conventional Wells

Landfills and Other

May 24th 2015 Total Enhancement

Modeled Methane Enhancement (in ppm)

Barkley et al., ACP, 2017
Step 3: Optimize Natural Gas Emissions

May 29$^{th}$ 2015:

Wind Vector

Atmospheric CH$_4$ enhancement (in ppm)

Barkley et al., ACP, 2017
Aircraft emissions estimate on May 29th 2015

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 29$^{th}$ flight (in ppm)
Enhancement (ppm)

Natural Gas CH$_4$ Enhancement (ppm)

Barkley et al., ACP, 2017

Observation-derived natural gas CH$_4$ enhancement for the May 29$^{th}$ 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 24th, 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)
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

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

Barkley et al., ACP, 2017

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

**GOOD NEWS:** Total flux is *easier to quantify*

**BAD NEWS:** Total flux is *harder to attribute*

Barkley et al., GRL, 2019A
September 14, 2015

Optimized Model vs Obs solution using:

- UNG Rate = 0%
- Coal rate = 1.8 x EPA inventory
September 14, 2015

Optimized Model vs Obs solution using:

UNG Rate = 1.6%
Coal rate = 1.0 x EPA inventory

Barkley et al., GRL, 2019A
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% $\text{C}_2\text{H}_6/\text{CH}_4$

Kim 1973

SWPA Gas: 7.0% $\text{C}_2\text{H}_6/\text{CH}_4$

Colon-Roman 2016

Biogenic sources: 0% $\text{C}_2\text{H}_6/\text{CH}_4$

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

Mixture Ratio = 2.6%

UNG = 0.9% of production
Coal Rate = 1.3 x EPA Inventory

Barkley et al., GRL, 2019A
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!!!
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

Gridded EPA Inventory for 2012

Includes all methane emissions included in the National Greenhouse Gas Inventory.
Fly downwind of gas production in southern US and use frontal transects to estimate emissions.
Southerly winds begin 2 days of steady state winds Plume converges at front

Barkley et al., GRL, 2019B
How we are obtaining measurements

- 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

Oct 18, 2017
Original

CH₄ Enhancement (ppm)

Barkley et al., GRL, 2019B
We’re really good at recreating the total methane plume

Figure 2. Observed vs. modelled CH₄ 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)

Oil and Gas

Animal Agriculture

Everything else

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
<table>
<thead>
<tr>
<th>ID</th>
<th>Basin</th>
<th>$\text{C}_2\text{H}_6/\text{CH}_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Anadarko</td>
<td>0.080</td>
</tr>
<tr>
<td>B</td>
<td>Woodford</td>
<td>0.070</td>
</tr>
<tr>
<td>C</td>
<td>Permian</td>
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<tr>
<td>D</td>
<td>Ft. Worth</td>
<td>0.067</td>
</tr>
<tr>
<td>E</td>
<td>East Texas</td>
<td>0.040</td>
</tr>
<tr>
<td>F</td>
<td>Gulf</td>
<td>0.051</td>
</tr>
</tbody>
</table>

Methane emissions (Mg a$^{-1}$ km$^{-2}$)

Barkley et al., GRL, 2019B
10/21/2017

Methane Enhancement (ppm)

Ethane Enhancement (ppb)

Barkley et al., GRL, 2019B
Figure 4. Observed vs. modelled C$_2$H$_6$ for each of the 7 flights using the optimized gas and animal ag emission rates for each flight.

Barkley et al., GRL, 2019B
Best estimate of oil and gas emissions is roughly 2x inventory.

Animal agriculture emissions estimate is roughly equal to inventory.

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$_2$H$_6$ data. (purple?) Both gas and animal ag inventories were optimized using the joint CH$_4$-C$_2$H$_6$ technique.

Barkley et al., GRL, 2019B
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Introduction to the challenges of complementary methods.
Describe atmospheric methods for deriving regional methane emissions. How we can account for:

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

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

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- Princeton study
- Penn State airborne work

Outline research needs moving forward
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.*
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- 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.

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
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.

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

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)

Table 1. Summary of this work’s bottom-up estimates of CH₄ 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).

<table>
<thead>
<tr>
<th>Industry segment</th>
<th>2015 CH₄ Emissions (Tg/y)</th>
<th>This work (bottom-up)</th>
<th>EPA GHGI (/7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>7.6 (+1.9/-1.6)</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>Gathering</td>
<td>2.6 (+0.59/-0.18)</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Processing</td>
<td>0.72 (+0.20/-0.071)</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>Transmission and Storage</td>
<td>1.8 (+0.35/-0.22)</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Local Distribution*</td>
<td>0.44 (+0.51/-0.22)</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>Oil Refining and Transportation*</td>
<td>0.034 (+0.050/-0.008)</td>
<td>0.034</td>
<td></td>
</tr>
<tr>
<td>U.S. O/NG total</td>
<td>13 (+2.1/-1.7)</td>
<td>8.1 (+2.1/-1.4)†</td>
<td></td>
</tr>
</tbody>
</table>

*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!

Alvarez et al., Science, 2018

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 $13 \pm 2$ 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...
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
Median vs Mean are a factor of 6 different.

Median: 0.7  Mean: 4.2

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?
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?

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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

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

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

Coordinates, elevations, and sampling heights of the 4 towers

Barkley et al, in prep

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

Barkley et al, in prep
South as background

Barkley et al, in prep
Recreate pdf of enhancements

Observations Modelled DEP Inventory

Enhancement (ppm)  Enhancement (ppm)

Barkley et al, in prep
Recreate pdf of enhancements

Observations

Gas Emissions x2

Barkley et al, in prep
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
References