**High-resolution North American methane emissions inferred from an inversion of 2019 TROPOMI satellite dthis ata**

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**Abstract.** …

**1 Introduction**

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Inversion at 25 km resolution enabled by reduced-rank approach

Paragraph on the reduced-rank approach

**2** **Data and methods**

We conduct an inversion of 2019 TROPOMI methane observations over North America. The TROPOMI observations are fit to simulated concentrations from the GEOS-Chem chemical transport model (CTM, [www.geos-chem.org](http://www.geos-chem.org)) to optimize mean methane emissions at 0.25° x 0.3125° spatial resolution. We calculate the optimal emissions and the associated error covariance and information content by finding the analytical minimum of a Bayesian cost function regularized by a prior emissions estimate (section 2.1). Section 2.2 describes the inversion forward model, GEOS-Chem, and the novel, reduced-rank method used to calculate the Jacobian matrix. Section 2.3 describes the state vector, prior emissions, and prior errors. Section 2.4 describes the TROPOMI observations and the observing system errors. We also conduct a suite of sensitivity tests to provide additional constraints on the error of the optimized emissions, which are summarized in section 2.5.

**2.1 Analytical inversion procedure**

We optimize the state vector of gridded emissions assuming normal errors by minimizing a Bayesian cost function

where and are the prior emissions estimate and error covariance, respectively (section 2.x); and are the observational vector and error covariance, respectively (section 2.x); is the chemical transport model (CTM) that simulates observations as a function of emissions (section 2.x); and is a regularization factor that accounts for errors in the estimated observational error covariance matrix (Brasseur and Jacob, 2017). The nested methane CTM is linear so that where is the Jacobian matrix (section 2.x) and is constant, allowing analytical minimization of the cost function yielding the optimal (posterior) state vector estimate and associated error covariance matrix :

The relative reduction in the prior error covariance defines the information content of the observing system, quantified by the averaging kernel matrix

The averaging kernel matrix describes the sensitivity of the posterior estimate to the true state vector, . The diagonal elements are therefore commonly referred to as averaging kernel sensitivities and their sum gives the degrees of freedom for signal (DOFS), the number of pieces of information independently constrained by the observing system (Rodgers, 2000).

* 1. **Forward model and Jacobian matrix**

We use the nested version of the GEOS-Chem chemical transport model (CTM) v12.7 at 0.25° x 0.3125° resolution over North America as the forward model for the inversion. Earlier versions of the methane simulation were described by Wecht et al. (2014) and Turner et al. (2015). The model is driven by \_\_\_ meteorological fields from the \_\_\_. Methane loss from OH, Cl, soil uptake, and stratospheric oxidation is described in Maasakkers et al. (2019). Initial conditions for January 2019 and 3-hourly boundary conditions for the year are given by the methane concentration fields from the global 2° ⨉ 2.5° TROPOMI inversion conducted by Qu et al. (2021). These concentration fields are informed initial and boundary conditions are unbiased

* The simulation is initialized in January 2019 with concentration fields from the posterior of Qu et al. (in prep), a global 2° x 2.5° inversion of TROPOMI observations for 2019.
* Boundary conditions are archived every three hours from the same posterior simulation, providing an unbiased fit to the global TROPOMI data

We find an aseasonal latitudinal bias in the GEOS-Chem – TROPOMI difference for the 2019 prior simulation. We define a latitudinal correction term (ppb) using the first-order polynomial

where is the degrees latitude. Previous studies used a quadratic correction (Turner et al. 2015, Maasakkers et al. 2019); in the absence of better information, we use the simplest correction that fits that fits the data.

The relationship between simulated methane concentrations and emissions in the nested version of GEOS-Chem is strictly linear. in th forward model for the inversion is parameterized by the Jacobian matrix **K**, which describes the linear relationship between

* The Jacobian is constructed using the reduced-rank method introduced by Nesser et al. (2020).
  + We construct the initial Jacobian matrix estimate using a mass-balance approximation. To decrease the sparsity of the Jacobian matrix and the resulting eigendecomposition, we spread emissions from the source grid cell over five concentric rings, allocating %% of the emissions from the source grid cell to the outer ring, respectively.
  + The initial eigendecomposition shows…
* We validate this product by comparing to …

**2.2 State vector, prior estimate, and prior error covariance**

We optimize emissions in 23,691 grid cells at 0.25° x 0.3125° resolution over North America, including all grid cells containing land or anthropogenic methane emissions larger than 0.1 Mg km-2 a-1, representing over 99% of methane emissions in North America. Methane chemical and soil sinks are not optimized because these loss processes are slow compared to the ventilation timescale.

Table 1 summarizes the prior emissions estimates and Figure 2 shows the spatial distribution of major source sectors. Anthropogenic emissions for the United States, Mexico, and Canada are given by the spatially disaggregated (gridded) versions of the EPA GHGI for 2012 (Maasakkers et al., 2016), the INECCC (?) for 20?? (Scarpelli et al. ?), and the ECCC estimates for 20?? (Scarpelli et al. ?), respectively. To account for changes in the distribution and magnitude of oil and natural gas emissions in the United States since 2012, we update the distribution of production fields using 2018 DrillingInfo data and scale the total natural gas transmission, processing, and distribution emissions to match 2018 emissions as reported in the 2020 GHGI. All other anthropogenic emissions in the North American domain are provided by the EDGAR v4.3.2 (?) global emission inventory for 2012 (?). Anthropogenic emissions are assumed aseasonal except for manure management and rice cultivation, for which we apply seasonal scaling factors as described by Maasakkers et al. (2016) and Zhang et al. (2016), respectively.

Wetlands are the dominant natural source of methane emissions. We use the high-performance WETCharts ensemble version 1.3.1, which selects 10 process-based models on the basis of their correspondence with GOSAT satellite observations (Ma et al. 2021). Other natural methane emission sources include open fires, termites, and geological seeps. Open fire emissions are from the Global Fire Emissions Database version 4 (GFED4, van der Werf et al., 2017), termite emissions from Fung et al. (1991), and geological seepage from Etiope et al. (2019) scaled to the 2 Tg a-1 global emission magnitude given by Hmiel et al. (2020).

We assume uniform relative errors of 50% in the absence of better information. We test this assumption in a series of sensitivity inversions in which we increase, decrease, and vary the errors over the domain.

**2.2 TROPOMI observations**

The Tropospheric Monitoring Instrument (TROPOMI) aboard the Sentinel-5 Precursor satellite has provided daily, global observations of dry column methane mixing ratios at 7 ⨉ 7 km2 nadir pixel resolution since May 2018 and at 5.5 ⨉ 7 km2 nadir pixel resolution since August 2019 (citation). TROPOMI is in sun-synchronous orbit with a local overpass time of 13:30 (Veefkind et al. 2012). TROPOMI uses the 2.3 μm methane absorption feature and a full-physics retrieval, which is limited by cloud cover, variable topography, albedo, and high aerosol loading (citation). As a result, TROPOMI has a xx% retrieval rate over North America for 2019. We use the retrieval described by Lorente et al. (2021), which includes an updated albedo bias correction. This data has a -3.4 ± 5.6 ppb bias relative to the Total Carbon Column Observing Network (TCCON).

We further validate the TROPOMI data by comparing it to surface and aircraft methane observations for May 2018. …

Figure 2 shows 2019 TROPOMI observations over North America, seasonally averaged on the 0.25° x 0.3125° GEOS-Chem grid. We include only high-quality retrievals as indicated by the quality assessment flag. We filter out snow- and ice-covered scenes, which are likely to have residual albedo biases, by removing data with a blended albedo [DESCRIBE] value greater than 1.1 (Wunch et al. 2011?) and winter (DJF) observations north of 50°N. We also remove scenes with shortwave albedo less than 0.05, which exhibit larger biases, following de Gouw et al. (2020?). The remaining 2948288 observations constitute our observation vector **y**.

**3 Results and discussion**

**4 Conclusions**