Estimating US methane emissions using GOSAT observations

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Why do we care about atmospheric methane?

1) Methane is a potent greenhouse gas
   - 2nd only to CO₂

2) Recent trends in atmospheric methane are not well understood

![Graph showing CH₄ concentration from 1985 to 2015](c/o E. Dlugokencky; NOAA)
Global methane emission sources

Anthropogenic
331 Tg a\(^{-1}\)

Biomass Burning [35]
Landfills [75]
Ruminants [89]
Rice [28]
Permafrost [1]

Natural
347 Tg a\(^{-1}\)

Wetlands [217]
Fossil Fuels [96]
Biomass Burning [35]
Freshwater [40]
Bitumen [54]
Geological [54]

Biogenic
Thermogenic
Pyrogenic

Kirschke et al. (2013) & IPCC (2013)
Methods of estimating methane emissions

Bottom-up

Satellites provide dense spatial coverage but have large uncertainties
Retrievals of methane from observed radiances

Satellites Observing Methane

Thermal IR
- AIRS, TES, IASI, CrIS

Shortwave IR
- SCIAMACHY
- GOSAT
- TROPOMI


GOSAT obs:

(UoL v4 proxy retrievals)
Prior emissions from EDGARv4.2 + LPJ + GFED3

Major Sources (Tg yr\(^{-1}\))

- Wetlands
- Livestock
- Oil/Gas
- Landfills
- Coal

Total: 537 Tg yr\(^{-1}\)

Turner et al. (2015)
Model compares well with observations

NOAA/ESRL Surface Flasks

Turner *et al.* (2015)
Latitudinal gradient and seasonal cycle are represented
- Compared to HIPPO, NOAA/ESRL, and TCCON

Captures surface, free trop, and total column background

Turner et al. (2015)
Model/satellite comparison identifies a high-latitude bias
- Latitudinal bias not seen in surface, aircraft, or column comparison

Remove bias before estimating methane emissions
- Bias is either due to the model stratosphere or GOSAT retrievals

Observations are ready for inversion!

Turner et al. (2015)
General inversion framework: 2009–2011 GOSAT data

Global inversion provides dynamic BCs for North America

Turner et al. (2015)
Global inversion results

- **Overestimate of Chinese methane emissions**
  - Consistent with previous work (e.g., Bergamaschi et al. 2013, Bruhwiler et al. 2014, Schwietzke et al. 2014)

- **Underestimate in South-Central US emissions**
  - Will further investigate using Nested North American simulation
Estimating methane emissions at high resolution

Adjoint is not ideal for long time horizons at hi-res!

Avoid the iterative process by constructing the Jacobian and solving analytically!

Simulation Walltime: 2.6 years
Estimating methane emissions at high resolution

Spatial error correlations are important at fine spatial scales!

Native resolution $\frac{1}{2}^\circ \times \frac{2}{3}^\circ$
state vector $x$ ($n = 7366$)

Reduced-resolution state vector $x_\omega$ (here $n = 8$)

Aggregation Matrix: $\Gamma_\omega$

$$x_\omega = \Gamma_\omega x$$

Posterior error depends on choice of state vector dimension

Optimal size must balance aggregation and smoothing error

Turner and Jacob (2015)
Radial Basis Functions retain high resolution

- Decompose the state vector into Gaussians
  - Group based on correlated prior emission patterns

- Retain high resolution
  - Coarsen weak or uniform signals

Turner and Jacob (2015)
Prior methane emissions from EDGARv4.2 + LPJ

**Major Sources (Tg a⁻¹)**

- **Wetlands**: 20.4 Tg a⁻¹
- **Livestock**: 14.5 Tg a⁻¹
- **Oil/Gas**: 10.8 Tg a⁻¹
- **Landfills**: 9.7 Tg a⁻¹
- **Coal**: 4.3 Tg a⁻¹

**Total**: 63/537 Tg a⁻¹

North America  Global

Turner et al. (2015)
Constraining North American methane sources

Prior Emissions (2009 – 2011 average)

Total: 63.3 Tg a\(^{-1}\)

Averaging Kernel Sensitivity

DOFs: 38.8

Posterior Methane Emissions

Total: 91.3 Tg a\(^{-1}\)

Emission Scaling Factors (Posterior / Prior)

\(\Delta CH_4: +27.9\) Tg a\(^{-1}\)

Turner et al. (2015)
Does this posterior inventory improve things?

- Consistent emission estimates with regional and local studies
  - Improves comparison with independent observations!

**State of California**

**SoCAB**

**EDGARv4.2**
- This work
- Santoni et al., (2014)
- Wecht et al., (2014b)
- Wennberg et al., (2012)

**NOAA/ESRL Tall Tower Network**
- NOAA/ESRL Aircraft Program
- NOAA/ESRL Surface Flasks

**Prior**
- $y = 516 + 0.72x \ (R^2 = 0.40)$
- $y = 468 + 0.75x \ (R^2 = 0.54)$
- $y = 605 + 0.67x \ (R^2 = 0.60)$

**Posterior**
- $y = -60 + 1.03x \ (R^2 = 0.48)$
- $y = 125 + 0.94x \ (R^2 = 0.61)$
- $y = -4 + 1.01x \ (R^2 = 0.67)$

*Turner et al. (2015)*

**Methane Emissions (Tg a⁻¹)**

**Observed Methane Concentration (ppbv)**
US emissions are a factor of 1.5 larger than the US EPA

Livestock + Oil/Gas are the largest underestimated sources

Attribution is sensitive to assumption about the prior error

Turner et al. (2015)
Partitioning between oil/gas and livestock is dependent on specification of prior error

- Prior error like Wecht et al. (2014a) yields more livestock emissions
- Prior error like CLT (more similar to Miller et al.) yields balance between oil/gas and livestock

Turner et al. (2015)
Development of a gridded EPA methane inventory

Improves potential of inversions to test and improve the EPA inventory

Maasakkers et al. (in prep)
What about the difference in magnitude between Wecht et al., Miller et al., and Turner et al.?
Top-down studies point to an increase in US methane, not seen in bottom-up estimates.
What data do we have to corroborate this trend?

- Surface observations from the NOAA/ESRL flask network
- Nadir-mode observations from the GOSAT satellite
- Glint-mode observations from the GOSAT satellite
Increasing difference in NOAA/DOE observations coincides with increase in US methane emissions seen by top-down studies.

(data c/o S.C. Biraud & E. Dlugokencky)
Use GOSAT for regional trend analysis

- Look at trends over locations where GOSAT samples
- Compare ocean glint to contiguous US observations
Increasing difference in GOSAT observations

GOSAT and NOAA background are consistent

Contiguous US enhanced from background
Where do we find regional trends?

Increases are coincident with agriculture and oil/gas
Potential cause of the increase in US emissions

- 9-fold increase in US shale gas production from 2002–2014
- 125% increase in active drill rigs from 2002–2014

*Potentially* explained by oil/gas increases
Summary

- Space-borne observations can be used to estimate regional methane emissions
- US methane emissions have increased more than 30% in the past decade
  - Likely due to anthropogenic (oil/gas or agriculture) sources
- Could be a driver in the renewed methane growth

![Graph showing methane concentration over time](c/o E. Dlugokencky; NOAA)