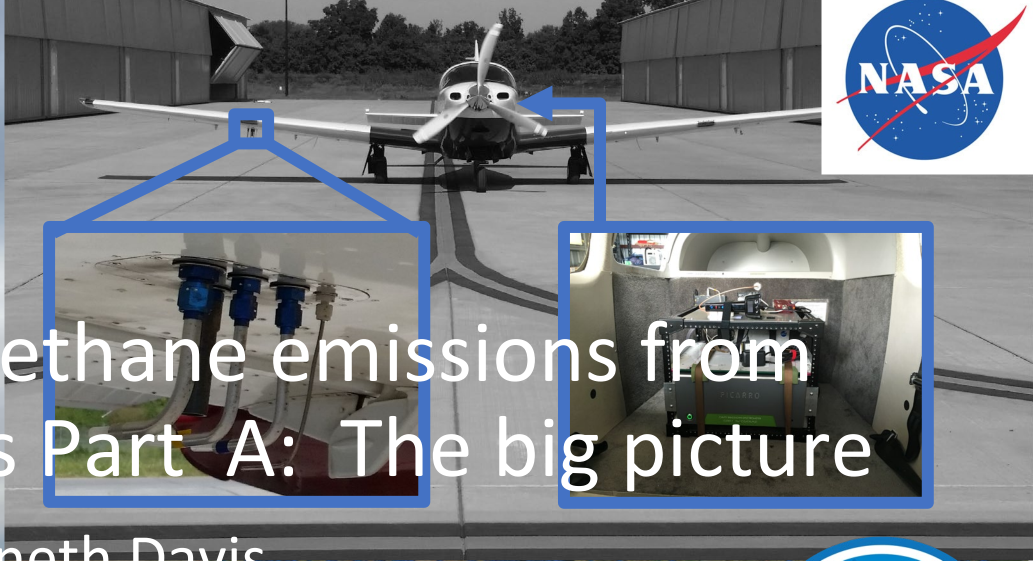

Understanding methane emissions from natural gas systems Part A: The big picture

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The Pennsylvania State University

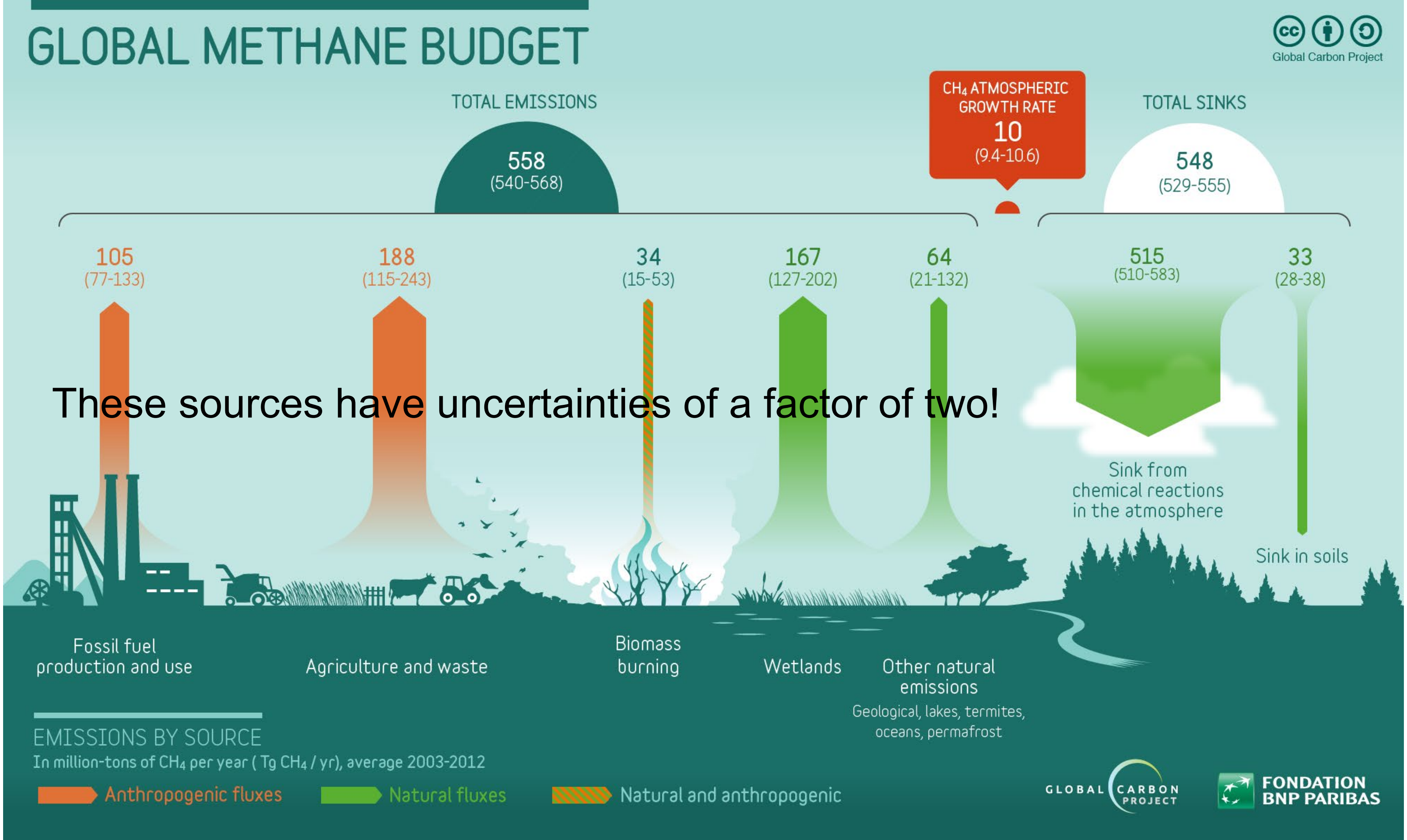
with contributions from many, many colleagues.

CH_4 Connections

11 October, 2021 Fort Collins, CO

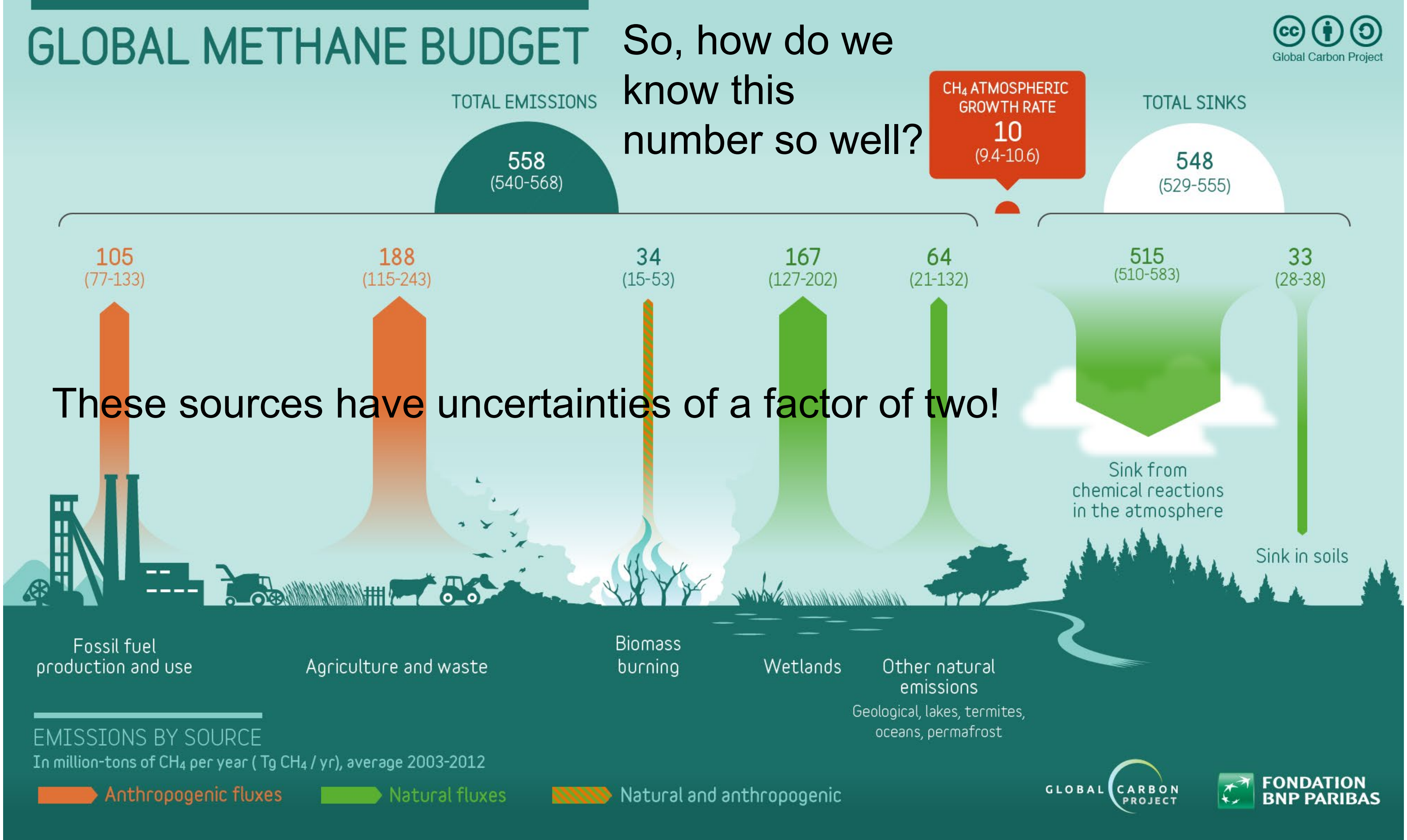
The very big picture

- Do we need atmospheric data to understand methane emissions?

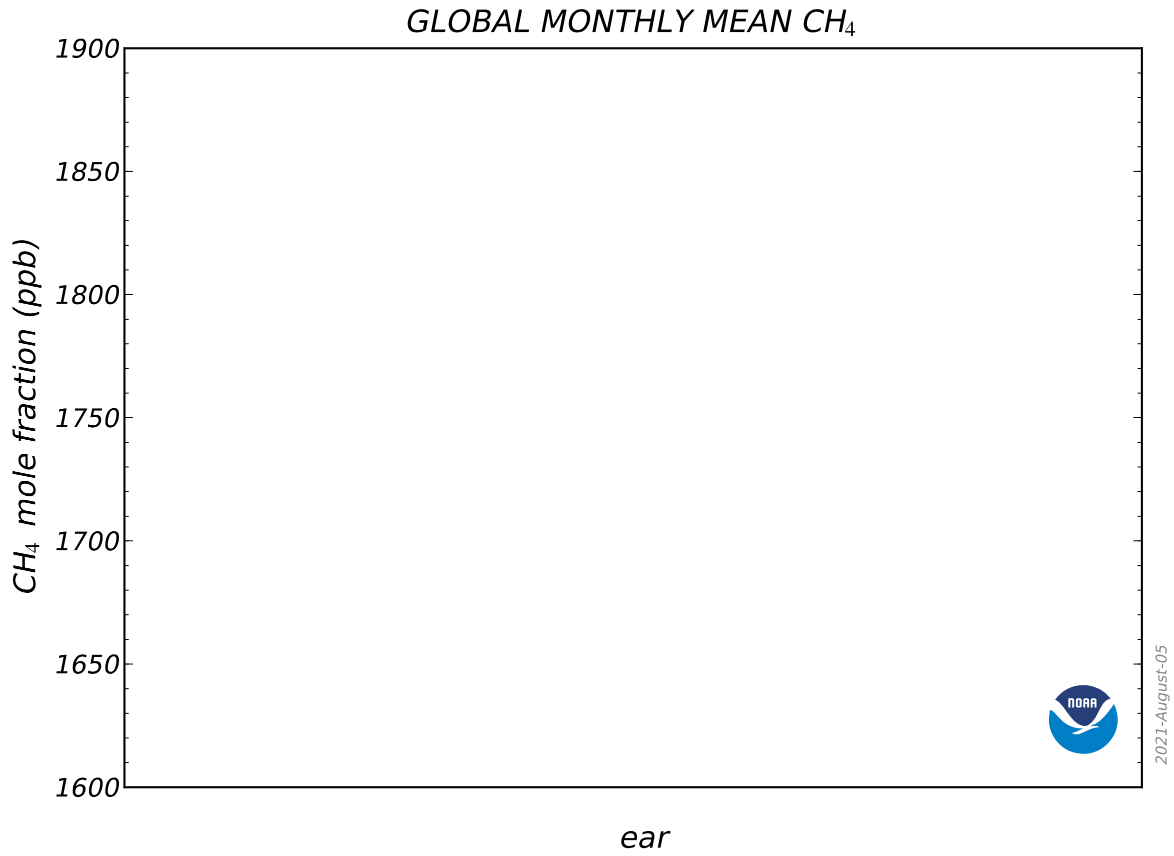

GLOBAL METHANE BUDGET
Global Carbon Project
TOTAL EMISSIONS
558
(540-568)
CH_4 ATMOSPHERIC GROWTH RATE
10
(9.4-10.6)
TOTAL SINKS
548
(529-555)
105
(77-133)
188
(115-243)
34
(15-53)
167
(127-202)
64
(21-132)
515
(510-583)
33
(28-38)
These sources have uncertainties of a factor of two!
Sink from chemical reactions in the atmosphere
Sink in soils
Fossil fuel production and use
Agriculture and waste
Biomass burning
Wetlands
Other natural emissions
Geological, lakes, termites, oceans, permafrost
EMISSIONS BY SOURCE
In million-tons of CH_4 per year (Tg CH_4 / yr), average 2003-2012
Anthropogenic fluxes
Natural fluxes
Natural and anthropogenic
GLOBAL CARBON PROJECT
FONDATION BNP PARIBAS

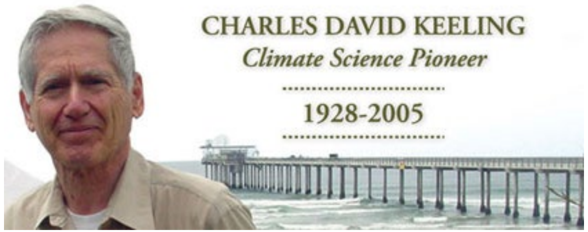
So, how do we know this number so well?

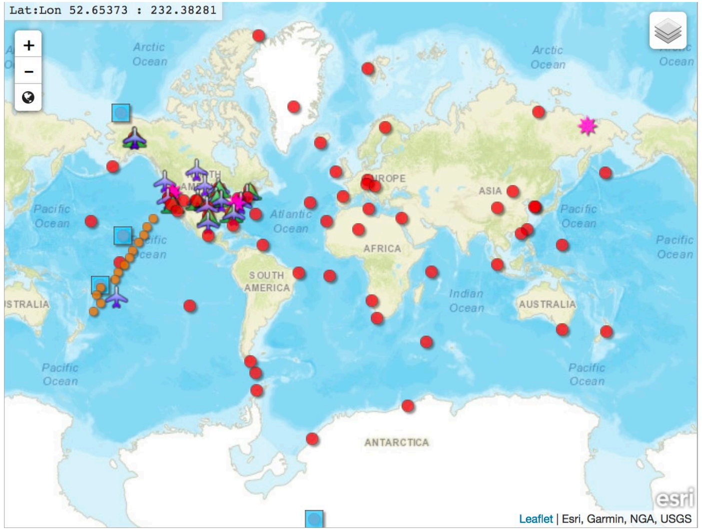
These sources have uncertainties of a factor of two!



Atmospheric data!





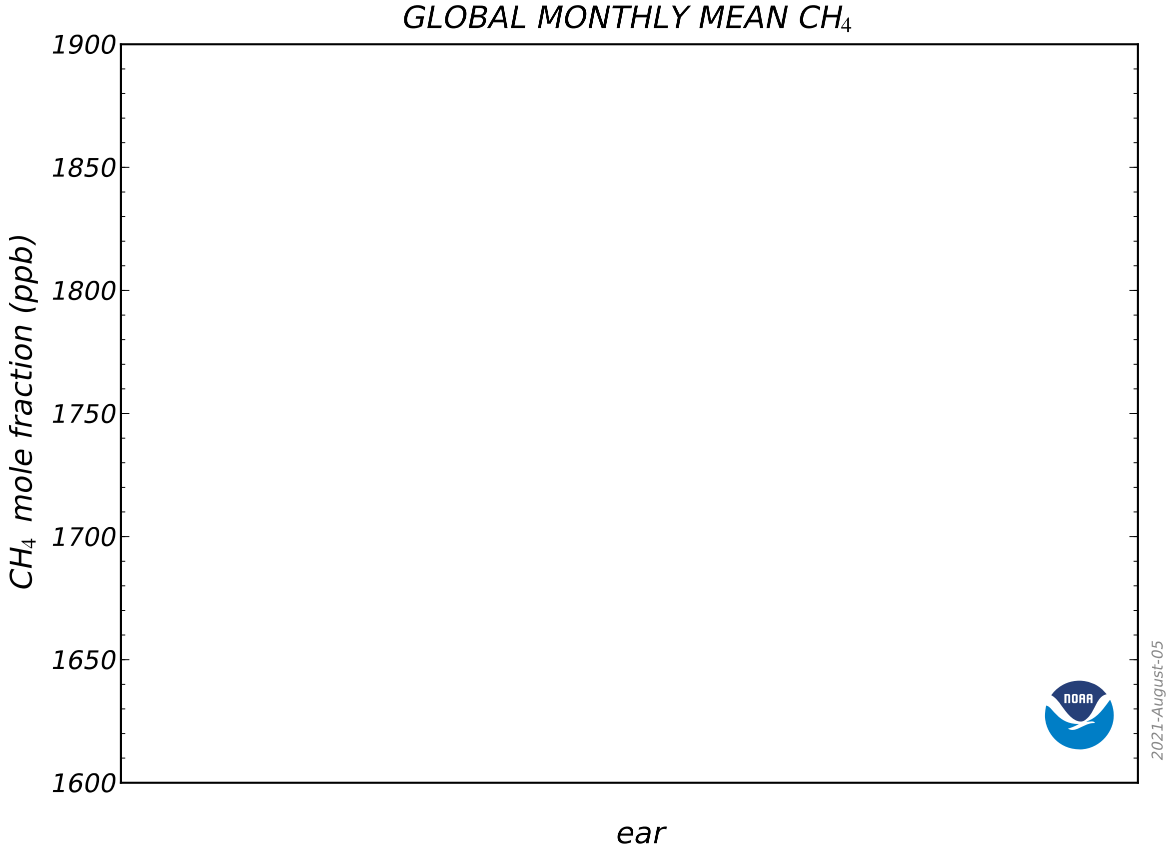


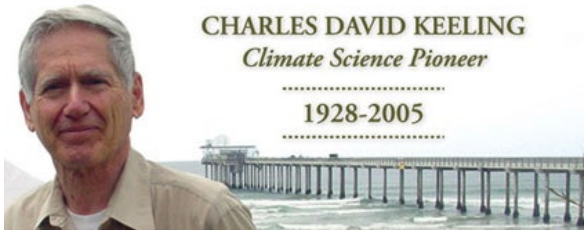
NOAA GML, 2021

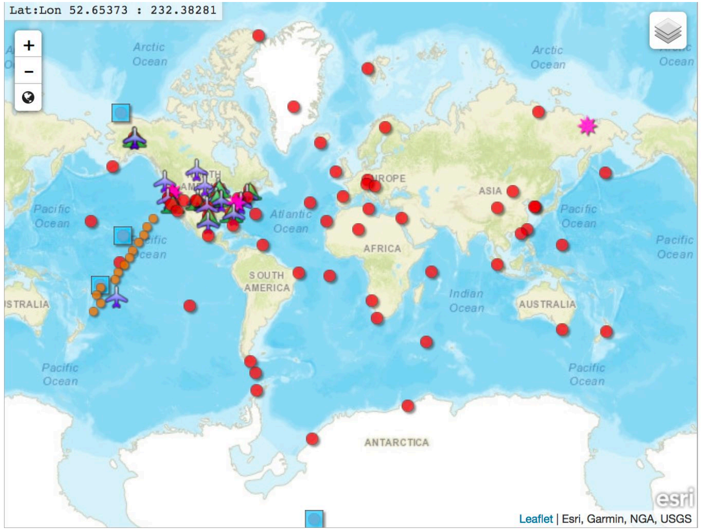
Data site:
https://gml.noaa.gov/ccgg/

Atmospheric data!

We need atmospheric data to understand methane emissions.







NOAA GML, 2021

Data site: https://gml.noaa.gov/ccgg/

The big picture

- Do we need atmospheric data to understand methane emissions?
- Many greenhouse gas (GHG) sources, e.g. methane emissions from the natural gas system, are very difficult to quantify accurately using "bottom up" methods…
    - Inventories
    - Process-based models

The big picture

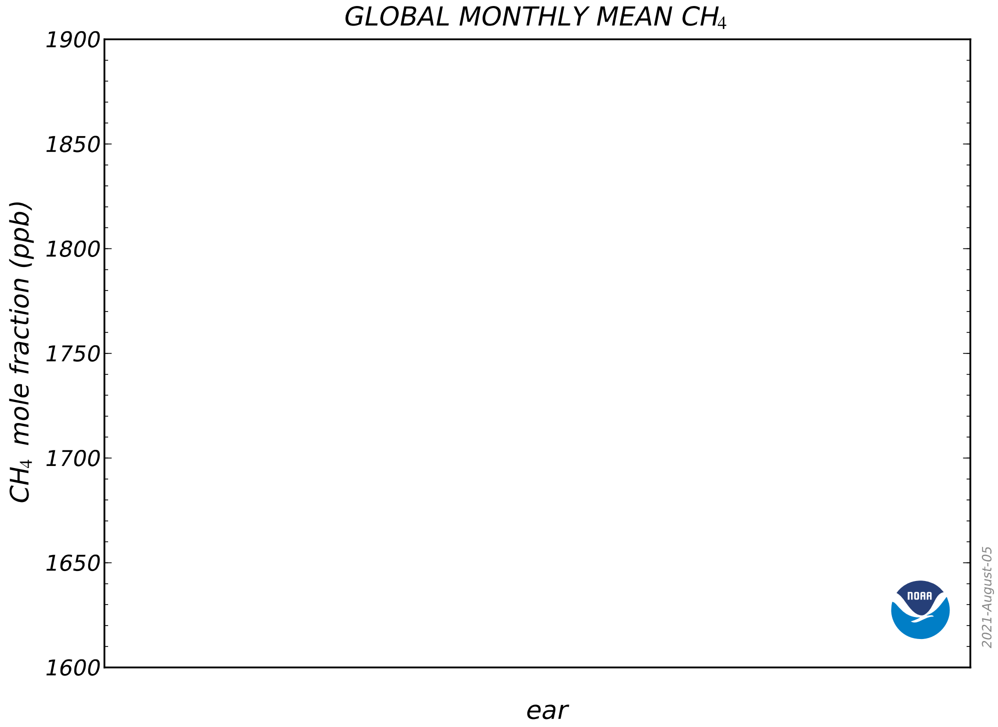
- Do we need atmospheric data to understand methane emissions?
- Many greenhouse gas (GHG) sources, e.g. methane emissions from the natural gas system, are very difficult to quantify accurately using "bottom up" methods…
  - Inventories
  - Process-based models
- Why?

The big picture

- Do we need atmospheric data to understand methane emissions?
- Many greenhouse gas (GHG) sources, e.g. methane emissions from the natural gas system, are very difficult to quantify accurately using “bottom up” methods…
    - Inventories
    - Process-based models
- Why?
    - Many small sources. No established accounting system.
    - Leaks don’t report themselves.
- We need atmospheric data. GHG emissions audits.

The big picture

- But this…
- Is global.
- Can we use atmospheric data to “zoom in” on natural gas systems?
- *Yes!*



How?

- Measure atmospheric CH_4 upwind and downwind of a source.
- Methane "enhancement" = downwind concentration – upwind concentration
  - $C^{enh} = C^D - C^U$

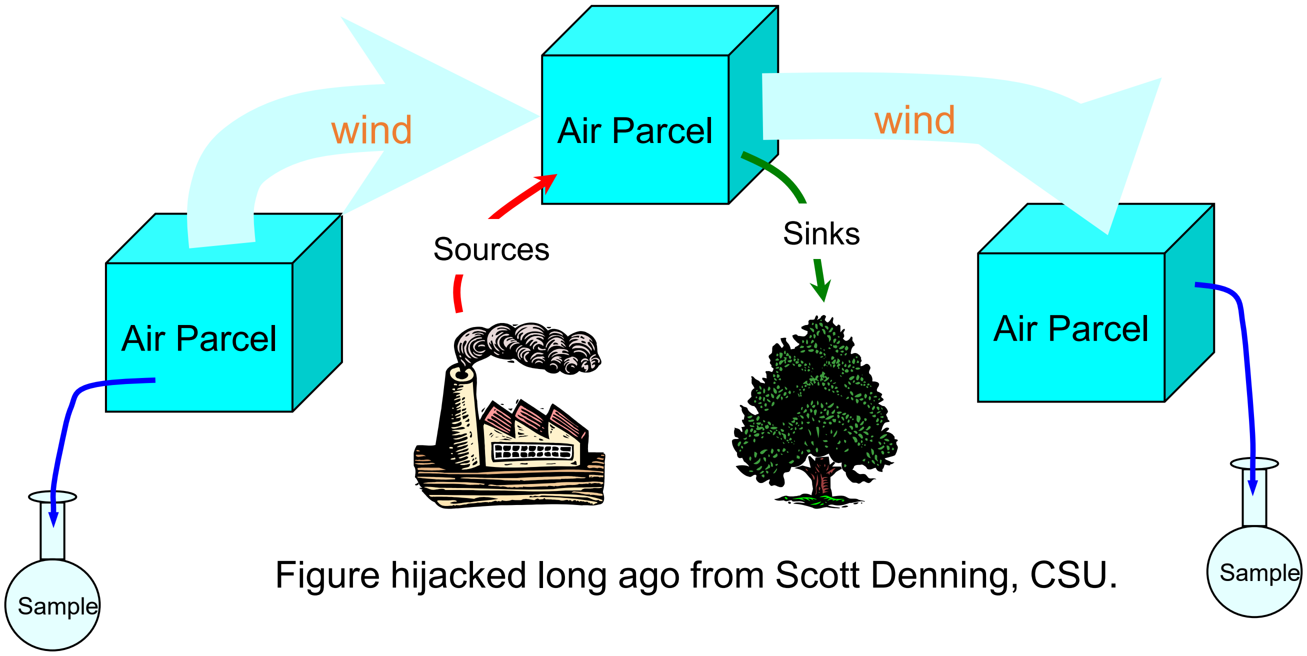


Figure hijacked long ago from Scott Denning, CSU.

- Emission rate is proportional to C^{enh} times (mixing depth) times (wind speed)

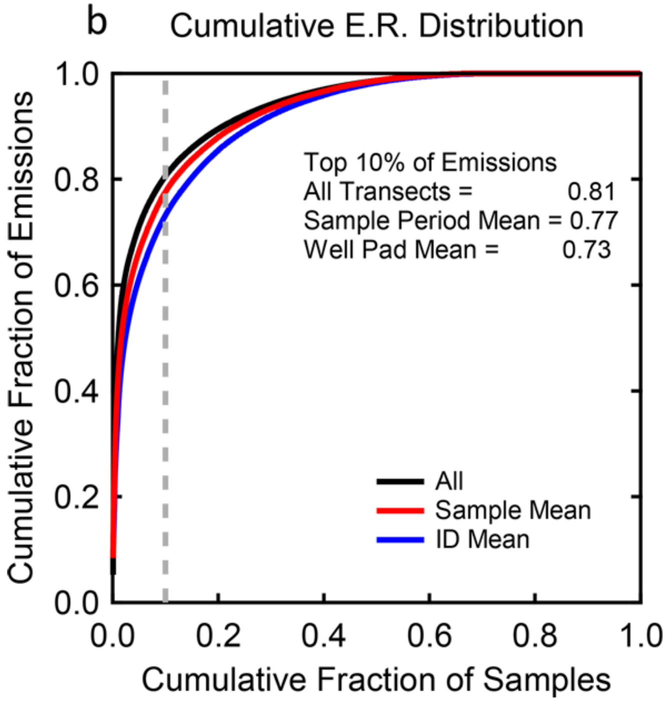
How do we observe?

- Automobiles
- Aircraft
- Towers
- Satellites

What have we learned?

- Automobiles
- Aircraft
- Towers
- Satellites

Fly or drive upwind and downwind of individual sites.



In gas production regions, a small number of sources are responsible for a majority of emissions.

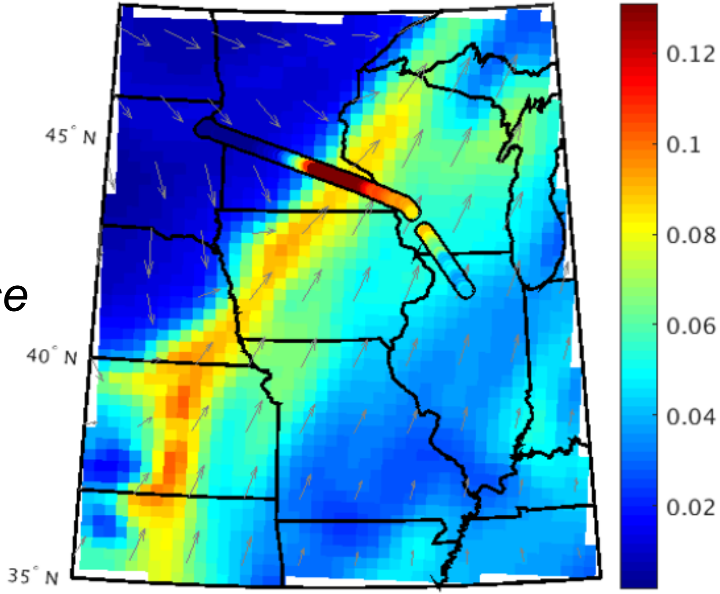
Example:
Caulton et al, Environmental Science and Technology, 2019

What have we learned?

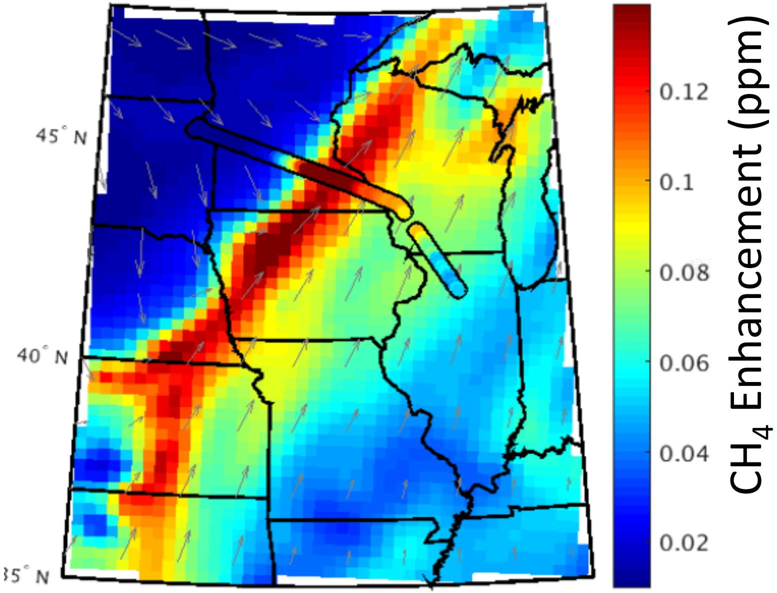
- Automobiles
- Aircraft
- Towers
- Satellites

Fly upwind and downwind of entire gas basins (or groups of gas basins). (ethane/methane study)

Oct 18, 2017: Original



Oct 18, 2017: Optimized



Emissions from natural gas production are about twice those estimated by current EPA inventories.

Example:
Barkley et al., 2019

What have we learned?

- Automobiles
- Aircraft
- Towers
- Satellites

The site-level atmospheric emissions data, when upscaled to entire basins, agree with the aircraft data.

Alvarez et al., 2018

Merge the site- and basin-level data

Site-by-site atmospheric data

Whole gas-basin atmospheric data

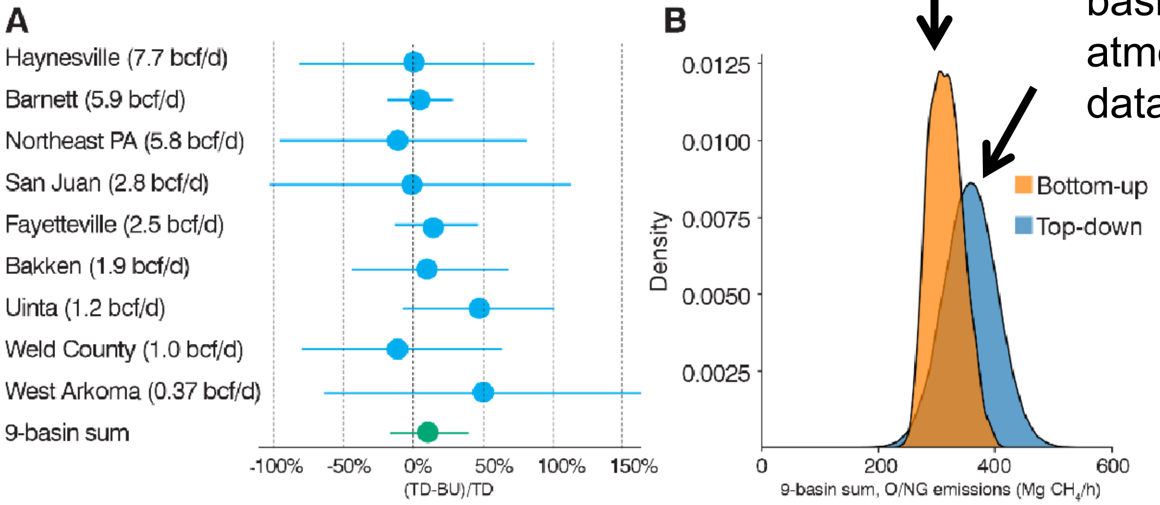


Fig. 1. Comparison of this work's bottom-up (BU) estimates of methane emissions from oil and natural gas (O/ NG) sources to top-down (TD) estimates in nine U.S. O/ NG production areas. (A)

What have we learned?

- Automobiles
- Aircraft
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Merge the site- and basin-level data

Aside:

Inventory underestimates appear to be proportional to productivity per well.

Emissions as a fraction of production appear to be proportional inversely proportional to productivity per well.

What can we do going forward?

- Automobiles
- Aircraft
- Towers
- Satellites

Find the large leaks

See Riley Duren's presentation

What can we do going forward?

- Automobiles
- Aircraft
- Towers
- Satellites

Understand why current inventories don't match atmospheric data and update our understanding.

See Clay Bell's presentation

Continuously monitor CH_4 emissions from basins

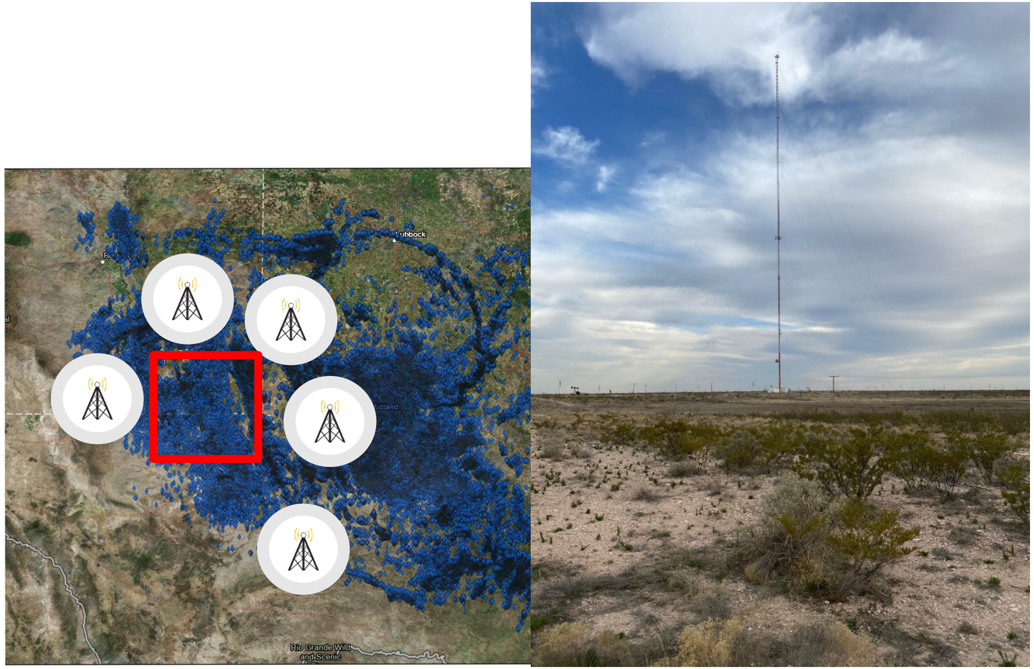
- Automobiles
- Aircraft
- Towers
- Satellites

Environmental Defense Fund PermianMAP project

and NASA Carbon Monitoring System analyses of observations from the TROPOMI satellite

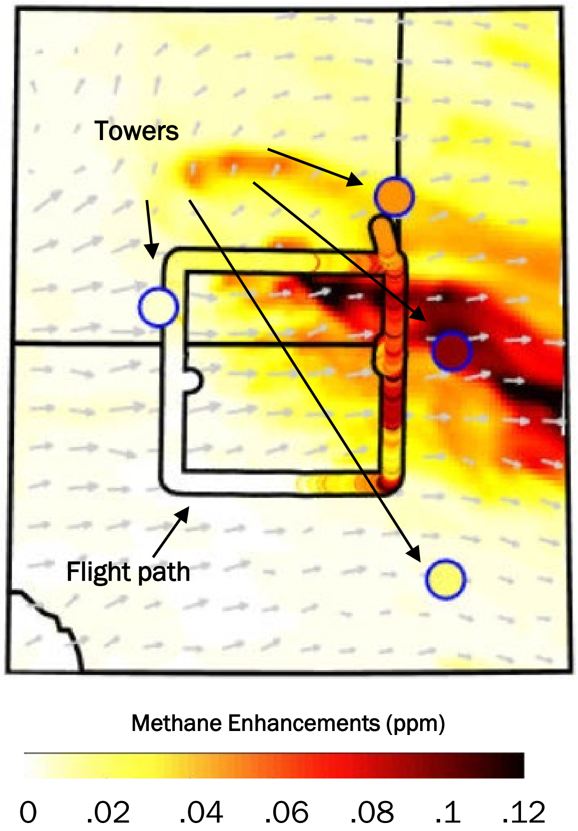
Observational platforms

Mass balance flights
Scientific Aviation



Tower-based atmospheric transport modeling
Pennsylvania State University

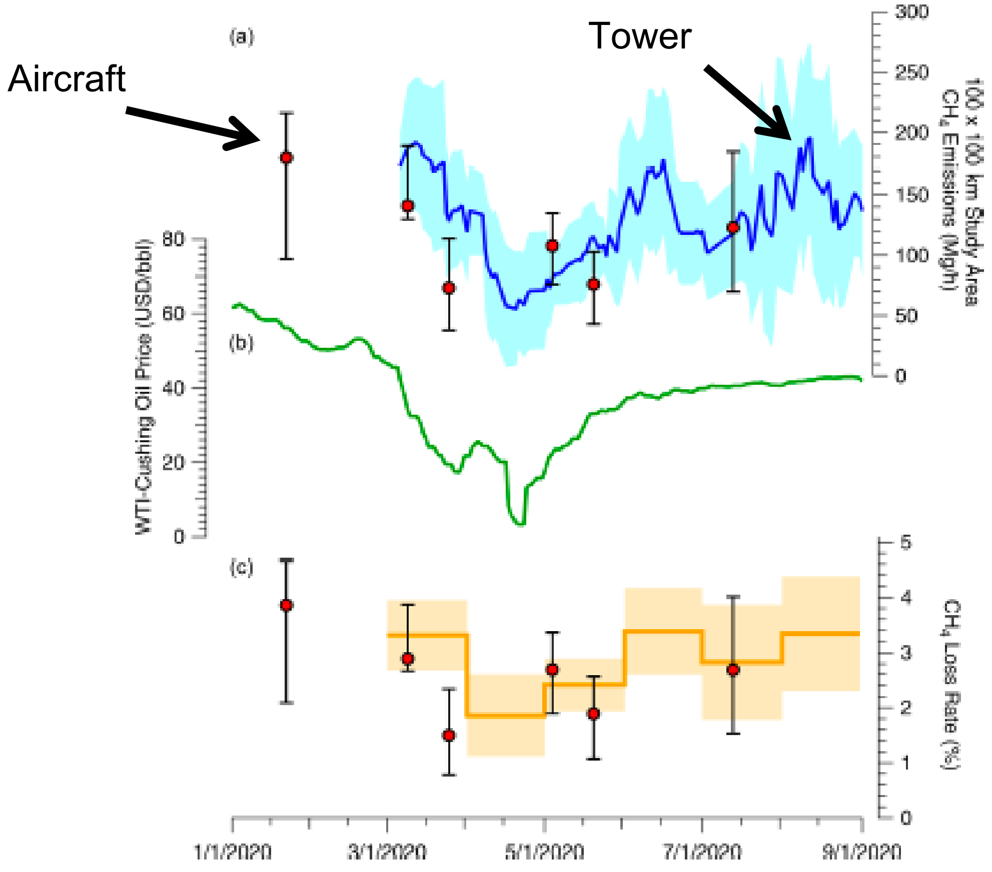
Model-data synthesis to estimate basin-wide emissions



Tower and aircraft observations are analyzed to estimate daily methane emissions from study area.

- On March 9th, study area emission rate of ~135,000 metric tons per hour (3.5% of gas production) best matches the tower and aircraft observations.
- *This procedure is repeated daily to estimate changes in emissions over time.*

Continuous monitoring enables study of emissions trends



Methane emissions from the Permian dropped at the same time that oil prices dropped.

We can monitor the "metabolism" of a gas production basin.

Tower-based measurements and analyses are ongoing (Barkley et al, in prep).

Annual emissions estimates from TROPOMI satellite observations (Zhang et al, 2020) appear to agree with mean values being retrieved by the tower network.

Lyon et al, 2021.

What can we do going forward?

- Monitor basin emissions continuously in time, and with roughly 20-30% accuracy and precision on a monthly basis (Ken's back of the envelope).
- Distinguish oil and gas sources from other methane sources.
- Integrate the emissions from the many big leaks that exist within basins.
- Test inventory models.
- Watch for emissions changes.
- Verify. Audit.

  - Tower, aircraft, satellite.

What can we *not yet* do going forward (with tower-based atmospheric measurements)?

- Zoom in with these methods to fine temporal (e.g. daily) and spatial (e.g. fractions of a basin) resolution.
  - Why not?
    - Limited atmospheric data density
    - Limited accuracy and precision in atmospheric transport reanalyses
- Find individual leaks.
  - (see Riley and Clay for help)
- Diagnose the causes of changes in emissions over time.
  - We need to understand the processes within the basin to do this.
  - (see Riley and Clay for help)

References

Alvarez, Ramón A., Daniel Zavala-Araiza, David R. Lyon, David T. Allen, Zachary R. Barkley, Adam R. Brandt, Kenneth J. Davis, Scott C. Herndon, Daniel J. Jacob, Anna Karion, Eric A. Kort, Brian K. Lamb, Thomas Lauvaux, Joannes D. Maasakkers, Anthony J. Marchese, Mark Omara, Stephen W. Pacala, Jeff Peischl, Allen L. Robinson, Paul B. Shepson, Colm Sweeney, Amy Townsend-Small, Steven C. Wofsy, and Steven P. Hamburg, 2018. Assessment of Methane Emissions from the U.S. Oil and Gas Supply Chain, Science, 10.1126/science.aar7204.

Barkley, Z. R., K. J. Davis, S. Feng, N. Balashov, A. Fried, J. DiGangi, Y. Choi, and H. S. Halliday, 2019. Forward Modeling and Optimization of Methane Emissions in the South Central United States Using Aircraft Transects Across Frontal Boundaries. *Geophysical Research Letters*. 46, 13,564–13,573. https://doi.org/10.1029/2019GL084495

Caulton, Dana R., Jessica M. Lu, Haley M. Lane, Bernhard Buchholz, Jeffrey P. Fitts, Levi M. Golston, Xuehui Guo, Qi Li, James McSpiritt, Da Pan, Lars Wendt, Elie Bou-Zeid, and Mark A. Zondlo, 2019. Importance of Superemitter Natural Gas Well Pads in the Marcellus Shale. *Environmental Science & Technology 53* (9), 4747-4754, DOI: 10.1021/acs.est.8b06965

Lyon, David R., Benjamin Hmiel, Ritesh Gautam, Mark Omara, Katherine A. Roberts, Zachary R. Barkley, Kenneth J. Davis, Natasha L. Miles, Vanessa C. Monteiro, Scott J. Richardson, Stephen Conley, Mackenzie L. Smith, Daniel J. Jacob, Lu Shen, Daniel J. Varon, Aijun Deng, Xander Rudelis, Nikhil Sharma, Kyle T. Story, Adam R. Brandt, Mary Kang, Eric A. Kort, Anthony J. Marchese, and Steven P. Hamburg, 2021. Concurrent variation in oil and gas methane emissions and oil price during the COVID-19 pandemic. Atmos. Chem. Phys., 21, 6605–6626, 2021 https://doi.org/10.5194/acp-21-6605-2021

Zhang, Y., Gautam, R., Pandey, S., Omara, M., Maasakkers, J. D., Sadavarte, P., Lyon, D. R., Nesser, H., Sulprizio, M. P., Varon, D. J., Zhang, R., Houweling, S., Zavala-Araiza, D., Alvarez, R. A., Lorente, A., Hamburg, S. P., Aben, I., and Jacob, D. J.: Quantifying methane emissions from the largest oil-producing basin in the United States from space, Sci. Adv., 6, eaaz5120, https://doi.org/10.1126/sciadv.aaz5120, 2020.