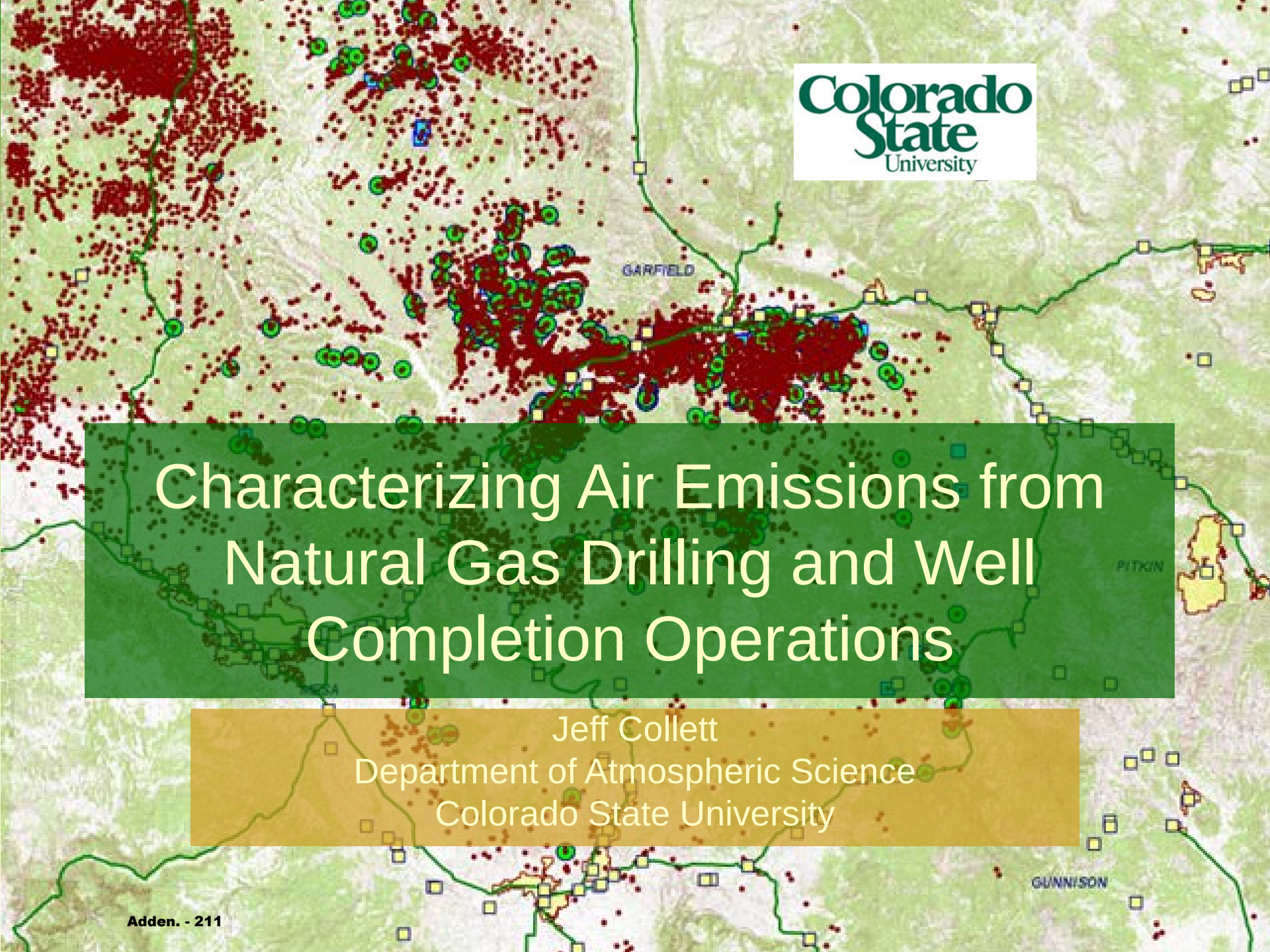
ADDENDUM INDEX

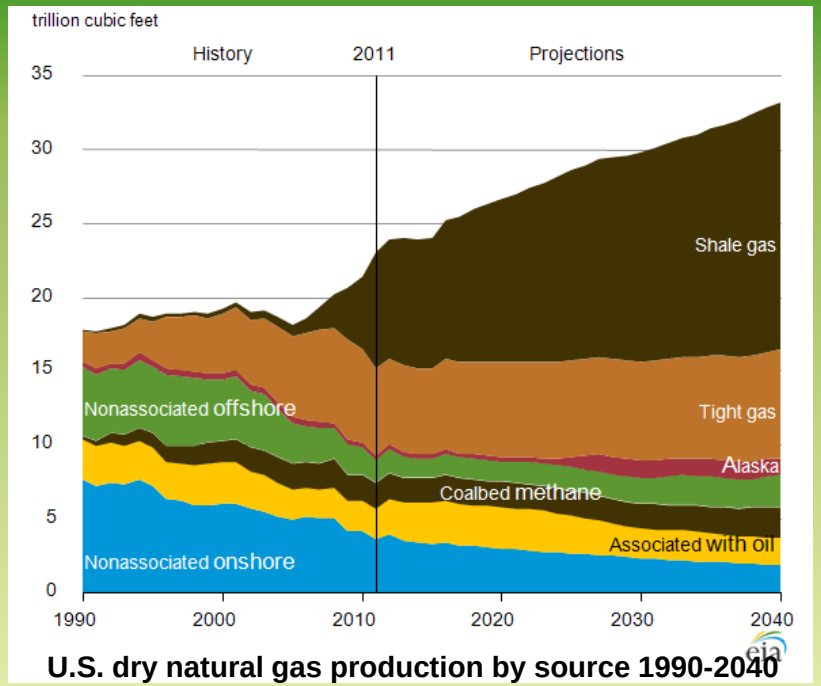


Characterizing Air Emissions from Natural Gas Drilling and Well Completion Operations

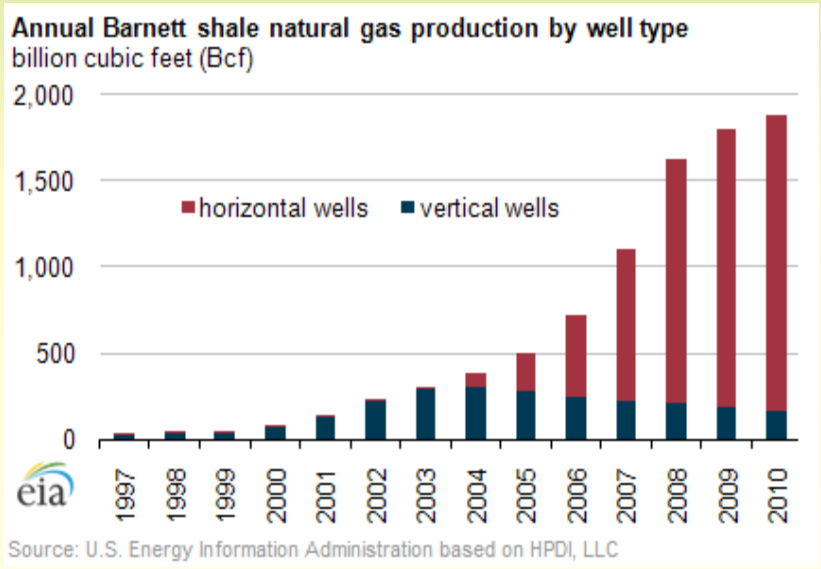
Jeff Collett
Department of Atmospheric Science
Colorado State University

Unconventional Gas Extraction

Lower 48 States shale plays



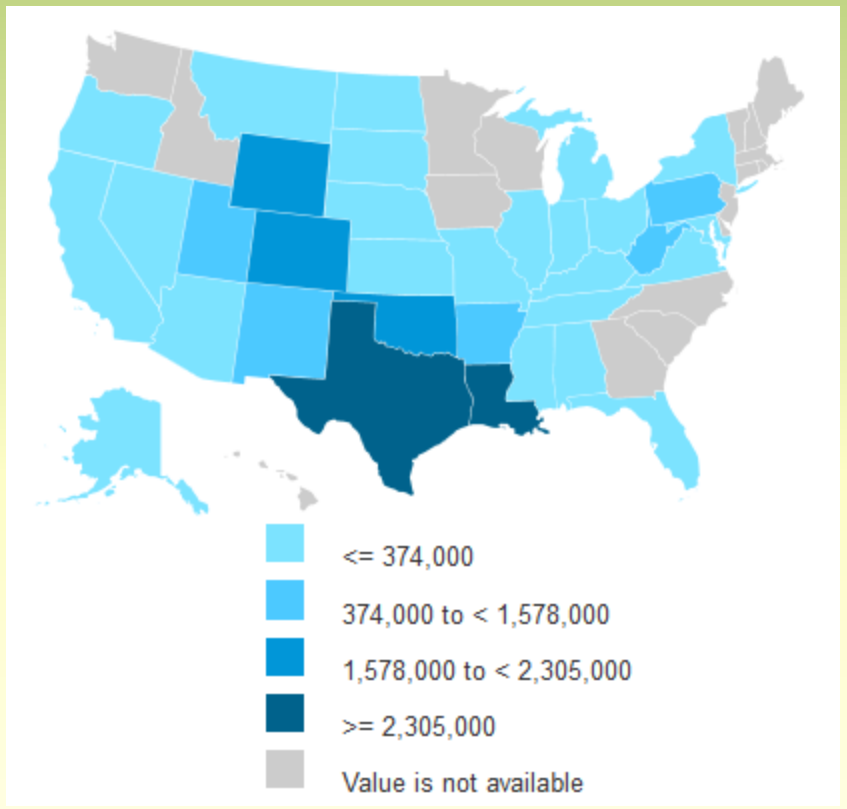
U.S. dry natural gas production by source 1990-2040

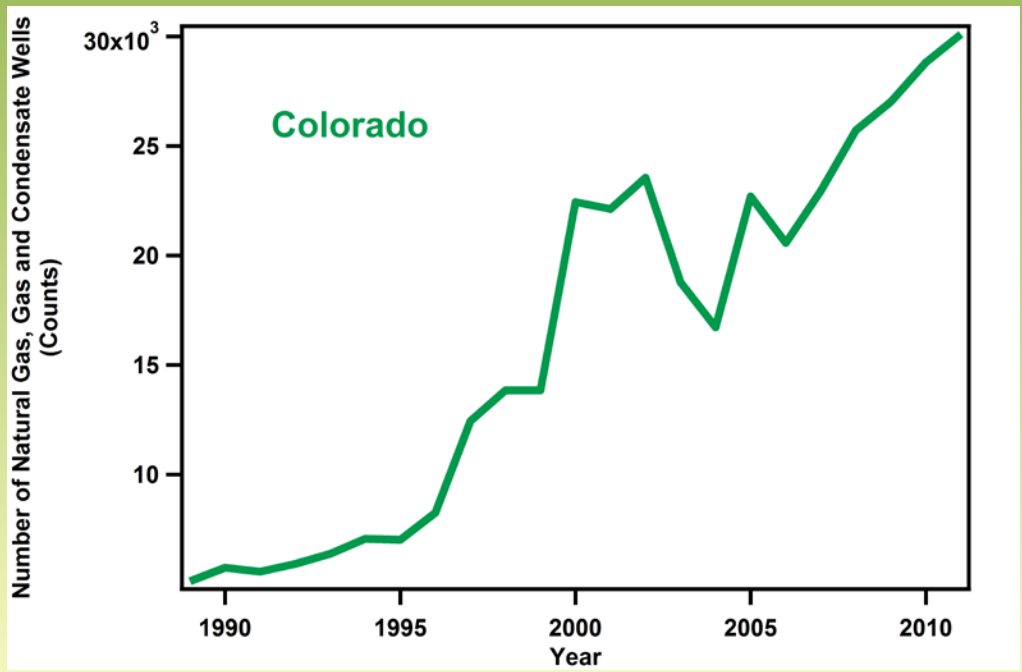


Source: U.S. Energy Information Administration (EIA)

Natural Gas Wells and Production in U.S.

Rankings: Natural Gas Marketed Production, 2011 (million cu. ft.)





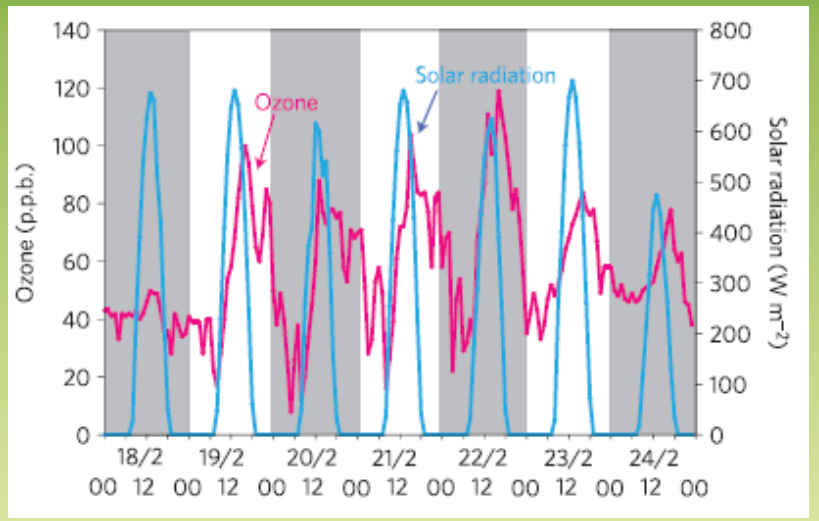
Number of Natural Gas Producing Wells in Colorado

Source for Figures: U.S. Energy Information Administration (EIA)

Potential Air Quality Concerns

- Criteria Pollutants
  - O_3 (VOC + NO_x + sunlight)
  - NO_2
  - $PM_{2.5}$
- Hazardous Air Pollutants / Air toxics, for example
  - Diesel particulate matter
  - Formaldehyde
  - Benzene, toluene, ethylbenzene, xylenes
- Climate
  - CH_4
  - Black carbon

Schnell et al., 2009

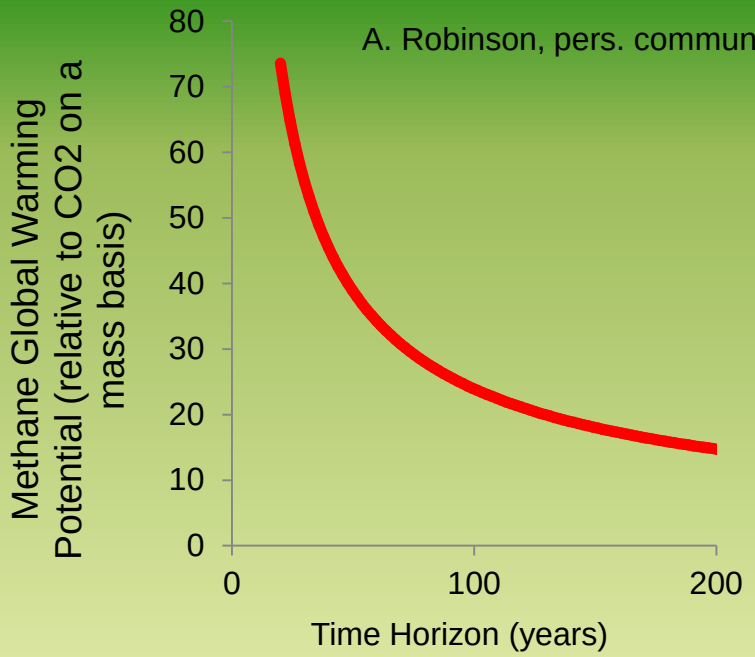


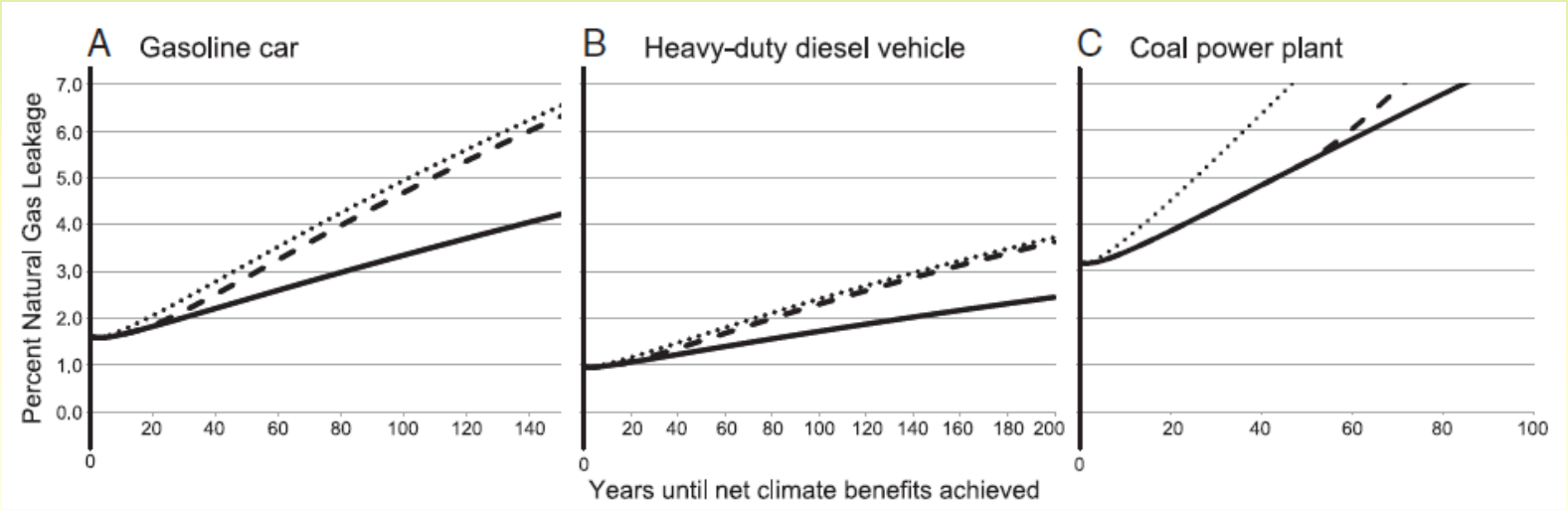
Denver brown cloud (Denver Post)

Methane and climate

- Although natural gas use offers reduced carbon dioxide emissions, methane is a much more potent greenhouse gas

- Net climate benefit of fuel switching to natural gas depends on leakage rate and time horizon





Alvarez et al., PNAS, 2012

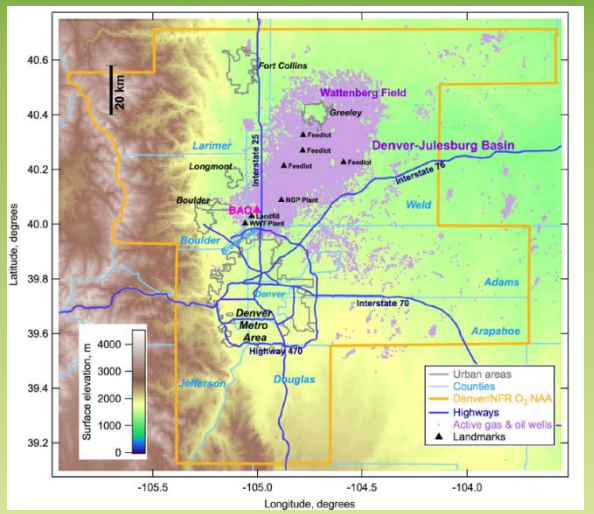
Previous VOC Measurements in Colorado

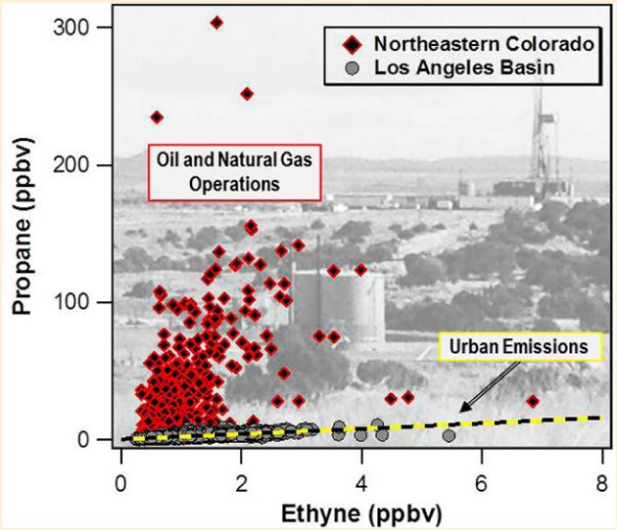
- Characterization of VOCs in the Colorado Front Range

  Pétron et al., *J. Geophys. Res.*, Vol. 117, D04304, 2012

  – Regional overview of processes impacting ambient alkane and benzene levels in Northeastern Colorado.

  – Observation of enhanced atmospheric alkane ratio with signature from oil and gas operations.





- Signature of VOCs from Oil and Gas Operations

  Gilman et al., *Env. Sci. & Tech. Res.*, 47, 1297-1305, 2013

  – Observed signature of oil and natural gas activities.

  – Observed VOCs associated with oil and gas activities at all sites

- A gap exists in direct measurement of emissions of specific activities, especially for new well development

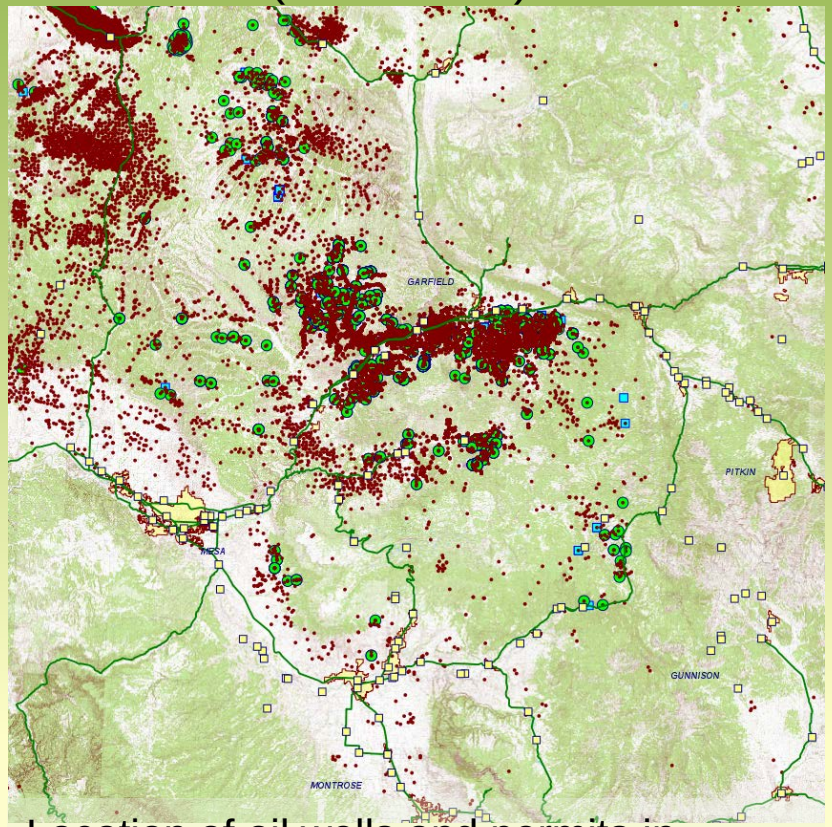
CSU Emissions Study Goals

- Characterize emissions and downwind dispersion of air toxics, ozone precursors, and methane
- Consider oil and gas sources in western Colorado and Front Range
- Work with industry to gain full site access and activity information
- Focus on new wells (Garfield County). Focus on new wells and other activities where emissions are least well understood (Front Range).

Two studies…

Garfield County Study

(2012-2015)



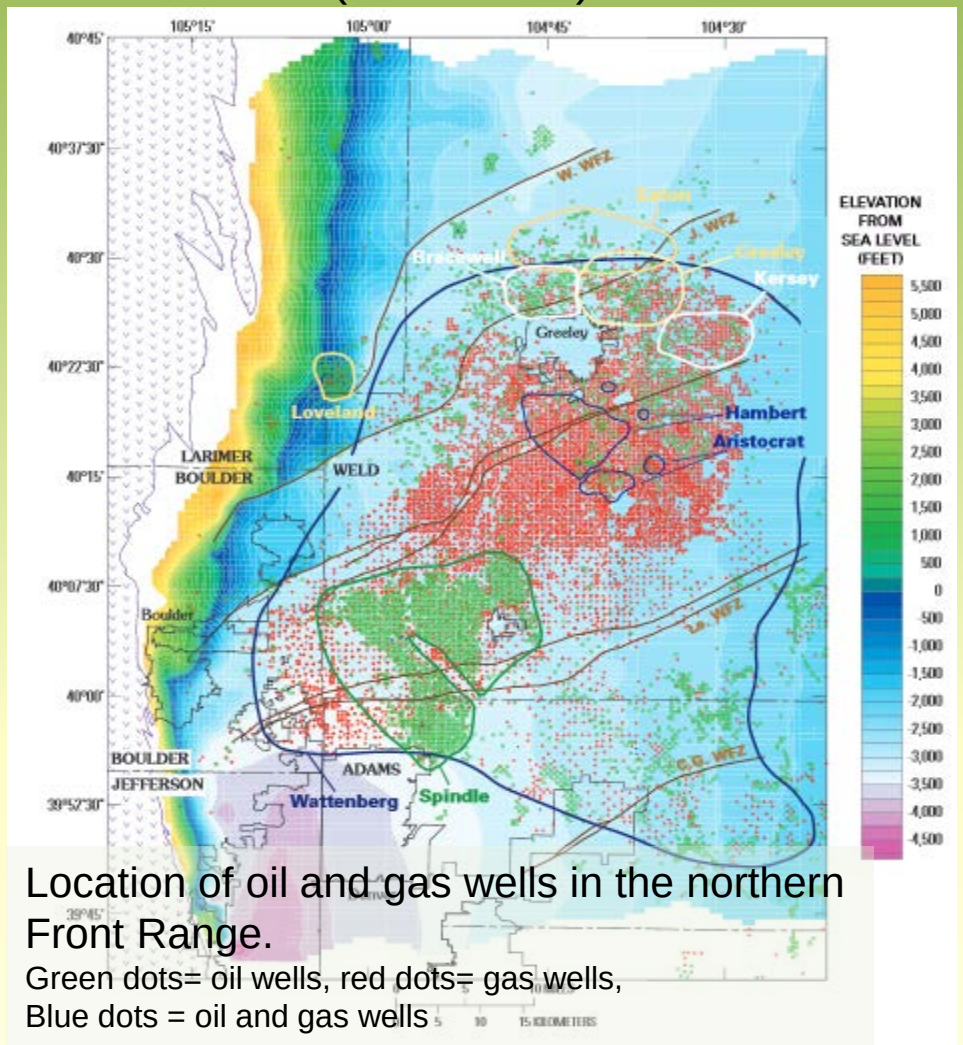
Location of oil wells and permits in Garfield County, CO and the surrounding area.

Red dots= oil wells, green circles= issued permits, blue squares= pending permits

Source: COGCC

Front Range Study

(2013-2016)

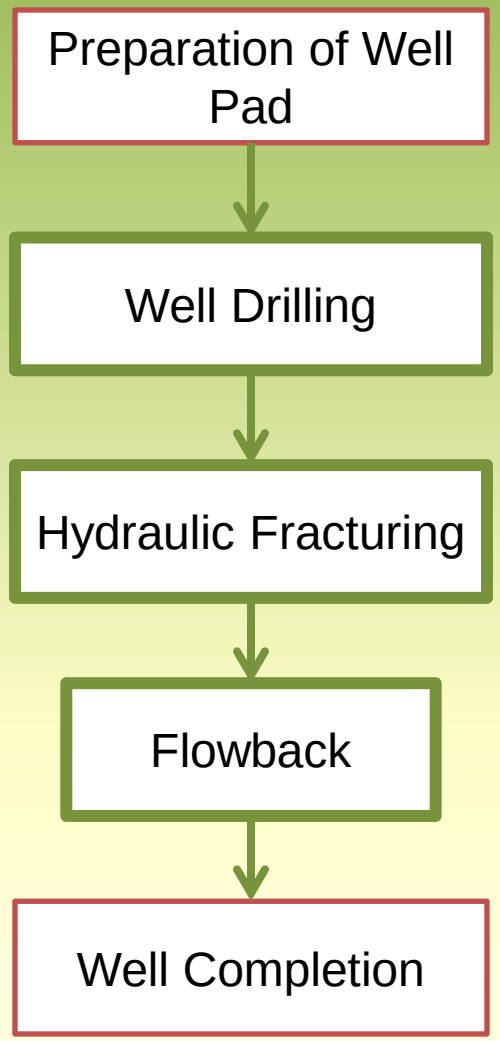


Location of oil and gas wells in the northern Front Range.

Green dots= oil wells, red dots= gas wells, Blue dots = oil and gas wells

Source: http://pubs.usgs.gov/dds/dds-069/dds-069-p/REPORTS/69_P_CH_2.pdf

Garfield Study Overview



Objectives

- Quantify emissions of chemical compounds (especially VOCs) during new well development
- Characterize how these compounds are dispersed in the atmosphere downwind of the site
- Produce a peer-reviewed, public dataset of high quality emissions data

Source of Figures: http://lingo.cast.uark.edu/LINGOPUBLIC/natgas/wellprep/index.htm

Study partners

- Study team
  - Colorado State University
    - Jeff Collett, PI
    - Jay Ham, co-PI
  - Air Resource Specialists, Inc.

- Technical Advisory Committee
  - Representatives from industry, CDPHE, USEPA, NCAR, BLM
- Operations Committee
- Sponsors
  - Garfield County
  - Encana, WPX Energy, Bill Barrett Corp., and Ursa Resources

Technical Objectives

- Quantify air emissions during specific activities
  - Mass of each compound released vs. time (e.g., g/s)
  - Detailed operator information about on-site activity
  - Focus on air toxics, ozone precursors, and CH_4
- Measure and model the spatial extent of the dispersing plume
  - Concentration vs. distance from source
  - Up to a few km

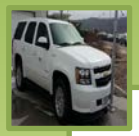
Source of Figure: West COGA Piceance

Approach

- Multiple, independent approaches
  - Tracer method
  - Inverse dispersion modeling
- Combination of time-integrated and continuous measurements to observe temporal and spatial variability
- Mobile and fixed sampling platforms

Source of Figure: Source: http://fracfocus.org/hydraulic-fracturing-how-it-works/site-setup

Study Measurements



Mobile 4WD Plume Tracker

- C_2H_2
- CH_4
- GPS

CSU Mobile Lab

- VOCs
- NO_X
- CO
- WD & WS data

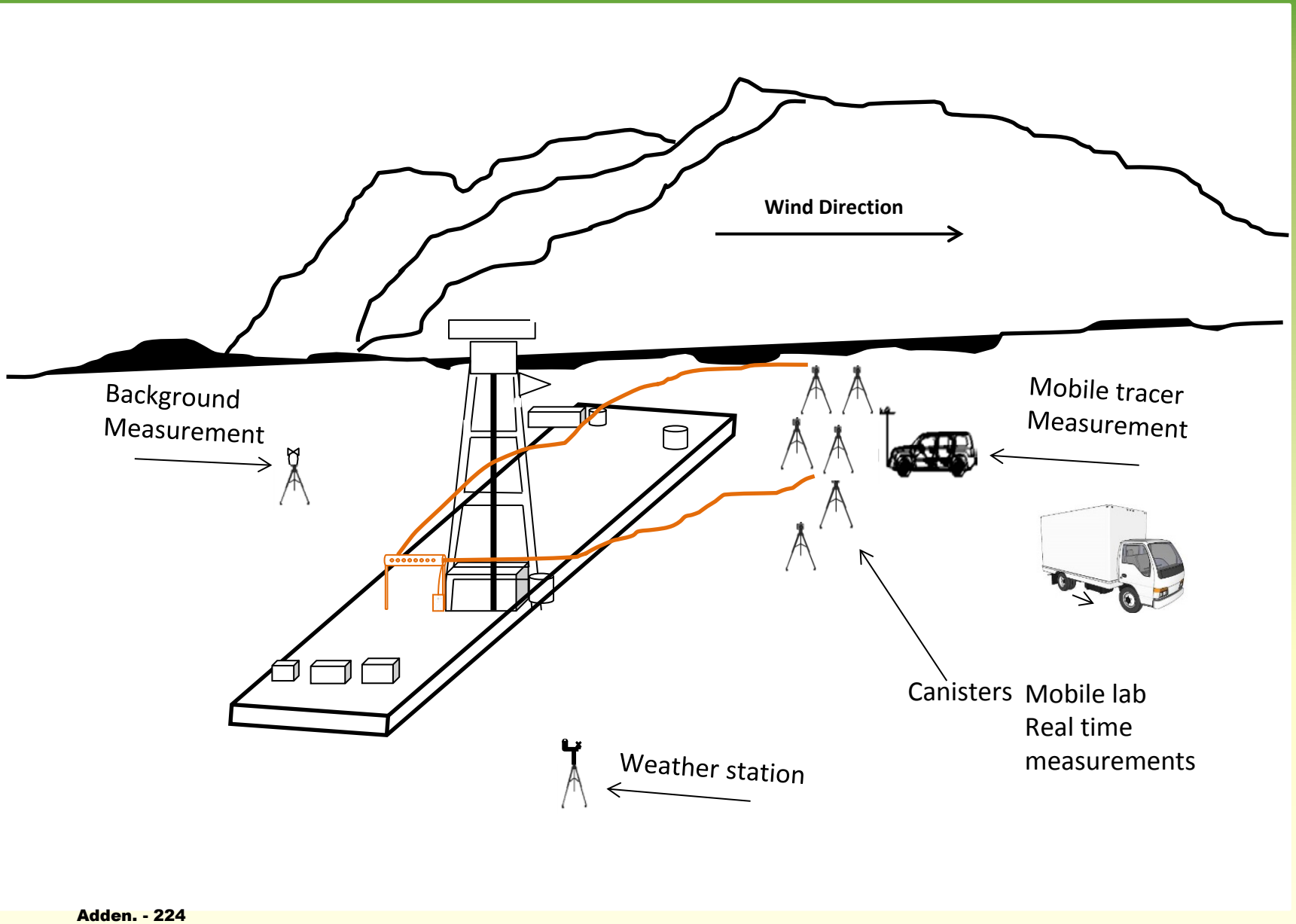
Integrated Measurements

- VOCs
- Carbonyls
- C_2H_2

Meteorological Measurements

- Temp.
- RH
- Wind Direction
- Wind Speed

Field deployment strategy



Meteorological Measurements

- Meteorological measurements help predict plume location and are used as modeling input
- Three tripod met stations with sonic anemometers
- One crank up tower to collect data at different heights

VOC Measurements (Offline)

- VOCs (TO-15 and O_3 precursors)
  - Silonite® coated canisters
  - GC-MS/FID
  - Several canisters per case study
  - Collection time of 3-30 min.

- Carbonyls (TO-11a)
  - Cartridges
  - ~ 3-5 cartridges /case study
  - Collection time of a few hours

VOC Measurements (Online)

- CSU Mobile Lab
  - Real time measurements of VOCs using PTRMS
  - Real time measurements of NO_X, CO, and O_3
- Hand-held ppb-RAE 3000
  - T-VOC measurements
  - Used to detect sources on well pad

Tracer Measurements

- Tracer (Acetylene) released at a known rate

- Measurements
  - Real Time:
    - Cavity Ring Down Spectroscopy
  - Offline:
    - Canister

Tracer Ratio Method

- Conservative tracer is released at a known rate (Q_T) near the source
  - Acetylene (C_2H_2)
- Dual analyzer measures concentrations of tracer (C_T) and compounds of interest ($C_{i,j,k}$) downwind of source
- Emission rates ($Q_{i,j,k}$) are calculated from Q_T and the ratio of concentration between C_2H_2 and the compound of interest (e.g., C_i/C_T).

Tracer Ratio Method

- Theoretical Assumptions
  - Assumes the release point for tracer is the same as that for the VOCs
  - Assumes turbulent processes transporting tracer and VOCs are the same
  - Assumes no chemical transformation between release point and sample point
- Measurement Challenges
  - Must accurately measure mass flow of the tracer and the VOC/tracer concentration ratios
- Key Advantages
  - Don't need to capture entire plume
  - Provides independent estimate of emissions for use in dispersion modeling
  - Tracer released (acetylene) naturally occurring concentration less than 1 ppbv
  - Acetylene decomposes slowly in atmosphere with a half life of ~13 days

Model dispersion using real-time on-site met. and smoke release

Release tracer @ source

Confirm plume trajectory with in situ measurement of tracer and CH_4

Position sample canister tripods and "arm"

Trigger sampling via wireless network when wind conditions optimal

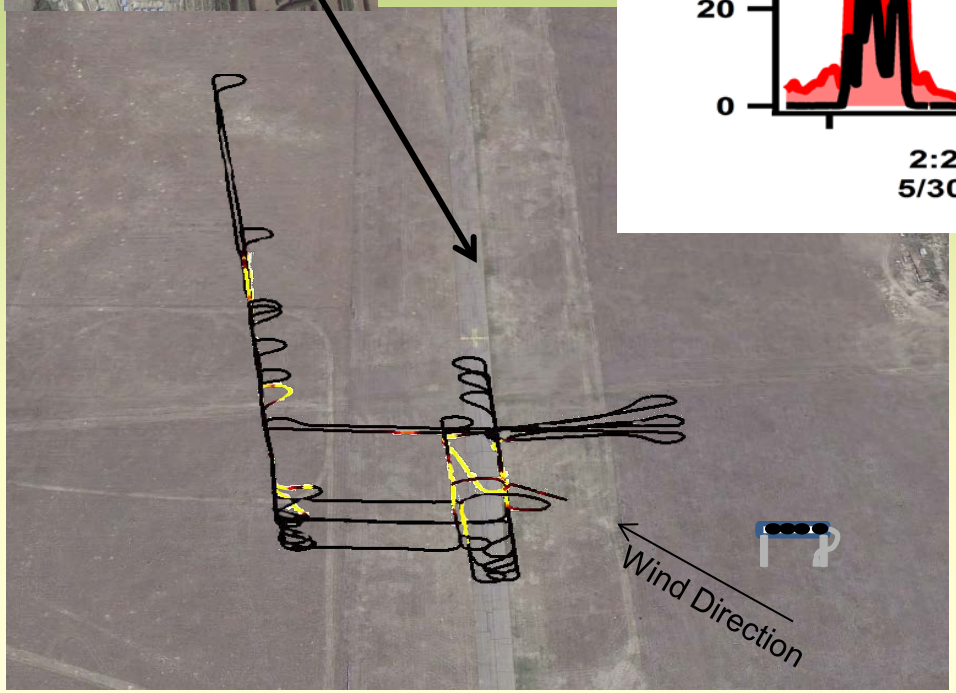
Verification of Tracer Ratio Method

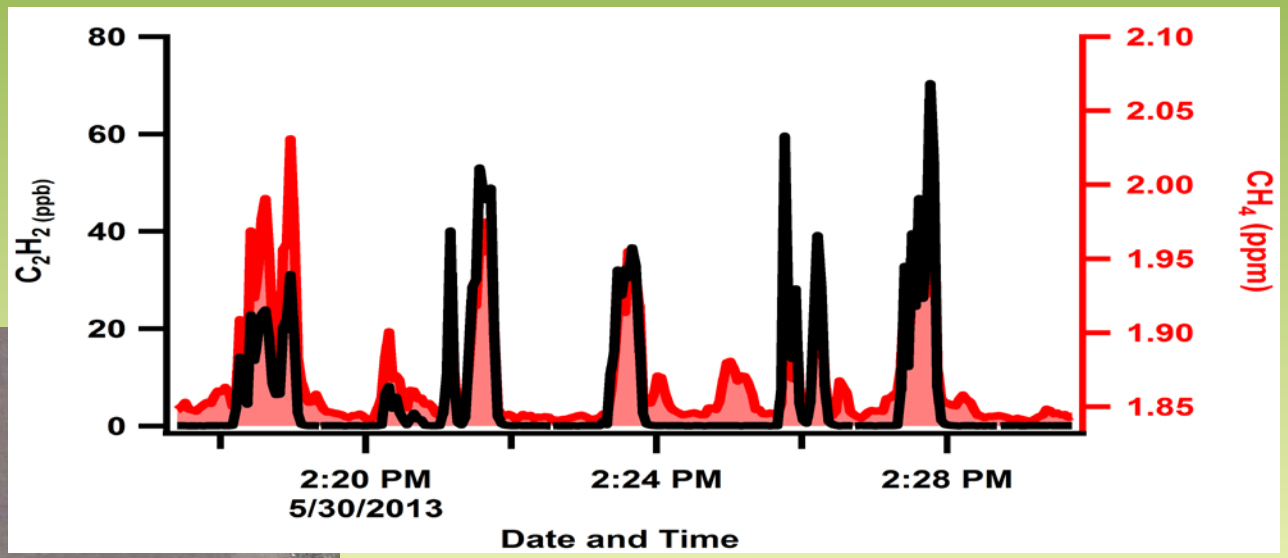
Release of tracer (acetylene) and methane

Location: Christman Field, Fort Collins, CO

- Comparison of point vs. manifold release systems
- Co-located and mis-located tracer release tests
- Various release rates
- Diverse meteorological conditions
- These tests improve field tracer measurements, allow model testing, and help assess measurement uncertainty

Tracer Release System Validation





Released tracer and methane

View of plume trackers transects
Observed tracer plumes are shown in yellow

Modeling the Plumes

- System for Atmospheric Modeling (SAM)
  - 3D Thermodynamic, fluid-dynamic model
  - Resolution: 20m x 20m x variable
  - 2 tracers
  - Unidirectional wind