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A global gridded (0.1º x 0.1º) inventory of methane emissions from oil, gas, and coal exploitation based on national reports to the United Nations Framework Convention on Climate Change

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Abstract. Individual countries report national emissions of methane, a potent greenhouse gas, in accordance with the United Nations Framework Convention on Climate Change (UNFCCC). We present a global inventory of methane emissions from oil, gas, and coal exploitation that spatially disaggregates the national emissions reported to the UNFCCC (Scarpelli et al., 2019). Our inventory is at 0.1° x 0.1° resolution and resolves the subsectors of oil and gas exploitation, from upstream to downstream, and the different emission processes (leakage, venting, flaring). Global emissions for 2016 are 41.5 Tg a^{-1} for oil, 24.4 Tg a^{-1} for gas, and 31.3 Tg a^{-1} for coal. An array of databases is used to spatially allocate national emissions to infrastructure including wells, pipelines, oil refineries, gas processing plants, gas compressor stations, gas storage facilities, and coal mines. Gridded error estimates are provided in normal and lognormal forms based on emission factor uncertainties from the IPCC. Our inventory shows large differences with the EDGAR v4.3.2 global gridded inventory both at the national scale and in finer-scale spatial allocation. Use of our inventory as prior estimate in inverse analyses of atmospheric methane observations allows investigation of individual subsector contributions and can serve policy needs by evaluating the national emissions totals reported to the UNFCCC. Gridded data sets can be accessed at https://doi.org/10.7910/DVN/HH4EUM (Scarpelli et al., 2019).

1 Introduction

Methane is the second most important anthropogenic greenhouse gas after CO_2, with an emission-based radiative forcing of 1.0 W m^{-2} since pre-industrial times as compared to 1.7 W m^{-2} for CO_2 (Myhre et al., 2013). Major anthropogenic sources of methane include the oil/gas industry, coal mining, livestock, rice cultivation, landfills, and wastewater treatment. Individual countries must estimate and report their anthropogenic methane emissions by source to the United Nations in accordance with the United Nations Framework Convention on Climate Change (UNFCCC; 1992). These estimates rely on emission factors (amount emitted per unit of activity) that can vary considerably between countries in particular for oil and gas (Larsen and Marsters, 2015). This variation may reflect differences in infrastructure between countries but also large

uncertainties (Allen et al., 2015; Brantley et al., 2014; Mitchell et al., 2015; Omara et al., 2016; Robertson et al., 2017), including a possible under-accounting of abnormally high emitters (Zavala-Araiza et al., 2015).

Top-down inverse analyses of atmospheric methane observations can provide a check on the national emission inventories (Jacob et al., 2016), but they require prior information on the spatial distribution of emissions within the country. This information is not available from the UNFCCC reports. The EDGAR v4.2 global emission inventory with 0.1° x 0.1° gridded resolution (European Commission, 2011) has been used extensively as prior estimate for methane emissions in inverse analyses. EDGAR prioritizes the use of a consistent methodology between countries for emissions estimates, including the use of IPCC Tier 1 methods (IPCC, 2006), and then spatially distributes emissions using proxy data like satellite observations of gas flaring (Janssens-Maenhout et al., 2019). However, its oil/gas emissions show large differences compared to inventories that utilize more detailed data specific to a country or region (Jeong et al., 2014; Lyon et al., 2015; Maasakkers et al., 2016; Sheng et al., 2017). The latest public version, EDGAR v4.3.2 (European Commission, 2017; Janssens-Maenhout et al., 2019), provides one single gridded product for oil, gas, and coal exploitation emissions (labeled as: "Fuel Exploitation") for each year from 1990 to 2012 but with no further sectoral breakdown. Some other regional and global multi-species emission inventories also include methane but have coarse spatial and/or sectoral resolution (Hoesly et al., 2018; Höglund-Isaksson, 2012; Kurokawa et al., 2013; Stohl et al., 2015). Gridded emission inventories for the oil, gas, and coal sectors with greater sectoral resolution and/or specific facility information have been produced for individual production fields (Lyon et al., 2015), California (Jeong et al., 2014; Jeong et al., 2012; Zhao et al., 2009), and a few countries including Australia (Wang and Bentley, 2002), Switzerland (Hiller et al., 2014), the United Kingdom (Defra, 2014), China (Peng et al., 2016; Sheng et al., 2019), the US (Maasakkers et al., 2016), and Canada and Mexico (Sheng et al., 2017).

Here we create a global 0.1° x 0.1° gridded inventory of methane emissions from the oil, gas, and coal sectors, resolving individual activities (subsectors) and scaling emissions to match those reported to the UNFCCC. The inventory provides a spatially downscaled representation of the UNFCCC national reports by linking the national emissions to the locations of corresponding infrastructure. Our premise is that the national totals reported by individual countries contain country-specific information that is not publicly available or easily accessible. In addition, these UNFCCC national totals provide the most policy-relevant estimates of emissions to be compared with results from top-down inverse analyses. Our downscaling relies on global data sets for oil/gas infrastructure locations available from DrillingInfo (DrillingInfo, 2017), Rose (Rose, 2017), and the National Energy and Technology Laboratory's Global Oil & Gas Infrastructure (GOGI) inventory and geodatabase (Rose et al., 2018; Sabbatino et al., 2017). National emissions from coal mining are distributed according to mine locations from EDGAR v4.3.2. We present results for 2016, but our method is readily adaptable to other years.

2 Data and methods

2.1 National emissions data

Figure 1 gives a flow chart of the emission processes from oil, gas, and coal exploitation as resolved in our inventory. The emissions characterized here correspond to the IPCC category "fugitive emissions from fuels" (category code 1B). Here and elsewhere we refer to "sectors" as oil, gas, or coal. We refer to "subsectors" as the separate activities for each sector resolved in Fig. 1, e.g., "Gas production". The subsectors were chosen to match UNFCCC reporting. We refer to "processes" as the means of emission which can be leakage, venting, or flaring. Leakage emissions include all unintended non-venting and flaring emissions such as from equipment leaks, evaporation losses, and accidental releases. Coal emissions are lumped together, including contributions from surface and underground mines during mining and post-mining activities (IPCC, 2006), without further partitioning because the emissions are mainly at the locations of the mines. We create a separate gridded inventory file for each sector, subsector, and process as specified by the individual boxes of Fig. 1. The subsectors reported by countries to the UNFCCC vary, so our first step is to compile national emissions for each subsector and process of Fig. 1 so that emissions can then be allocated to the appropriate infrastructure locations as described in Sect. 2.2.

2.1.1 UNFCCC reporting

The UNFCCC receives inventory reports from 43 developed countries as 'Annex I' parties and communications from 151 countries as 'non-Annex I' parties. The 43 Annex I countries report annually and disaggregate emissions to subsectors. Non-Annex I countries report total emissions for the combined oil/gas sector and total emissions for the coal sector, but they are not required to report annually or disaggregate emissions to subsectors. We use the UNFCCC GHG Data Interface as of May 2019 (UNFCCC, 2019) to download emissions reported by Annex I countries for the year 2016 and emissions reported by non-Annex I countries for the year 2016 if available or the most recent year reported (reporting year ranges from 1994 to 2015).

Annex I countries report oil/gas leakage emissions by subsector, and these emissions can be used in the inventory as reported. An exception is for gas transmission and gas storage which are only reported as a combined total and have to be disaggregated. Annex I venting and flaring emissions are only reported as sector totals (oil venting, oil flaring, gas venting, and gas flaring) which have to be disaggregated to the subsectors of Fig. 1.

The emissions reported for oil/gas and coal by non-Annex I countries also have to be disaggregated. If a non-Annex I country does not report coal emissions separate from oil/gas we consider them as a non-reporting country as described in Sect. 2.1.4. Some non-Annex I countries choose to report oil/gas emissions by subsectors similar to Annex I countries. These reported emissions are not available in the GHG Data Interface and require inspection of reports submitted by each country, including National Communications (submitted every 4 years; COP, 2002) and Biennial Update Reports (submitted every 2

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years; COP, 2011). We utilize these reports for countries with estimated or reported oil+gas emissions greater than or equal to 1 Tg a^{-1} including Algeria, Brazil, China, India, Indonesia, Iran, Iraq, Malaysia, Nigeria, Qatar, Saudi Arabia, Turkmenistan, Uzbekistan, and Venezuela. For countries with more recent data included in reports compared to the GHG Data Interface we use the more recent data. The extent of emissions disaggregation for these non-Annex I countries varies.

5 Algeria, India, Malaysia, Nigeria, Saudi Arabia, and Uzbekistan report similar to Annex I countries while other countries only provide limited disaggregation which all require further disaggregation.

2.1.2 Disaggregation by subsectors and processes

Reported emissions are disaggregated by separately estimating emissions using IPCC Tier 1 methods (IPCC, 2006) and then using the relative subsector contributions from the IPCC estimate to allocate the reported emissions to the desired subsectors.

10 The IPCC estimate applies emission factors for each subsector to national activity data from the U.S. Energy and Information Administration (EIA; EIA, 2018a). Oil production volume is used as activity data for oil exploration and production emissions while volume of oil refined is used for oil refining emissions. Oil transported by pipeline (oil production + imported volume) is used for oil transport leakage emissions and 50% of oil production volume is used for oil transport venting emissions (assumed to occur during truck and rail transport). Total gas production volume is used as

15 activity data for gas production and processing; marketable gas volume (consumed gas + exported gas) is used for gas transmission and storage; and gas consumption is used for gas distribution. Disaggregated subsector emissions from non-Annex I countries are then adjusted to 2016, if necessary, using the EIA activity data.

We disaggregate Annex I venting and flaring emissions using the relative contribution of each subsector to total venting or 20 flaring as estimated by IPCC methods. We cannot do this for the exploration or oil refining subsectors because IPCC methods do not separate venting and flaring emissions from leaks. Instead we compare the IPCC estimate for total emissions from each subsector (leakage + venting + flaring) with the reported leakage emissions. If the IPCC emissions total is greater than the reported leakage emissions we assume that the excess emissions can be attributed to venting and flaring. Venting and flaring emissions from gas storage and gas distribution similarly cannot be separated from leaks, but we assume that 25 leaks dominate these subsectors.

2.1.3 Non-reporting countries

For the few countries that do not report emissions from oil, gas, and coal to the UNFCCC we estimate emissions following IPCC Tier 1 methods applied to the 2016 EIA activity data. This is the case notably for Libya. We also use this method for countries that do not separately report coal and oil/gas emissions, notably Angola. For the countries that do not have EIA 30 activity data (notably Uganda and Madagascar), we use the infrastructure data described in Sect. 2.2 together with the average emissions per infrastructure element based on countries that do report emissions.

2.1.4 Coal emissions

For coal, Annex I emissions for 2016 are used as reported. Non-Annex I emissions reported as total coal emissions are adjusted to 2016 as needed using activity data provided by the EIA (EIA, 2018a). For the few countries that do not report to the UNFCCC, we use the coal emissions data embedded in EDGAR v4.3.2 Fuel Exploitation with additional information from EDGAR to separate coal from oil/gas; these countries account for less than 1% of global coal emissions.

2.2 Spatially mapping emissions

Our next step is to allocate the national emissions from each subsector of Fig. 1 spatially on a 0.1º x 0.1º grid. National emissions are allocated following the procedure described below for all countries except for the contiguous US (Maasakkers et al., 2016) and for oil/gas in Canada and Mexico (Sheng et al., 2017), where we use existing inventories constructed on the same 0.1º x 0.1º grid. The national emissions in the North American inventories are based on non-UNFCCC or older UNFCCC reports, so we scale emissions to match those reported to the UNFCCC for 2016. We estimate emissions for Alaska using the EPA State Inventory Tool (EPA, 2018) following the methods outlined in the Alaska Greenhouse Gas Emission Inventory (Alaska Department of Environmental Conservation, 2018) and apply the procedures described below to distribute these emissions spatially. Other previously reported gridded national emission inventories are not used here due to limited spatial resolution and/or limited disaggregation of emissions (Defra, 2014; Hiller et al., 2014; Höglund-Isaksson, 2012; Kurokawa et al., 2013; Wang and Bentley, 2002).

2.2.1 Allocating upstream emissions to wells

Upstream emissions, including exploration and production, are allocated spatially to wells as illustrated in Fig. 2. Our principal source information on wells is DrillingInfo (DrillingInfo, 2017). It provides worldwide point locations of onshore and offshore wells, well activity status, and well content. Well activity status is used to separate active from inactive wells. Inactive wells are assumed not to emit. Well content is used to separate oil and gas wells, though this separation can be difficult as oil wells also have production of associated gas. We label wells as unknown content if their content is either unavailable or not clearly defined as oil or gas in DrillingInfo (this makes up approximately 24% of DrillingInfo wells outside North America). We uniformly distribute emissions over the appropriate wells in each country. Within each country we determine the percentage of wells with unknown content and uniformly distribute this percentage of total oil and gas upstream emissions to those wells. We then uniformly distribute the remaining oil and gas emissions to oil and gas wells, respectively.

Well data are missing from DrillingInfo for a number of countries. An alternative global well database with wells drilled up to 2016 is available from Rose (Rose, 2017) based on a combination of open source data and proprietary data from IHS Markit (IHS Markit, 2017) and mapped on a 0.1º x 0.1º grid (total number of wells per grid cell). The Rose database does not

include information on oil versus gas content. We use this database for all countries that are either missing from the DrillingInfo database or for which the Rose database has 50% greater number of wells than DrillingInfo. This includes 47 of the 134 countries with active well infrastructure notably Russia, United Arab Emirates (UAE), China, Libya, Saudi Arabia, Turkmenistan, Ukraine, and Azerbaijan. We distribute total upstream emissions from both oil and gas uniformly over all active wells within each country. The Rose database includes offshore wells, but they are not identified by country so we rely solely on DrillingInfo for offshore wells. Between the Drillinginfo and Rose databases, over 99% of global upstream emissions can be spatially allocated. We use pipelines to allocate upstream emissions if wells are missing in both databases.

2.2.2 Allocating emissions to midstream infrastructure

Midstream emissions from oil refining, oil transport, gas processing, gas transmission, and gas storage within a given country are allocated using infrastructure location data from the GOGI database (Rose et al., 2018; Sabbatino et al., 2017) as shown for pipelines in Fig. 2. Spatial information on non-well infrastructure in Alaska was sourced from the U.S. Energy Mapping System (EIA, 2018b). Oil refining emissions are distributed uniformly to refinery locations within a given country. Oil transport emissions can occur during pipeline, truck, or tanker transport but we assume that they are mainly along pipelines and allocate them by pipeline length on a 0.1º x 0.1º grid. Gas processing, transmission, and storage emissions are distributed uniformly among the processing plant, compressor station, and storage facilities, respectively, in each country. Annex I countries report "Other" emissions for oil and gas which are distributed equally to wells and pipelines.

The GOGI database was created through a machine-learning web search of public databases for mention of oil and gas infrastructure, so it is limited to open-source information available as of 2017. It misses some infrastructure locations (Rose et al., 2018), so the spatial allocation of emissions within a country may be biased. To alleviate this bias, we check each country for exceedance of an oil or gas volume-per-facility threshold (e.g., volume of gas processed per day per processing plant). If the threshold is exceeded we estimate the percentage of facilities missing, and the corresponding percentage of subsector emissions is allocated to pipelines since non-well infrastructure tend to lie along pipeline routes. Visual inspection suggests that countries with pipelines in the GOGI database are not missing any significant pipeline locations which is consistent with a gap analysis for the GOGI database (Rose et al., 2018).

For oil refining in each country, we determine a refining rate per refinery by distributing the total volume of oil refined (EIA, 2018a) for 2016 over the GOGI refineries in that country. If the refining rate exceeds the threshold set by the Jamnagar Refinery in India of 1.24 million barrels of crude oil per day (Duddu, 2013), then oil refining emissions corresponding to the missing refineries are allocated to pipelines. The same is done for processing plants, storage facilities, and compressor stations. Processing plants are missing if production of natural gas (EIA, 2018a) distributed over processing plants exceeds 57 million cubic meters of gas per day per facility based on the Ras Laffan processing plant in Qatar (Hydrocarbons-Technology, 2017). Storage facilities are missing if production of marketable gas (EIA, 2018a) exceeds 68 billion cubic feet

per year per facility, corresponding to the total US capacity determined from marketable gas volume and number of active storage facilities (EIA, 2015). Compressor stations are missing if the implied gas pipeline length (CIA, 2018) between GOGI stations is more than 100 miles.

5   We separate the GOGI pipelines into oil and gas when possible though a significant number have unknown content. For each country, we determine the percentage of pipelines with unknown content and distribute this percentage of total oil and gas pipeline emissions to those pipelines. The remaining oil and gas emissions are allocated to oil and gas pipelines, respectively. In order to avoid allocating Russia's significant gas transmission emissions to unknown content pipelines, we instead use a gridded 0.1º x 0.1º map of gas pipelines based on the detailed Oil & Gas Map of Russia/Eurasia & Pacific
10   Markets (Petroleum Economist Ltd, 2010).

2.2.3 Allocating downstream emissions

Downstream gas distribution emissions are associated with residential and industrial gas use. We allocate these emissions within each country on the basis of population using the Gridded Population of the World (GWP) v4.10 30 arc second map (Center for International Earth Science Information Network, 2017) for 2010. Midstream emissions are also allocated to
15   population for countries missing in the GOGI database (<1% of global midstream emissions).

2.2.4 Allocating coal emissions

Coal mining and post-mining emissions from individual countries are allocated spatially to mines based on EDGAR v4.3.2 emission grid maps for 2012 (0.1° x 0.1° resolution). China specific inventories show a greater number of mines than EDGAR v4.3.2 (Sheng et al., 2019), but to the author's knowledge EDGAR is the only fine resolution database of coal mine
20   locations with global coverage. EDGAR v4.3.2 estimates surface and underground mine emissions separately but distributes them to mines as a combined total, so emissions from both types of mines are combined here. Alaskan emissions are allocated to Alaska's single operational coal mine, Usibelli (EIA, 2018b).

2.3 Error estimates

Inverse analyses of atmospheric methane observations require error estimates on the prior emission inventories as a basis for
25   Bayesian optimization (Jacob et al., 2016). Here we use uncertainty ranges from IPCC (IPCC, 2006) to estimate error standard deviations in our inventory. The IPCC reports relative uncertainty ranges for the emission factors used in Tier 1 national estimates, as summarized in Table 1. Uncertainties in national estimates are dominated by emission factors (typically 50-100%) as compared to the better known activity data (5-25%; IPCC, 2006). The emission factor uncertainties in Table 1 correspond to the subsectors and processes of our inventory (Fig. 1). We differentiate between Annex I and non-
30   Annex I countries based on IPCC uncertainty ranges for 'Developed' and 'Developing' countries.

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In the absence of better information, we interpret the IPCC uncertainty ranges as representing the 95% confidence intervals. The ranges are generally asymmetric, but we approximate them in Table 1 in terms of either (1) a relative error standard deviation (RSD) assuming a normal error probability density function (pdf), or (2) a geometric error standard deviation (GSD) assuming a lognormal error pdf. The 95% confidence interval then represents ± 2 standard deviations in linear space

5   for the normal pdf and in log space for the lognormal pdf. For the assumption of a normal error pdf, we take the average of the IPCC upper and lower uncertainty limits for each subsector and halve this value to get the RSD with an allowable maximum RSD of 100%. For the assumption of a lognormal error pdf, the IPCC limits are log-transformed, halved, averaged and transformed back to linear space to yield the GSD for the lognormal error pdf. The lower limits of the IPCC uncertainty ranges are capped at 90% when determining the GSD. We provide both normal and log-normal error standard deviations in

10   our inventory, as both may be useful for inverse analyses. Assuming a normal error pdf has the advantage of providing a proper model of mean emissions, while assuming a log-normal error pdf has the advantage of enforcing positivity and better allowing for anomalous emitters (Maasakkers et al., 2019).

Our relative errors are defined by the national scale errors and we apply them to the 0.1º x 0.1º grid for lack of better

15   information. An error analysis for the gridded EPA inventory based on comparison to a more detailed inventory for the Barnett Shale showed that the error in emissions from oil systems was not significantly higher on the 0.1º x 0.1º grid than the national error estimate of 87%, while the error for gas systems on the 0.1º x 0.1º grid was twice the national estimate of 25% (Maasakkers et al., 2016). That work further showed that displacement error due to spatial misallocation of emissions is negligibly small as long as the error in emission location is considered isotropic.

20   **3 Results & discussion**

3.1 Global, national, and grid scale emissions

Table 2 lists the global methane emissions from oil, gas, and coal, broken down by the subsectors and processes resolved in our inventory. Global emissions in 2016 are 97.2 Tg a^{-1} including 41.5 Tg a^{-1} from oil, 24.4 Tg a^{-1} from gas, and 31.3 Tg a^{-1} from coal. Oil emissions are mainly from production, in part because oil fields often lack the capability to capture associated

25   gas. Gas emissions are distributed over the upstream, midstream, and downstream subsectors. EDGAR v4.3.2 has similar global emissions as our inventory for total Fuel Exploitation (107 Tg a^{-1}), but the spatial distribution is very different as discussed in Sect. 3.3. Bottom-up estimates compiled by the Global Carbon Project (Saunois et al., 2016) give a range across studies of 123-141 Tg a^{-1} for 2012 emissions while their compilation of top-down inverse analyses gives a range across studies of 90-137 Tg a^{-1}.

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Figure 3 lists the top 20 emitting countries for emissions from oil, gas, and coal in our inventory. They account for over 90% of global emissions for each sector. The largest emissions are from Russia for oil, the US for gas, and China for coal. Oil and

gas emissions for individual countries tend to be dominated by either of the two fuels. Notable exceptions are Russia, the US, Iran, Canada, and Turkmenistan which have large emission contributions from both. Annex I and non-Annex I countries reporting to the UNFCCC account for 49% and 47% of global emissions, respectively, with the remaining 4% of emissions contributed by countries that do not report to the UNFCCC.

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Figure 4 shows the global distribution of methane emissions separately for oil, gas, and coal. Oil emissions are mainly in production fields. Contributions from gas production, transmission, and distribution can all be important with the dominant subsector varying between countries. The highest emissions are from oil/gas production fields, gas transmission routes, and coal mines. Most emissions along gas transmission routes are from compressor stations, processing plants, and storage
10   facilities.

3.2 Differences between our work and EDGAR v4.3.2

Figure 5 shows our global combined distribution of methane emissions from oil, gas, and coal in 2016 compared to EDGAR v4.3.2 'Fuel Exploitation' emissions for 2012. There are large differences between the inventories in terms of spatial patterns within each country, due to differences in both subsector contributions and spatial allocation of these contributions.
15   Emissions along pipelines are generally lower in our work and emissions from production fields are generally higher. EDGAR v4.3.2 has more of a tendency to allocate midstream emissions to pipelines rather than to specific facilities.

There are also large differences between our work and EDGAR for national emissions estimates. Figure 6 compares national emissions from oil, gas, and coal as reported to the UNFCCC versus EDGAR v4.3.2 emissions in the same year. If countries
20   report emissions more recently than 2012 we compare to EDGAR 2012 emissions. Russia, Venezuela, and Uzbekistan report emissions that are at least a factor of 2 greater than EDGAR v4.3.2. Iraq, Qatar, and Kuwait report emissions that are at least an order of magnitude lower than EDGAR v4.3.2 though their reporting years are outdated (1997, 2007, and 1994, respectively). The discrepancies between our work and EDGAR v4.3.2 in Russia and the Middle East lead to a greater emissions contribution from high latitudes and a lesser contribution from low latitudes in the Northern Hemisphere in our
25   work.

The causes of differences between the UNFCCC national totals used in our work and EDGAR v4.3.2 are country-specific and difficult to explain without knowledge of EDGAR v4.3.2 estimates for each emission subsector. Emission factors per unit of activity inferred from the UNFCCC reports can vary by orders of magnitude between countries (Larsen and Marsters,
30   2015). This may reflect real differences in regulation of venting and flaring (especially for oil production), maintenance and age of infrastructure, and the size and number of facilities within a country. For example, Middle East countries report low emissions relative to their production volumes and this may reflect a tendency to have a small number of high producing wells. In contrast, Russia and Uzbekistan report high emissions relative to oil production and gas processing volumes. For

Russia, differences may be due to the inclusion of accidental releases in UNFCCC reporting which are not estimated by EDGAR v4.3.2 (Janssens-Maenhout et al., 2019). Russia also reports large emissions from intentional venting. The National Report of Uzbekistan (2016) attributes their high emissions to leaky infrastructure and significant increases in produced and transported gas volumes which may lead to operation of equipment at over-capacity. Beyond these considerations, there may

5   also be large errors in the emission estimates reported by individual countries to the UNFCCC. Inverse analyses of atmospheric methane observations using our inventory as prior estimate would provide insight into these errors.

4 Data availability

The annual gridded emission fields and gridded errors for each subsector in Fig. 1 are available on the Harvard Dataverse at https://doi.org/10.7910/DVN/HH4EUM (Scarpelli et al., 2019). Input data and code is available upon reasonable request.

10   ## 5 Conclusions

We have constructed a global inventory of methane emissions from oil, gas, and coal with 0.1º x 0.1º resolution by spatially disaggregating the national emissions reported by individual countries to the United Nations Framework Convention on Climate Change (UNFCCC). The inventory differentiates oil/gas contributions from individual subsectors along the production and supply chain, and from specific processes (leakage, venting, flaring). It also includes error estimates based on

15   IPCC. Our inventory is designed for use as prior estimate in inverse analyses of atmospheric methane observations aiming to improve knowledge of methane emissions. Corrections to emission estimates revealed by the inverse analyses can be of direct benefit to policy by identifying biases in the national inventories. Our inventory is for 2016 but can be readily adjusted to subsequent years by updating the reported UNFCCC emissions and the Energy Information Administration's (EIA) activity data, assuming that infrastructure locations change only slowly.

20   ## Author Contribution

TRS compiled data sets and created the inventory. DJJ conceived of and provided guidance for the project. JDM and JS provided guidance on North American inventories. MPS assisted in processing of spatial data. KR and LR processed and provided guidance for the infrastructure spatial data. JRW provided guidance and feedback during inventory construction. GJM was consulted for EDGAR comparison. All authors reviewed the resulting inventory and assisted with paper writing.

25   ## Competing Interests

The authors declare no conflict of interest.

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References

National Report: Inventory of Anthropogenic Emissions Sources and Sinks of Greenhouse Gases in the Republic of Uzbekistan, 1990-2012, available at: https://unfccc.int/national_reports/non-annex_i_natcom/items/2979.php, 2016.

United Nations Framework Convention on Climate Change, United Nations Treaty Series, New York, NY, U.S.vol. 1771, No. 30822, p.
5   107, 1992.

Alaska Department of Environmental Conservation: Alaska Greenhouse Gas Emission Inventory 1990-2015, available at: https://dec.alaska.gov/air/anpms/projects-reports/greenhouse-gas-inventory, last access: June 2018, 2018.

Allen, D. T., Sullivan, D. W., Zavala-Araiza, D., Pacsi, A. P., Harrison, M., Keen, K., Fraser, M. P., Daniel Hill, A., Lamb, B. K., Sawyer, R. F., and Seinfeld, J. H.: Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Liquid
10 Unloadings, Environmental Science & Technology, 49, 641-648, 2015.

Brantley, H. L., Thoma, E. D., Squier, W. C., Guven, B. B., and Lyon, D.: Assessment of Methane Emissions from Oil and Gas Production Pads using Mobile Measurements, Environmental Science & Technology, 48, 14508-14515, 2014.

Center for International Earth Science Information Network – CIESIN – Columbia University: Gridded Population of the World, Version 4 (GPWv4): Population Count Adjusted to Match 2015 Revision of UN WPP Country Totals, Revision 10. NASA Socioeconomic Data
15 and Applications Center (SEDAC), Palisades, NY, available at: https://doi.org/10.7927/H4JQ0XZW, 2017.

CIA: The World Factbook 2018. Washington, DC, available at: http://cia.gov/library/publications/the-world-factbook, 2018.

COP: Report of the Conference of the Parties on its eighth session (FCCC/CP/2002/7/Add.2), Decision 17, New Delhi, India, 23 October – 1 November, 2002.

COP: Report of the Conference of the Parties on its seventeenth session (FCCC/CP/2011/9/Add.1), Decision 2, Annex III, Durban, South
20 Africa, 28 November – 11 December, 2011.

Defra: National Atmospheric Emissions Inventory, available at: http://naei.beis.gov.uk/, 2014.

DrillingInfo: DI International, available at: http://drillinginfo.com/, 2017.

Duddu, P.: http://hydrocarbons-technology.com/, available at: http://hydrocarbons-technology.com/, 2013.

EIA: The Basics of Underground Natural Gas Storage, available at: http://eia.gov/naturalgas/storage/basics/, 2015.
25 EIA: International Energy Statistics, available at: http://eia.gov/beta/international/, 2018a.

EIA: U.S. Energy Mapping System, available at: https://www.eia.gov/state/maps.php, last access: 2018, 2018b.

EPA: State Inventory and Projection Tool, available at: https://www.epa.gov/statelocalenergy/download-state-inventory-and-projection-tool, 2018.

European Commission: Emission Database for Global Atmospheric Research (EDGAR), 527 release version 4.2, available at:
30 http://edgar.jrc.ec.europa.eu/overview.php?v=42, 2011.

European Commission: Emission Database for Global Atmospheric Research (EDGAR), release version 4.3.2, available at: http://edgar.jrc.ec.europa.eu/overview.php?v=432&SECURE=123, 2017.

Hiller, R. V., Bretscher, D., DelSontro, T., Diem, T., Eugster, W., Henneberger, R., Hobi, S., Hodson, E., Imer, D., Kreuzer, M., Künzle, T., Merbold, L., Niklaus, P. A., Rihm, B., Schellenberger, A., Schroth, M. H., Schubert, C. J., Siegrist, H., Stieger, J., Buchmann, N., and
35 Brunner, D.: Anthropogenic and natural methane fluxes in Switzerland synthesized within a spatially explicit inventory, Biogeosciences, 11, 1941-1959, 2014.

Hoesly, R. M., Smith, S. J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J. J., Vu, L., Andres, R. J., Bolt, R. M., Bond, T. C., Dawidowski, L., Kholod, N., Kurokawa, J. I., Li, M., Liu, L., Lu, Z., Moura, M. C. P., O'Rourke, P. R., and Zhang, Q.: Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS),
40 Geosci. Model Dev., 11, 369-408, 2018.

Höglund-Isaksson, L.: Global anthropogenic methane emissions 2005-2030: technical mitigation potentials and costs, Atmos. Chem. Phys., 12, 9079-9096, 2012.

Hydrocarbons-Technology: Dolphin Gas Project, Ras Laffan, available at: http://hydrocarbons-technology.com/projects/dolphin-gas/, 2017.

45 IHS Markit: https://ihsmarkit.com/products/oil-gas-tools-enerdeq-browser.html, last access: July 2015, available at: https://ihsmarkit.com/products/oil-gas-tools-enerdeq-browser.html, 2017.

IPCC: Chapter 4: Fugitive Emissions. In: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Ed.), Volume 2: Energy, The National Greenhouse Gas Inventories Program, Hayama, Kanagawa, Japan, 2006.

50 Jacob, D. J., Turner, A. J., Maasakkers, J. D., Sheng, J., Sun, K., Liu, X., Chance, K., Aben, I., McKeever, J., and Frankenberg, C.: Satellite observations of atmospheric methane and their value for quantifying methane emissions, Atmos. Chem. Phys., 16, 14371-14396, 2016.

Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., Bergamaschi, P., Pagliari, V., Olivier, J., Peters, J., van Aardenne, J., Monni, S., Doering, U., Petrescu, R., Solazzo, E., and Oreggioni, G.: EDGAR v4.3.2 Global Atlas of the three major
55 Greenhouse Gas Emissions for the period 1970-2012, Earth Syst. Sci. Data Discuss., 2019, 1-52, 2019.

Jeong, S., Millstein, D., and Fischer, M. L.: Spatially Explicit Methane Emissions from Petroleum Production and the Natural Gas System in California, Environmental Science & Technology, 48, 5982-5990, 2014.

Jeong, S., Zhao, C., Andrews, A. E., Bianco, L., Wilczak, J. M., and Fischer, M. L.: Seasonal variation of CH4 emissions from central California, Journal of Geophysical Research: Atmospheres, 117, 2012.

5   Kurokawa, J., Ohara, T., Morikawa, T., Hanayama, S., Janssens-Maenhout, G., Fukui, T., Kawashima, K., and Akimoto, H.: Emissions of air pollutants and greenhouse gases over Asian regions during 2000–2008: Regional Emission inventory in ASia (REAS) version 2, Atmos. Chem. Phys., 13, 11019-11058, 2013.

Larsen, K. D., M.; Marsters, P.: Untapped Potential: Reducing Global Methane Emissions from Oil and Natural Gas Systems. Rhodium Group, 2015.

10 Lyon, D. R., Zavala-Araiza, D., Alvarez, R. A., Harriss, R., Palacios, V., Lan, X., Talbot, R., Lavoie, T., Shepson, P., Yacovitch, T. I., Herndon, S. C., Marchese, A. J., Zimmerle, D., Robinson, A. L., and Hamburg, S. P.: Constructing a Spatially Resolved Methane Emission Inventory for the Barnett Shale Region, Environmental Science & Technology, 49, 8147-8157, 2015.

Maasakkers, J. D., Jacob, D. J., Sulprizio, M. P., Scarpelli, T. R., Nesser, H., Sheng, J. X., Zhang, Y., Hersher, M., Bloom, A. A., Bowman, K. W., Worden, J. R., Janssens-Maenhout, G., and Parker, R. J.: Global distribution of methane emissions, emission trends, and
15 OH concentrations and trends inferred from an inversion of GOSAT satellite data for 2010–2015, Atmos. Chem. Phys. Discuss., 2019, 1-36, 2019.

Maasakkers, J. D., Jacob, D. J., Sulprizio, M. P., Turner, A. J., Weitz, M., Wirth, T., Hight, C., DeFigueiredo, M., Desai, M., Schmeltz, R., Hockstad, L., Bloom, A. A., Bowman, K. W., Jeong, S., and Fischer, M. L.: Gridded National Inventory of U.S. Methane Emissions, Environmental Science & Technology, 50, 13123-13133, 2016.

20 Mitchell, A. L., Tkacik, D. S., Roscioli, J. R., Herndon, S. C., Yacovitch, T. I., Martinez, D. M., Vaughn, T. L., Williams, L. L., Sullivan, M. R., Floerchinger, C., Omara, M., Subramanian, R., Zimmerle, D., Marchese, A. J., and Robinson, A. L.: Measurements of Methane Emissions from Natural Gas Gathering Facilities and Processing Plants: Measurement Results, Environmental Science & Technology, 49, 3219-3227, 2015.

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A.
25 Robock, G. Stephens, T. Takemura and H. Zhang: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley (Ed.), Cambridge University Press, Cambridge, U.K. and New York, NY, U.S., 2013.

Omara, M., Sullivan, M. R., Li, X., Subramanian, R., Robinson, A. L., and Presto, A. A.: Methane Emissions from Conventional and
30 Unconventional Natural Gas Production Sites in the Marcellus Shale Basin, Environmental Science & Technology, 50, 2099-2107, 2016.

Peng, S., Piao, S., Bousquet, P., Ciais, P., Li, B., Lin, X., Tao, S., Wang, Z., Zhang, Y., and Zhou, F.: Inventory of anthropogenic methane emissions in mainland China from 1980 to 2010, Atmos. Chem. Phys., 16, 14545-14562, 2016.

Petroleum Economist Ltd: Oil & Gas Map of Russia/Eurasia & Pacific Markets, 1st edition, Petroleum Economist Ltd in association with VTB Capital, London, U.K., 2010.

35 Platts: North   America   Natural   Gas   Pipelines,   available   at: https://arrowsmith.mit.edu/mitogp/layer/MIT.SDE_DATA.NA_H8NATGASPIPELNS_08_2008/, 2008.

Robertson, A. M., Edie, R., Snare, D., Soltis, J., Field, R. A., Burkhart, M. D., Bell, C. S., Zimmerle, D., and Murphy, S. M.: Variation in Methane Emission Rates from Well Pads in Four Oil and Gas Basins with Contrasting Production Volumes and Compositions, Environmental Science & Technology, 51, 8832-8840, 2017.

40 Rose, K. B., J.; Baker, V.; Bean, A.; DiGiulio, J.; Jones, K.; Justman, D.; Miller, R. M.; Romeo, L.; Sabbatino, M.; Tong, A.: Development of an Open Global Oil and Gas Infrastructure Inventory and Geodatabase; NETL-TRS-6-2018; NETL Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Albany, OR, DOI: 10.18141/1427573, last access: 2018, 2018.

Rose, K. K.: Signatures in the Subsurface - Big & Small Data Approaches for the Spatio-Temporal Analysis of Geologic Properties & Uncertainty Reduction, Oregon State University, Ph.D. thesis, 2017.

45 Sabbatino, M., Romeo, L., Baker, V., Bauer, J., Barkhurst, A., Bean, A., DiGiulio, J., Jones, K., Jones, T.J., Justman, D., Miller III, R., Rose, K., Tong., A.: Global Oil & Gas Features Database, DOI: 10.18141/1427300, 2017.

Saunois, M., Bousquet, P., Poulter, B., Peregon, A., Ciais, P., Canadell, J. G., Dlugokencky, E. J., Etiope, G., Bastviken, D., Houweling, S., Janssens-Maenhout, G., Tubiello, F. N., Castaldi, S., Jackson, R. B., Alexe, M., Arora, V. K., Beerling, D. J., Bergamaschi, P., Blake, D. R., Brailsford, G., Brovkin, V., Bruhwiler, L., Crevoisier, C., Crill, P., Covey, K., Curry, C., Frankenberg, C., Gedney, N., Höglund-
50 Isaksson, L., Ishizawa, M., Ito, A., Joos, F., Kim, H. S., Kleinen, T., Krummel, P., Lamarque, J. F., Langenfelds, R., Locatelli, R., Machida, T., Maksyutov, S., McDonald, K. C., Marshall, J., Melton, J. R., Morino, I., Naik, V., O'Doherty, S., Parmentier, F. J. W., Patra, P. K., Peng, C., Peng, S., Peters, G. P., Pison, I., Prigent, C., Prinn, R., Ramonet, M., Riley, W. J., Saito, M., Santini, M., Schroeder, R., Simpson, I. J., Spahni, R., Steele, P., Takizawa, A., Thornton, B. F., Tian, H., Tohjima, Y., Viovy, N., Voulgarakis, A., van Weele, M., van der Werf, G. R., Weiss, R., Wiedinmyer, C., Wilton, D. J., Wiltshire, A., Worthy, D., Wunch, D., Xu, X., Yoshida, Y., Zhang, B.,
55 Zhang, Z., and Zhu, Q.: The global methane budget 2000–2012, Earth Syst. Sci. Data, 8, 697-751, 2016.

Scarpelli, T. R., Jacob, D. J., Maasakkers, J. D., Sulprizio, M. P., Sheng, J.-X., Rose, K., Romeo, L., Worden, J. R., and Janssens-Maenhout, G.: Global Inventory of Methane Emissions from Fuel Exploitation. Harvard Dataverse, available at: https://doi.org/10.7910/DVN/HH4EUM, 2019.

Sheng, J., Song, S., Zhang, Y., Prinn, R. G., and Janssens-Maenhout, G.: Bottom-Up Estimates of Coal Mine Methane Emissions in China:
5   A Gridded Inventory, Emission Factors, and Trends, Environmental Science & Technology Letters, doi: 10.1021/acs.estlett.9b00294, 2019. 2019.

Sheng, J.-X., Jacob, D. J., Maasakkers, J. D., Sulprizio, M. P., Zavala-Araiza, D., and Hamburg, S. P.: A high-resolution (0.1° × 0.1°) inventory of methane emissions from Canadian and Mexican oil and gas systems, Atmospheric Environment, 158, 211-215, 2017.

Stohl, A., Aamaas, B., Amann, M., Baker, L. H., Bellouin, N., Berntsen, T. K., Boucher, O., Cherian, R., Collins, W., Daskalakis, N.,
10   Dusinska, M., Eckhardt, S., Fuglestvedt, J. S., Harju, M., Heyes, C., Hodnebrog, Ø., Hao, J., Im, U., Kanakidou, M., Klimont, Z., Kupiainen, K., Law, K. S., Lund, M. T., Maas, R., MacIntosh, C. R., Myhre, G., Myriokefalitakis, S., Olivié, D., Quaas, J., Quennehen, B., Raut, J. C., Rumbold, S. T., Samset, B. H., Schulz, M., Seland, Ø., Shine, K. P., Skeie, R. B., Wang, S., Yttri, K. E., and Zhu, T.: Evaluating the climate and air quality impacts of short-lived pollutants, Atmos. Chem. Phys., 15, 10529-10566, 2015.

UNFCCC: Greenhouse Gas Inventory Data Interface, available at: http://di.unfccc.int/detailed_data_by_party, 2019.

15   Wang, Y.-P., Bentley, S.: Development of a spatially explicit inventory of methane emissions from Australia and its verification using atmospheric concentration data, Atmos. Environ., 36, 4965-4975, 2002.

Zavala-Araiza, D., Lyon, D., Alvarez, R. A., Palacios, V., Harriss, R., Lan, X., Talbot, R., and Hamburg, S. P.: Toward a Functional Definition of Methane Super-Emitters: Application to Natural Gas Production Sites, Environmental Science & Technology, 49, 8167-8174, 2015.

20   Zhao, C., Andrews, A. E., Bianco, L., Eluszkiewicz, J., Hirsch, A., MacDonald, C., Nehrkorn, T., and Fischer, M. L.: Atmospheric inverse estimates of methane emissions from Central California, Journal of Geophysical Research: Atmospheres, 114, 2009.

Table 1. Uncertainty ranges for IPCC emission factors and corresponding error standard deviations.[a]

Subsector	Annex I countries				Non-Annex I countries			
	Lower (%)	Upper (%)	RSD (%)	GSD	Lower (%)	Upper (%)	RSD (%)	GSD
Oil								
Exploration[b]	100	100	50	2.11	12.5	800	100	1.79
Production (leakage)	100	100	50	2.11	12.5	800	100	1.79
Production (venting)	75	75	37.5	1.63	75	75	37.5	1.63
Production (flaring)	75	75	37.5	1.63	75	75	37.5	1.63
Refining	100	100	50	2.11	100	100	50	2.11
Transport (leakage)	100	100	50	2.11	50	200	62.5	1.57
Transport (venting)	50	50	25	1.32	50	200	62.5	1.57
Gas								
Exploration[b]	100	100	50	2.11	12.5	800	100	1.79
Production (leakage)	100	100	50	2.11	40	250	72.5	1.55
Production (flaring)	25	25	12.5	1.14	75	75	37.5	1.63
Processing (leakage)	100	100	50	2.11	40	250	72.5	1.55
Processing (flaring)	25	25	12.5	1.14	75	75	37.5	1.63
Transmission (leakage)	100	100	50	1.41	40	250	72.5	1.55
Transmission (venting)	75	75	37.5	1.63	40	250	72.5	1.55
Storage (leakage)	20	500	100	1.65	20	500	100	1.65
Distribution (leakage)	20	500	100	1.65	20	500	100	1.65
Coal	66	200	66.5	1.72	66	200	66.5	1.72

[a] The uncertainty ranges (lower, upper) are provided by the IPCC and apply to the estimation of national emissions using emission factors specified in Tier 1 methods (IPCC, 2006). We interpret them here as 95% confidence intervals, and infer the corresponding relative standard deviation (RSD, %) for the assumption of a normal error pdf and geometric standard deviation (GSD, dimensionless) for the assumption of a lognormal pdf. The IPCC provides uncertainty ranges for 'developed' and 'developing' countries and we apply them to Annex I and non-Annex I countries, respectively.

[b] Well drilling

Table 2. Global methane emissions from oil, gas, and coal in 2016.

Sector/Subsector	Total (Tg a^{-1})
Oil	41.5
Exploration	1.4
Production (leakage)	17.8
Production (venting)	21.6
Production (flaring)	0.5
Refining	0.1
Transport (leakage)	<0.1
Transport (venting)	<0.1
Gas	24.4
Exploration	<0.1
Production (leakage)	7.4
Production (flaring)	<0.1
Processing (leakage)	2.3
Processing (flaring)	0.1
Transmission (leakage)	7.1
Transmission (venting)	0.6
Storage (leakage)	1.0
Distribution (leakage)	5.7
Coal	31.3
Total	97.2
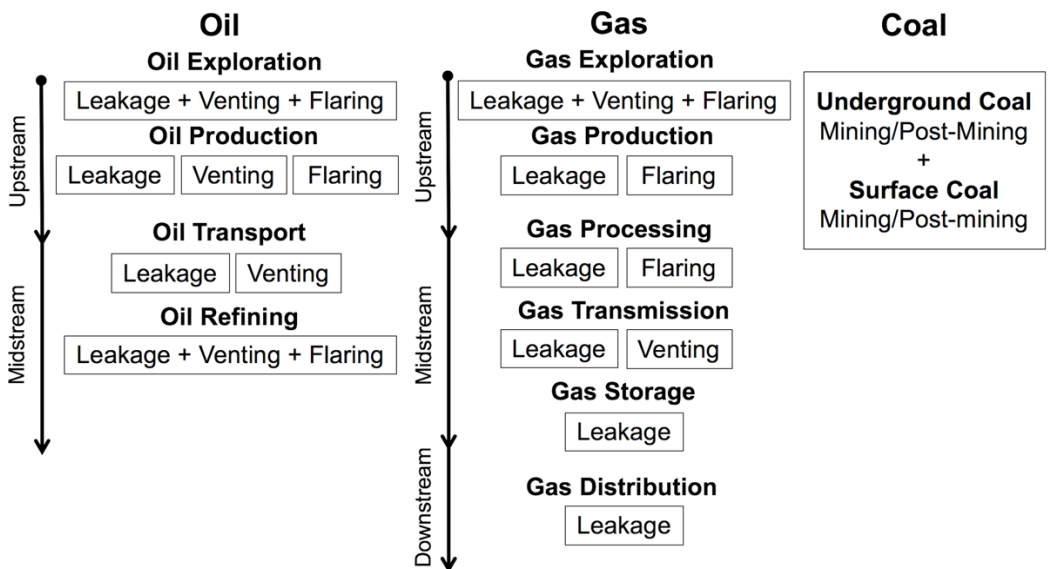
Figure 1. Methane emissions from oil, gas, and coal as resolved in our inventory. Emissions for oil and gas are separated into subsectors representing the different lifecycle stages. Each box in the figure corresponds to a separate 0.1º x 0.1º gridded product in the inventory.
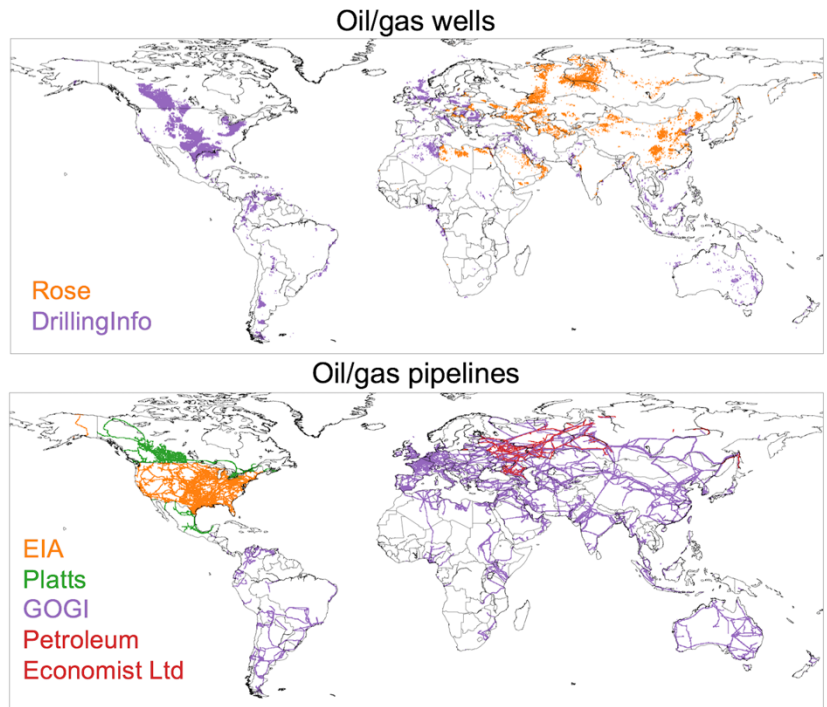

Figure 2. Global distributions of oil/gas wells (DrillingInfo, 2017; Rose, 2017; top) and pipelines (EIA, 2018b; Petroleum Economist Ltd, 2010; Platts, 2008; Sabbatino et al., 2017; bottom) used in our inventory. The data are at 0.1º x 0.1º grid resolution but are degraded here to 0.2º x 0.2º for visibility.

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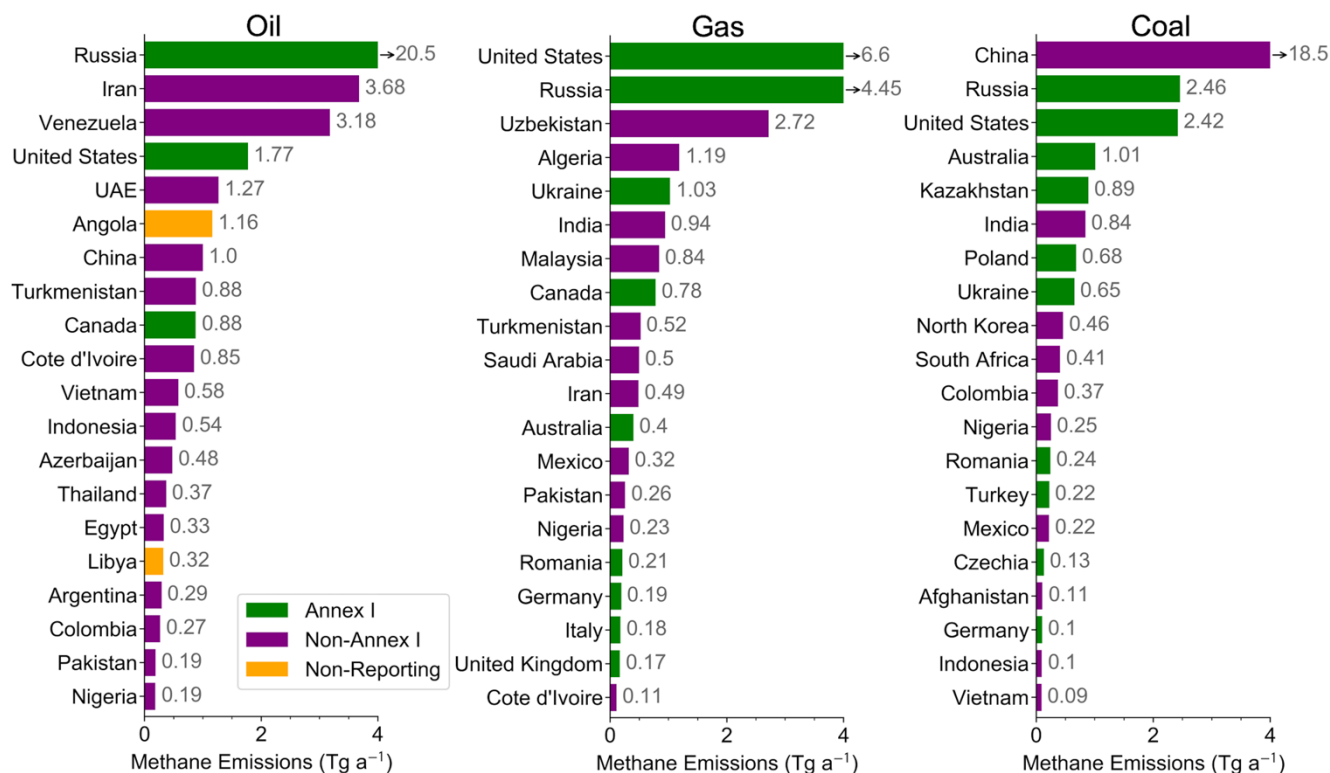
Figure 3. Methane emissions in 2016 from the top 20 emitting countries for the oil, gas, and coal sectors. Arrows next to the top bars (highest emitting countries) indicate that emissions are not to scale.
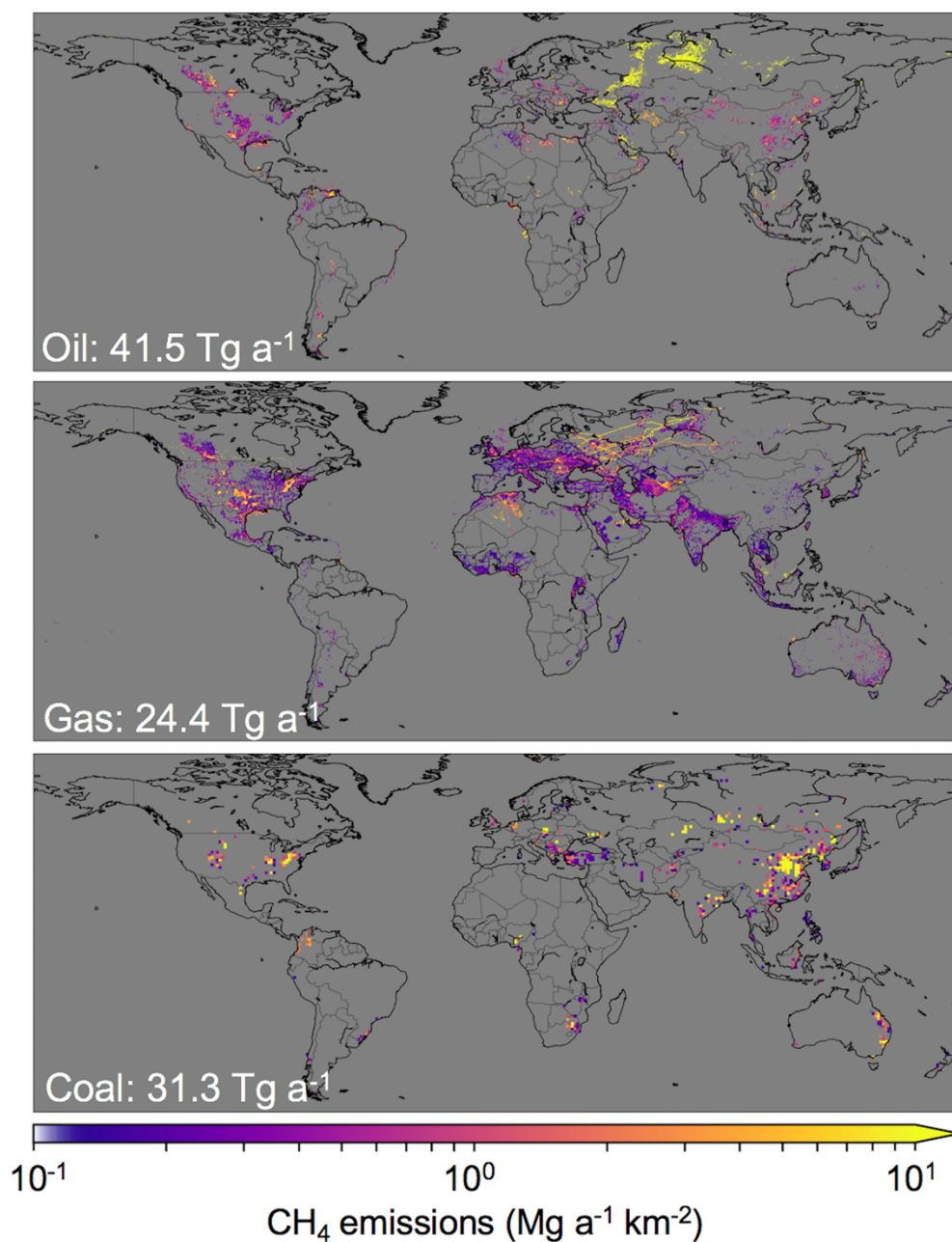
Figure 4. Global distribution of 2016 methane emissions from oil, gas, and coal. The inventory is at 0.1º x 0.1º grid resolution. Coal is shown here at 1º x 1º resolution for visibility.
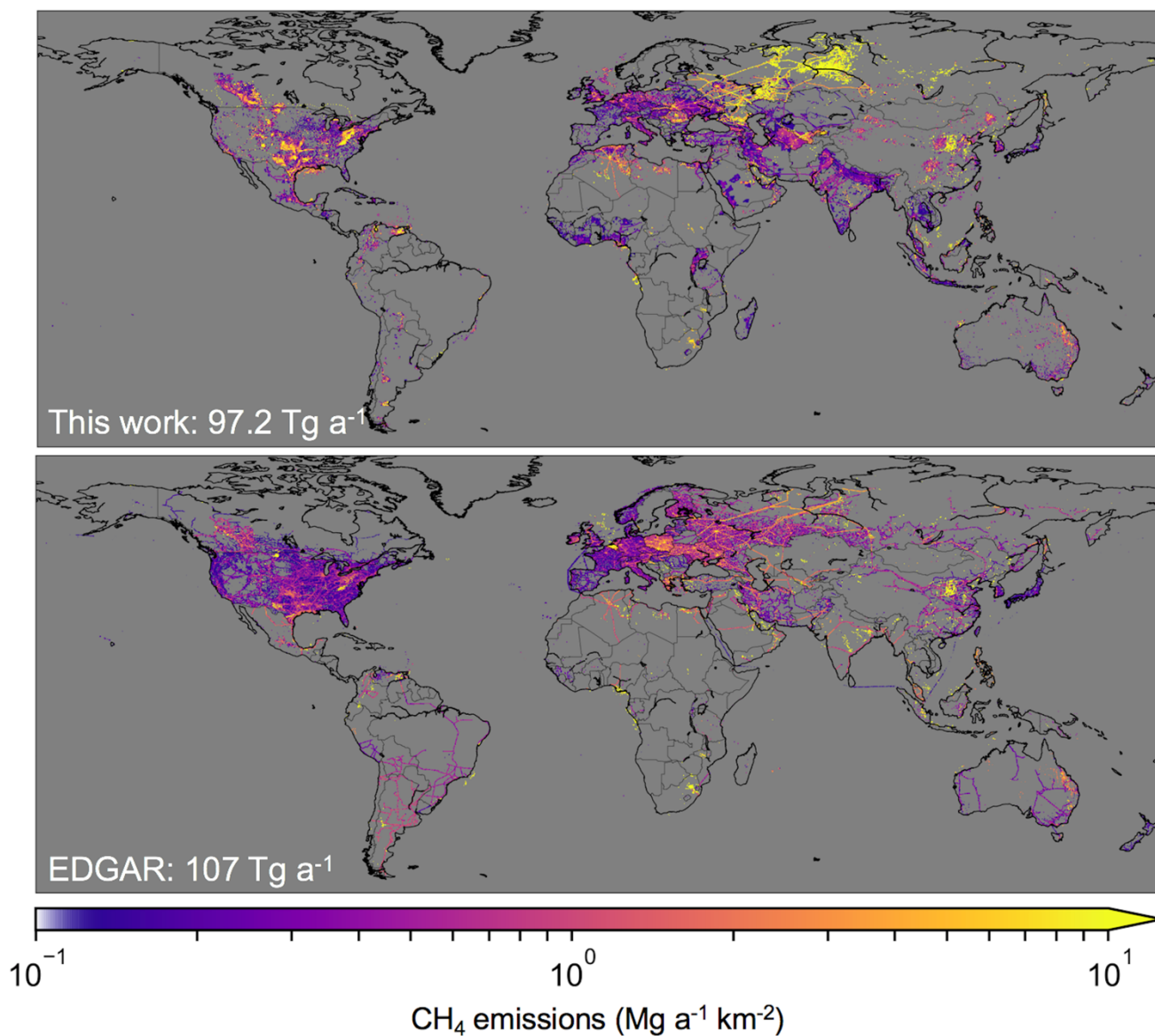
Figure 5. Total methane emissions from oil, gas, and coal in 2016 for this work (top) and in 2012 for EDGAR v4.3.2 (bottom).
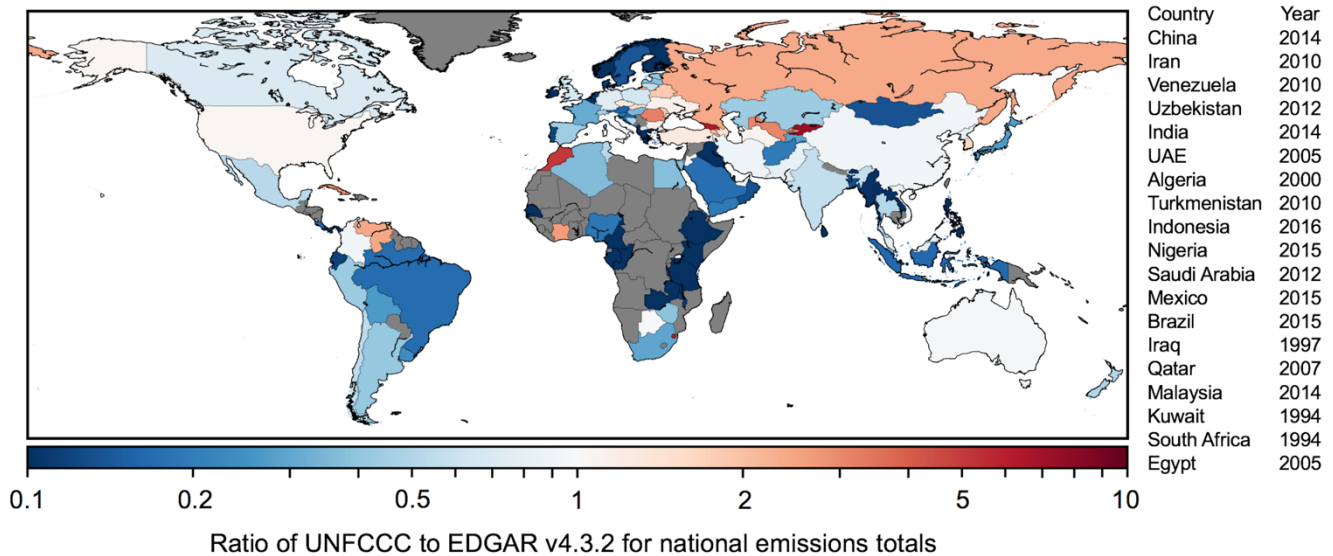
Figure 6. Comparison of national methane emissions from oil, gas, and coal reported by individual countries to the UNFCCC and estimated by the EDGAR v4.3.2 inventory. The figure shows the ratio of UNFCCC to EDGAR v4.3.2 with warmer colors indicating higher UNFCCC emissions. Emissions are taken from the most recent year reported to the UNFCCC and compared to EDGAR for the same year or for 2012 if the reporting year is more recent than 2012. The reporting year for non-Annex I countries with emissions greater than 1 Tg a^{-1} in either inventory is shown to the right. Countries in gray do not report oil/gas and coal emissions to the UNFCCC.