communications
earth & environment

ARTICLE

https://doi.org/10.1038/s43247-023-01190-w OPEN

Assessment of methane emissions from oil, gas and coal sectors across inventories and atmospheric inversions

Kushal Tibrewal[1✉], Philippe Ciais[1,2], Marielle Saunois[1], Adrien Martinez[1], Xin Lin[1], Joel Thanwerdas[1,14], Zhu Deng[3], Frederic Chevallier[1], Clément Giron[4], Clément Albergel[5], Katsumasa Tanaka[1,6], Prabir Patra[7,8], Aki Tsuruta[9], Bo Zheng[10,11], Dmitry Belikov[8], Yosuke Niwa[6,12], Rajesh Janardanan[6], Shamil Maksyutov[6], Arjo Segers[13], Zitely A. Tzompa-Sosa[1,15], Philippe Bousquet[1] & Jean Sciare[2]

Emissions from fossil fuel exploitation are a leading contributor to global anthropogenic methane emissions, but are highly uncertain. The lack of reliable estimates hinders monitoring of the progress on pledges towards methane reductions. Here we analyze methane emissions from exploitation of coal, oil and gas for major producing nations across a suite of bottom-up inventories and global inversions. Larger disagreement in emissions exists for the oil/gas sector across the inventories compared to coal, arising mostly from disparate data sources for emission factors. Moreover, emissions reported to the United Nations Framework Convention on Climate Change are lower than other bottom-up and inversion estimates, with many countries lacking reporting in the past decades. Finally, comparison with previous global inversions, revealed a strong influence of the prior inventory on the inferred sub-sectoral emissions magnitude. This study highlights the need to improve consensus on the methodological inputs among the bottom-up inventories in order to obtain more consistent inverse modelling results at the sub-sectoral level.

[1] Laboratoire des Sciences du Climat et de l'Environnement (LSCE), IPSL, CEA/CNRS/UVSQ, Université Paris-Saclay, Gif-Sur-Yvette, France. [2] Climate and Atmosphere Research Center (CARE-C), The Cyprus Institute, 20 Konstantinou Kavafi Street, 2121 Nicosia, Cyprus. [3] Tsinghua University, Department of Earth System Science, Beijing, China. [4] Kayrros, 33 rue Lafayette, 75009 Paris, France. [5] European Space Agency Climate Office, ECSAT, Harwell Campus, Didcot, UK. [6] Earth System Division, National Institute for Environmental Studies (NIES), Onogawa 16-2, Tsukuba, Ibaraki 305-8506, Japan. [7] Research Institute for Global Change, JAMSTEC, 3173-25 Showa-machi, Kanazawa, Yokohama 236-0001, Japan. [8] Center for Environmental Remote Sensing, Chiba University, Chiba, Japan. [9] Finnish Meteorological Institute, P.O. Box, 503, 00101 Helsinki, Finland. [10] Institute of Environment and Ecology, Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen 518055, China. [11] State Environmental Protection Key Laboratory of Sources and Control of Air Pollution Complex, Beijing 100084, China. [12] Meteorological Research Institute (MRI), Nagamine 1-1, Tsukuba, Ibaraki 305-0052, Japan. [13] TNO, Department of Climate Air & Sustainability, P.O. Box 80015, NL-3508-TA Utrecht, The Netherlands. [14] Present address: Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland. [15] Present address: Clean Air Task Force, 114 State Street, 6th Floor, Boston 02109, USA. ✉email: kushal.tibrewal@lsce.ipsl.fr

Fossil fuel sources are the second largest sector contributing to anthropogenic methane (CH_4) emissions, dominated by the oil, gas, and coal sub-sectors. The estimated annual emissions from fossil fuel production (exploration, extraction, processing, transportation and distribution) and consumption for the decade 2008–2017 range from 111(81–131) Tg/yr (top-down inversions) to 128(113–154) Tg/yr (bottom-up)[1], with a marginal contribution from consumption of fossil fuels. CH_4 emissions from fossil fuels have large uncertainties[2–4] ranging from 80 to 146[5] Tg/yr mainly driven by uncertainties from the oil and gas sector. Better constraining those emissions, particularly for the highest emitting countries, is a global priority to define the baseline and monitor the progress of the Global Methane Pledge signed by 150 countries (representing <60% of global emissions) to reduce 30% of global methane emissions in 2020 by 2030[6,7].

Multiple studies have compared bottom-up inventories of CH_4 with atmospheric inversions at different scales: global and national[1,4,8,9], in North America[10–12], EU[13], China[14], and Australia[15,16]. Recent study[4], comparing UNFCCC-reported emissions to global inversions from the Global Carbon Project (GCP)[1], concluded that some of the highest fossil CH_4 emitting countries reported lower emissions to the UNFCCC than atmospheric inversions.

The main focus of this study is to further investigate such differences incorporating larger set of bottom-up inventories and a new ensemble of global inversions updated to 2020 by GCP (https://www.globalcarbonproject.org/) (Table 1). We discuss the differences between inventories and inversions separately for emissions from oil and gas vs. coal sub-sectors for selected countries (Table 2 and Methods). For Annex I countries, we also present the evolution of estimates across different versions of UNFCCC reports and compare them with inversions. Finally, we highlight the influence of prior bottom-up inventory for deriving sub-sectoral emissions from atmospheric inversions. Our work responds to the need for an integrated and more consistent assessment of bottom-up and top-down approaches[17]. The goal is to estimate the most important fossil fuel sources of CH_4 and to improve national reports of CH_4 in the context of the global stock-take and countries' pledges to reduce anthropogenic CH_4 emissions.

The top-down models include ten surface-based inversions (SURFACE) during 2000–2020 and two satellite-based inversions for the period 2010–2020 (GOSAT) from new GCP inversions. Fossil fuel emissions from oil & gas and coal sub-sectors in inversions were isolated in each grid cell based on the sub-sectoral contribution in the prior inventory. Additionally, 2019–2020 country-wide estimates of CH_4 ultra-emissions from oil and gas sources based on the TROPOMI satellite data[18] are also included. Ultra-emissions are leak events of short duration with high CH_4 release (>25 tCH_4/hour). These generally constitute a small fraction of national emissions but could also represent a large fraction for certain countries like Turkmenistan[18], and generally not included in bottom-up inventories. Sectoral emissions from the ensemble of bottom-up inventories (Supplementary Table S3) consists of national submissions to UNFCCC compiled from different sources[4] (including National Inventory Reports–NIR; National communications–NCs; Biennial Update Reports-BURs) and different global inventories, including the Community Emissions Data System (CEDS)[3,19], the Emissions Database for Global Atmospheric Research (EDGARv6)[20], the Greenhouse gas and Air pollutant Interactions and Synergies (GAINS)[21,22], the Global Fuel Exploitation Inventory (GFEI)[8], two versions from International Energy Agency [23] – a) global fossil emissions from 1990-2015 (IEA) and b) global oil and gas emissions for 2020 (IEA 2020) and the U.S. Environmental Agency (EPA)[24].

Results

Mean fossil fuel CH_4 emissions over the last decade. We first compare the mean fossil fuel CH_4 emissions across bottom-up (including ultra-emissions and UNFCCC where available) and top-down inventories (Table 1) for the selected countries (Table 2) over 2011–2020 (Fig. 1). Comparison with UNFCCC is presented in Supplementary Table S4.

China is the largest contributor with average emissions of 24(21–27) Tg/yr (bottom-up) and 22(16–33) Tg/yr (top-down) during 2011–2020, dominantly from the coal sector (~80%). For total fossil emissions, average estimates from bottom-up inventories (including UNFCCC) agree well with SURFACE, but GOSAT estimates are 20% lower. UNFCCC estimates are similar

Table 1 Bottom-up and top-down emission inventories of fossil fuel sources used in this study.

Emission inventory	Time period	Resolution	Sector/Subsector	Coverage	Reference
Bottom-up inventories					
UNFCCC	1986–2019	Yearly	Coal, Oil and gas	Global	UNFCCC 2021
GFEI	2010–2019	Yearly	Coal, Oil, Gas	Global	Scarpelli et al. 2022[8]
CEDS	1970–2019	Yearly	Coal, Oil, Gas	Global	O'Rourke et al. 2021[3]
EDGARv6	1970–2018	Yearly	Coal, Oil and gas	Global	Crippa et al. 2021[2]
GAINS	1990–2020	Yearly	Coal, Oil, Gas	Global	Höglund-Isaksson et al. 2020[21]
EPA	1990–2050	Every 5 years[a]	Coal, Oil, Gas	Global	USEPA, 2019[51]
	1990–2019	Yearly	Coal, Oil, Gas	U.S.A.	USEPA 2022[52]
IEA	1990–2015	Every 5 years[b]	Fossil	Global	IEA 2020[47]
IEA 2020	2020	Yearly	Oil, Gas	Global	IEA 2021[48]
Top-down approaches[c]					
SURFACE Inversions N = 10[b]	2000–2020	Monthly fluxes aggregated to yearly	Coal, Oil and gas[d]	Global	--
GOSAT Inversions N = 2[b]	2010–2020	Monthly fluxes aggregated to yearly	Coal, Oil and gas	Global	--
Ultra-emissions	2019-2020	Yearly	Oil and gas: ultra-emitters	Single events	Lauvaux et al. 2022[18]

The corresponding sectors and subsectors are presented in Table S3.
[a]Historical emissions correspond to 1990-2015 and extrapolations from 2020-2050.
[b]This dataset also includes the year 2012.
[c]See Supplementary Table S1 with a summary of each inversion.
[d]Separated from all sectors in each grid cell as described in Methods.

to the average bottom-up estimate but 7% higher than average inversion emissions. The lower estimate from inversions compared to UNFCCC emissions, using a previous inversion ensemble from GCP[1], is consistent with results reported earlier[4]. At the sub-sectoral level, UNFCCC estimates from the coal sector is 10% higher than other bottom-up inventories (except EPA) most likely because of higher coal production in national statistics[25]. The oil and gas sector from UNFCCC are at least 40% lower than other bottom-up estimates, however these constitute a small fraction to total emissions.

Russia emitted an average of 14(8–25) Tg/yr (bottom-up) and 10(8–11) Tg/yr (top-down) during 2011–2020, largely from the oil and gas sector (80%). Large disagreements exist among the bottom-up estimates, mostly driven by differences in the oil and gas sector (standard deviation of ~6 Tg/yr). EPA estimate is almost double the bottom-up average and CEDS/GAINS estimates are ~25% higher. IEA and EDGARv6 estimates are 25% lower than the bottom-up average, and UNFCCC and GFEI estimates are ~45% lower. These discrepancies arise from different emission factors for oil production, particularly venting and flaring of associated gas. EPA, IEA, EDGARv6 are based on different versions of NIR using different combination of emission factors from Intergovernmental Panel on Climate Change (IPCC)[26] for oil sector (Table S7) while GAINS use an independent estimation[27]. The total averaged emissions from inversions are ~30% lower than bottom-up average. All bottom-up inventories have higher/equivalent emissions than inversions except GFEI and UNFCCC (also reported previously[4]). Especially for oil and gas sectors, the UNFCCC estimate agrees well with GFEI that used UNFCCC totals from 2021, but is ~50% lower than the mean of other bottom-up inventories. A lower estimate in UNFCCC compared to inversions and bottom-up arises from the downward correction in the 2019 report, discussed further in detail and also noted by previous studies[28,29].

For the USA, total average emissions of 12(10–18) Tg/yr (bottom-up) and 11(8–13) Tg/yr (top-down) are largely dominated by the gas sector (50%). Bottom-up and top-down approaches have comparable mean emissions for 2011–2020, except for GAINS having 50% higher emissions. This can be most likely due to the accounting of separate emission factors for unconventional gas production from the extraction of shale gas[21]. UNFCCC estimates are slightly above other inventories but still quite comparable.

For countries in Arabian Peninsula (AP), average estimate from bottom-up inventories, 9(2–14) Tg/yr is 20% lower than global inversions,12(9–16) Tg/yr, with a large disagreement among the bottom-up inventories. EPA and GFEI have 80% and 50% lower and EDGARv6 and CEDS have ~30% higher emissions than other inventories. This can arise from a combination of both activity data and emission factors, as EPA and GFEI are based on energy statistics from the US Energy Information Administration (EIA) with IPCC default emission

Table 2 List of selected countries and regions.

Code	Country list	UNFCCC party group
AP	Saudi Arabia, Oman, United Arab Emirates, Kuwait, Bahrain, Iraq, and Qatar	Non-Annex I
AUS	Australia	Annex I
CHN	China	Non-Annex I
IRN	Iran	Non-Annex I
KAZ	Kazakhstan	Annex I
RUS	Russia	Annex I
TKM	Turkmenistan	Non-Annex I
USA	United States of America	Annex I
VEN	Venezuela	Non-Annex I

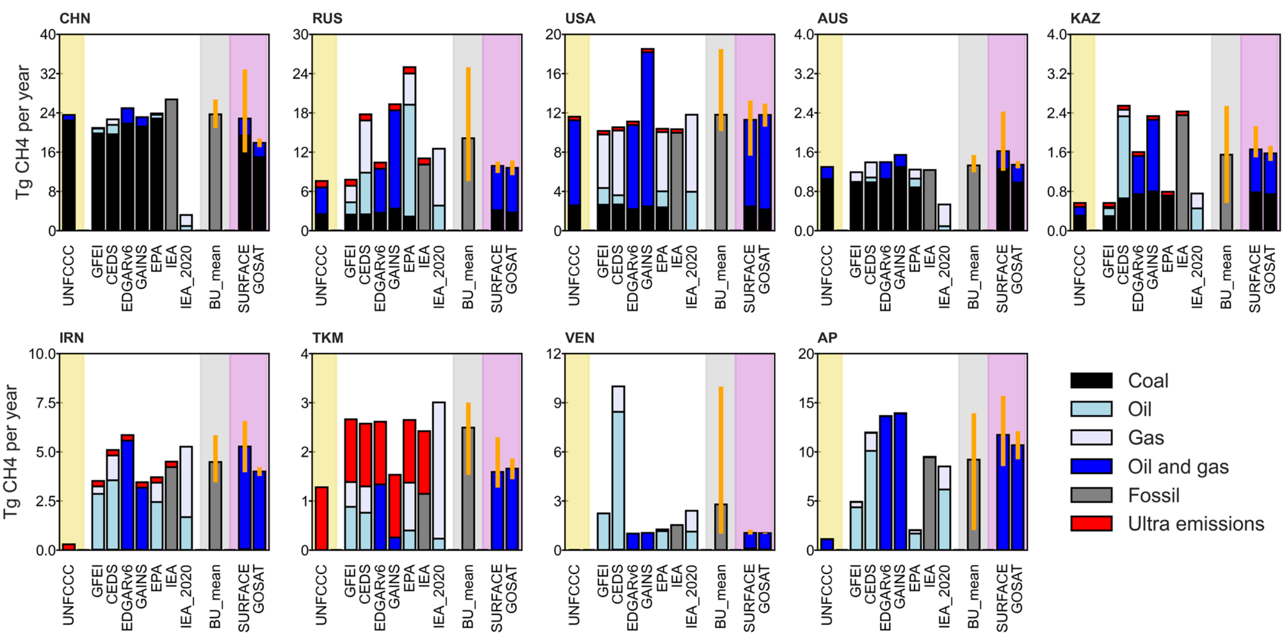

Fig. 1 Average CH_4 emissions (2011–2020) from fossil fuels across bottom-up and top-down approaches. UNFCCC emissions (with yellow shaded background) represent the mean of available country reports during the same period. BU_mean represents the mean of all bottom-up inventories including UNFCCC where available (with grey shaded background). Inversion emissions (with pink shaded background) from SURFACE and GOSAT correspond to the average of inversions from 2011 to 2020, as explained in Methods. Error bars denote minimum and maximum values from inversion ensembles. On top of all bottom-up inventories are emissions from ultra-emitters (red bars, as diagnosed from S5P TROPOMI measurements for 2019–2020[18]). Note 1) no reported emissions for IRN, VEN, TKM and most countries within AP from UNFCCC during the period (Supplementary Table S5), and 2) IEA_2020 only reported emissions from the oil and gas sector.

factors[26] as opposed to EDGARv6 and CEDS which use IEA energy statistics and different[27] emission factors (Table S7). IEA 2020 estimates are close to the bottom-up average and 20% lower than inversions. UNFCCC estimates are not included in the bottom-up mean as the values are only available for Kuwait and Saudi Arabia.

Australia emitted around 1.3(1.2–1.5) Tg/yr (bottom-up) and 1.6(1.2–2.4) Tg/yr (top-down), with 80% of emissions from the coal sector. For total fossil emissions, averaged over 2011–2020, global inversions were 15% higher than bottom-up approaches, with estimates across bottom-up inventories consistent within 10%, except for GAINS reporting ~20% higher values than the bottom-up mean. For the coal sector, estimates across all bottom-up inventories are also within 10%, except for GAINS reporting ~30% higher values, most likely due to larger activity data from IEA statistics and higher implied emission factors compared to NIRs. However, larger disagreements (but remaining small in absolute values) exist for the oil and gas sector, with estimates from UNFCCC, GFEI, and GAINS being 25–40% lower than the bottom-up mean but IEA 2020 and CEDS being ~60% and 20% higher, respectively.

Total average emissions from Kazakhstan are 1.5(0.6–2.5) Tg/yr (bottom-up) and 1.6(1.4–2.1) Tg/yr (top-down), with equal shares from the coal sector and oil & gas subsectors. While the average estimates for total fossil emissions from bottom-up and top-down approaches are nearly identical, there are large disagreements among the inventories. Estimates from CEDS, GAINS, and IEA are 65% higher than the mean of all inventories, while those from UNFCCC, GFEI, and EPA are 55% lower, with both sectors contributing to this discrepancy. Emissions from the oil & gas sectors for UNFCCC, GFEI, and EPA are ~80% lower than other bottom-up inventories, and those from the coal sector are 50% lower, likely from differences in emission factors. For coal, Kazakhstan shifted its emission factors downwards in recent NIRs to UNFCCC, (Table S6 and Fig. S3) which is also basis for emissions in GFEI and EPA (Table S7). Similarly, for oil and gas sectors, emission factors from NIR are lower than IPCC[26] and ref. [27] (used in other inventories; Table S7).

For Iran, the average estimates from bottom-up, 4(3–6) Tg/yr and global inversions, 5(4–7) are close, but disagreements exist among individual inventories. CEDS, EDGARv6, IEA inventories and SURFACE inversions are roughly 45% higher than EPA, GAINS, GFEI inventories and GOSAT inversions, for which the exact basis is unclear. The bottom-up average does not include estimate from UNFCCC, as the last communication from Iran was in 2000.

Turkmenistan emits 2.5(1.5–3.0) Tg/yr (bottom-up) and 1.6(1.3–2.3) Tg/yr (top-down), having the largest share of emissions from ultra-emitters (50% of the total). It appears all other bottom-up inventories fail to account for ultra-emissions as the estimates are almost 60% lower than IEA 2020, which includes ultra-emitters. After superimposing additional estimates for ultra-emissions, the estimates across all bottom-up inventories come to an agreement, except for GAINS having 50% lower emissions because of lower emission factors for leaks from gas production[27]. While the average bottom-up estimates after accounting for ultra-emissions are 60% higher than estimates from the mean of global inversions, they are still within the range from SURFACE inversions.

For Venezuela, total average emissions from global inversions, 1.0(0.9–1.2) Tg/yr is roughly three times lower than bottom-up inventories, 2.8(1.0–10.0) Tg/yr because of a ten times larger estimate from CEDS, for which the basis in unclear. Without CEDS, emissions from bottom-up inventories show a narrower range (1.0–2.4 Tg/yr). Still, EPA and IEA have 25–50% higher, GFEI and IEA 2020 have double emissions compared to inversions. IEA 2020 is based on satellite data and includes emissions from gas production which may be missed by other inventories. GFEI is based on the national communication of Venezuela which uses the higher end of the default emission factor for oil sector. Estimates from GAINS and EDGARv6 are identical to global inversions. The mean emissions from SURFACE and GOSAT are quite similar, reporting ~1.0 Tg/yr.

Time series and trends of fossil fuel methane emissions. In this section, we analyze the trends of CH_4 emissions from coal (Fig. 2) and oil & gas (Fig. 3) sectors for major emitters across the suite of bottom-up and top-down estimates. Coal emissions in China (Fig. 2) have an increasing trend during 2000–2010 across inventories with median time series of bottom-up (1.05 ± 0.05 Tg/yr^2) showing ~25% greater trend than top-down (0.83 ± 0.06 Tg/yr^2) estimates. GAINS shows a steeper trend (1.57 ± 0.16 Tg/yr^2) than other inventories during 2000–2005, as also highlighted previously[21]. Unlike global inversions, the median of bottom-up inventories continues to rise until 2013, followed by stable emissions. It appears that both SURFACE and GOSAT inversions do not capture the peak emissions in 2012–2013 reported across all bottom-up inventories (including UNFCCC) but rather indicate a plateau since 2010. Russian coal sector emissions (Fig. 2) also increase from 2000 to 2017 across all approaches but with 75% steeper trend in the median of global inversions (0.07 ± 0.01 Tg/yr^2) than bottom-up inventories (0.04 ± 0.00 Tg/yr^2). The higher trend in inversions is consistent with those reported in CEDS, GAINS and EDGARv6. Inventories report either a declining (e.g., UNFCCC, GFEI, GAINS) or stable (e.g., inversions) emissions after 2017. For the USA, all inventories report nearly stable emissions for the coal sector (Fig. 2) until 2007. The median of inversions shows a declining trend (-0.14 ± 0.01 Tg/yr^2) after 2007, consistent with EDGARv6 (used as prior) but the median of bottom-up inventories starts declining (-0.12 ± 0.01 Tg/yr^2) only after 2010. For Australia, coal emissions (Fig. 2) in the median of bottom-up inventories remain stable during 2000–2020 with a slight peak around 2007. On the contrary, the median of global inversions remains stable until 2009, then peak during 2010-2015, followed by a decline of -0.05 ± 0.02 Tg/yr^2 henceforth. The peak in inversions is consistent with that in EDGARv6 (used as prior) and GAINS. However, EDGARv6 emissions declined after 2012 while those in GAINS continued to grow. Trends of emission from the coal sector (Fig. 2) for Kazakhstan were consistent across all inventories growing at the rate of 0.02 ± 0.00 Tg/yr^2 (for both bottom-up and inversion estimates) till 2013, followed by stabilized emissions. The spread of inversions includes the ensemble of inventory estimates for China and USA. For other countries in Fig. 2, bottom-up ensemble generally appears in the lower range of top-down ensemble.

Unlike the coal sector, emission trends from the oil and gas sector (Fig. 3) are quite inconsistent across inventories, with top-down ensemble generally included in bottom-up range over a large part of the 20 years of analysis, except for Iran. Also, important increasing/decreasing jumps in emissions are observed for some inventories from one year to the next (for e.g., Kazakhstan, USA and Iran in Fig. 3) and seem unrealistic. For Russia, global inversions report a modestly increasing trend (0.08 ± 0.00 Tg/yr^2) during 2000–2020, consistent with their prior EDGARv6. Contrastingly, the median of bottom-up inversions shows a large growth (0.84 ± 0.08 Tg/yr^2) during 2000–2005, followed by stable emissions until 2020. This large initial growth is contributed by CEDS and EPA. GAINS reports a positive trend of 0.42 ± 0.05 Tg/yr^2 until 2007, followed by a decline (-0.23 ± 0.02 Tg/yr^2). Further, the time series of UNFCCC and

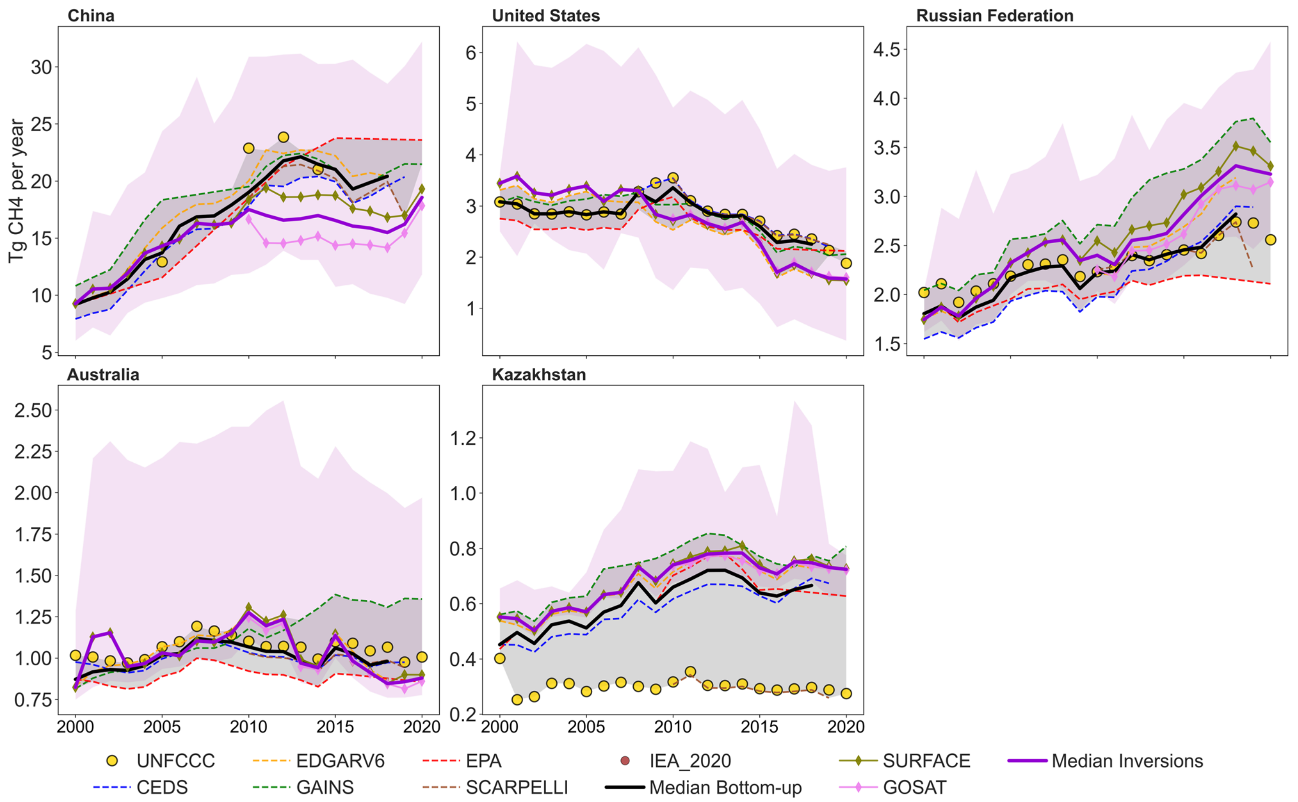

Fig. 2 Time series of CH_4 emissions (2000–2020) from coal sector across bottom-up and top-down approaches. The emissions time series are shown for selected countries. The shaded region represents the spread of the bottom-up inventories (gray) and inversions (pink). The thick lines are the median from bottom-up and top-down estimates. GOSAT and surface inversions median are represented as thin lines with diamond symbols (light pink and green). Thin dashed lines represent emissions from different bottom-up inventories.

GFEI (which is based on UNFCCC) report a declining trend of -0.14 ± 0.01 Tg/yr^2 each from 2005 and 2010, respectively, until 2020. For the AP region, emissions of the oil and gas sector (Fig. 3) showed a similar increasing trend in the median of both global inversions (0.28 ± 0.03 Tg/yr^2) and bottom-up inventories (0.27 ± 0.02 Tg/yr^2) from 2000 till 2020 and 2018 respectively. This is consistent with the trajectory of CEDS, but EDGARv6 reported a steeper increase (0.58 ± 0.04 Tg/yr^2) from 2010 onwards. There is no evident trend in GAINS which shows annual emissions fluctuating within 12–15 Tg/yr during 2000–2020. UNFCCC estimates included communications only from limited countries and in different years (Supplementary Table S5).

For Iran, median emissions of the oil and gas sector (Fig. 3) from global inversions (0.32 ± 0.08 Tg/yr^2) and bottom-up inventories (0.29 ± 0.05 Tg/yr^2) showed an increasing trend during 2001–2005, after which the inversions continued to increase (0.12 ± 0.02 Tg/yr^2) while the bottom-up median nearly stabilized. This opposite trend of bottom-up inventories compared to inversions is driven by GAINS, which reported a decline (-0.16 ± 0.01 Tg/yr^2) during 2005–2015. The increasing trend in inversions is consistent with EDGARv6 (used as prior) and CEDS. However, emissions from CEDS remain constant from 2015 onwards. For USA, emissions from the oil and gas sector (Fig. 3) remain quite stable throughout the time period across bottom-up inventories (except for GAINS) and inversions. GAINS reported a very steep increase of 1.04 ± 0.04 Tg/yr^2 since 2007, most likely due to the accounting of separate emission factors for unconventional gas production from the extraction of shale gas. There is a large disagreement among the inventories for the emissions trends from the oil and gas sector for Kazakhstan (Fig. 3). The median estimates from global inversions show a steady growth of 0.03 ± 0.00 Tg/yr^2 throughout the timeline, similar to EDGARv6 (used as prior). But the median of bottom-up inventories showed an initial growth (0.06 ± 0.00 Tg/yr^2) until 2004, followed by a declining trend of -0.12 ± 0.01 Tg/yr^2 until 2010, followed by stable emissions henceforth, similar to that of UNFCCC. GAINS also reported a similar trajectory as UNFCCC. CEDS reported stable emissions throughout but with a sudden doubling of emissions in 2012.

The reasons for discrepancies arise due to the combined effects of differences in activity data and implied emission factors. Some of the differences in implied emission factors are identified in the previous sub-section. In regard to the absolute magnitudes and trend in activity data, the exact basis is hard to identify as much of these data are not open source and/or superseded by newer versions. However, a recent analysis[25] highlights the potential range of disagreements among these international statistics.

Revisions of emissions reported by Annex1 countries to the UNFCCC. UNFCCC reports provide complete time-series with detailed sub-sector disaggregation every year for Annex I countries. However, emissions for specific years can vary with each emission report, as countries update and reanalyze earlier data. We analyzed the range of revisions (Fig. 4 and Supplementary Fig. S3) and their reasons (Supplementary Table S6), across different versions of UNFCCC reports, following a thorough analysis of NIRs[30].

Russia had the largest degree of change (within ±15 Tg/yr) among the Annex 1 countries analyzed in this study, mostly arising from the oil & gas sector (Fig. 4a). Inclusion of new sources - oil and gas exploration, distribution and venting/flaring

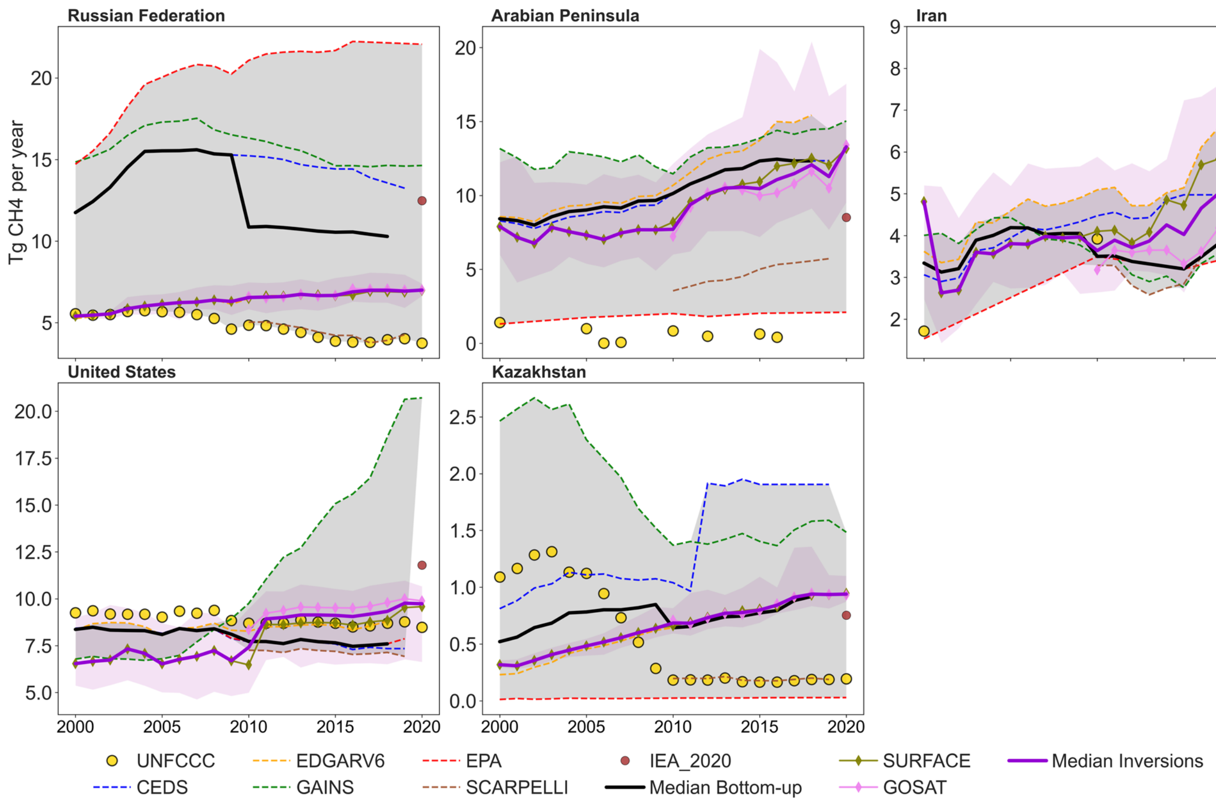

Fig. 3 Time series of CH_4 emissions (2000–2020) from oil & gas sector across bottom-up and top-down approaches. The emissions time series are shown for selected countries. The shaded region represents the spread of the bottom-up inventories (gray) and inversions (pink). The thick lines are the median from bottom-up and top-down estimates. GOSAT and surface inversions median are represented as thin lines with diamond symbols (light pink and green). Thin dashed lines represent emissions from different bottom-up inventories.

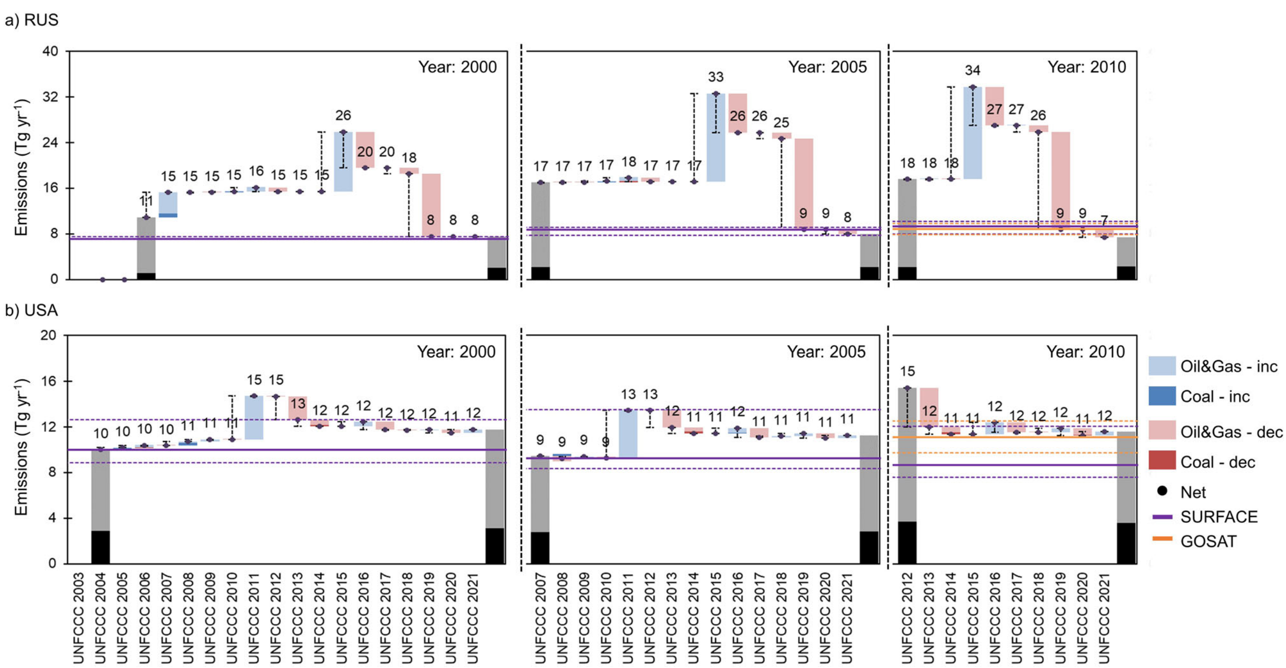

Fig. 4 Evolution of revisions in the estimates of fossil emissions in UNFCCC reports. Revisions are shown for emissions from **a** Russia and **b** USA and for years 2000,2005 and 2010 across all UNFCCC reports submitted from 2003 to 2021. The black dots represent the total fossil emissions mentioned in the corresponding report. Shaded bars represent the revisions ('Blue' for increases and 'Red' for decreases) in coal (dark shade) and oil+gas (light shade) sectors respectively. Dotted vertical lines represent the net revision observed in the following reporting year. Solid horizontal lines represent the mean emissions from inversions (purple for SURFACE inversions and orange for GOSAT inversions) with dotted horizontal lines representing the minimum and maximum across the inversion dataset.

in the 2007 reporting led to increases in emissions for years up to 2005. In the 2015 reporting, a net increase in emission magnitudes occurred from this sector due to revision of emission factors following the change in source material from IPCC 2000 to IPCC 2006 values recommended for developing countries. However, claiming its technological advancements to be at par with those in the Western countries, Russia adopted the emission factors values of developed countries for natural gas systems in the 2016 reporting, and for oil production systems in the 2019 reporting, leading to reductions in reported emissions. Additional downward correction to emission factors was found in the 2019 report, following a shift from default values to country specific values from national studies specifically for gas production. Overall, there is a net decrease in total fossil emissions, up to 70% in the latest reporting of 2021 with respect to the reportings around 2015 and within 30–50% with respect to initial reportings around 2010–2012.

For the USA (Fig. 4b), reported emissions magnitudes had a large increase in the 2011 report (~4 Tg/yr or 35–45%) followed by a decrease in the 2013 report (1.5–3.5 Tg/yr or 11–22%), along with relatively smaller changes (within ±10%) in the 2014–2017 reports. Increment in emission factors for natural gas production, arising from revision of methodology for gas wells with liquids unloading, condensate storage tanks, centrifugal compressors and addition of data for new sources (i.e., gas well completions and gas well workovers with hydraulic fracturing), contributed to the increase in 2011. Further, improved input data for liquid unloading, leading to a downward correction of emission factor from natural gas production, drove the decrease in the 2013 report and thereafter. The increases dominated for years prior to 2010 leading to a net increase in the latest reported emissions (v2021) for the former decade (2000–2009) while the emissions in the later decade (2010–2019) were subject mostly to downward corrections leading to net reductions.

For Australia, estimates across different versions of UNFCCC reports were mostly stable (within ±0.2 Tg/yr or ±15%) forming a series of increases and decreases in total fossil emissions (Supplementary Fig. S3a). Both sub-sectors saw large changes: changes in the coal sector dominated in the former decade, while those in the oil & gas sector occurred during the latter decade. A key change included updates in national statistics following the launch of National Greenhouse and Energy Reporting (NGER) system in 2008, mandating the reporting of facility-level data under certain conditions, for collecting inventory data. Consequently, increases occurred in reports of 2009 and 2010 from an upward correction of emission factors for underground coal mines following the inclusion of basin-specific data under the NGER system. A major decrease occurred in the 2015 reporting, arising from downward correction of activity data related to natural gas exploration and distribution from the inclusion of new datasets. Overall, the magnitudes of emissions for years in the former decade (2000–2009) were subject to compensating effects (increase in 2010 reporting and decrease in 2015 reporting) leading to negligible change in the latest report of 2021 w.r.t the first respective reporting for each year. However, emissions during the latter decade (2010–2019) saw net reductions in magnitudes in the latest report of 2021 due to the dominating effect of correction in 2015 reporting.

For Kazakhstan (Supplementary Fig. S3b), while most of the changes between successive UNFCCC reports in relative terms were as high as for Russia (within ±65%), in terms of absolute magnitude, these were quite low (within ±0.8 Tg/yr). The changes were driven by both the coal and oil & gas sectors. A 55–65% increase in emissions magnitudes occurred in its 2010 report due to an upward revision of emission factors for surface coal mining. The exact reason for the revision is unclear as the report did not provide any supporting document for the source data. These factors were revised slightly downward in the 2013 report following new inputs from mining enterprises, and in the 2018 report most likely due to change in assumed gas density. Another downward revision occurred in the recent 2021 report, most likely due to adoption of the IPCC 2006 default values[26] as new factors are still under development. The last three revisions reduced emissions magnitudes from the coal sector across the timeline. Similar updates to emissions factors also occurred for the oil & gas sector. Revisions in emission factors for oil and gas systems in the 2018 and 2021 led to large deviations in reported emissions, especially for the years in the former decade. Overall, the changes led to modest increases in emissions magnitudes for years in the former decade but nearly 50-65% reductions in magnitudes for years in the latter decade.

The evolution of changes in emission magnitudes are also compared against the inversion estimates for each year. For the USA, updates to reported emissions shifted the UNFCCC magnitudes slightly away from the inversions for emissions during 2000–2010 but closer to the inversions after 2010. Revisions in Russian reporting resulted in better alignment with inversion ensemble estimates throughout the timeline. For Australia, emissions reported to UNFCCC, remained closely aligned to inversion estimates both before and after the revisions. For Kazakhstan, revisions resulted in greater UNFCCC emissions than inversions during 2000–2010 but 60% lower during 2011–2020. It should be noted that for countries with limited observations, inversion may not be much different than their prior inventory and for some countries, uncertainties in inversion are larger than the changes in the reporting across the UNFCCC submissions.

Evolution of emissions from inversions and influence of priors. We compare the mean emissions from 2001–2012 (Fig. 5) having overlapping data for the new inversions presented here (GCP2023) with the previous inversion ensembles[1,4] (GCP2020) and their respective priors (based on EDGARv6 and EDGARv4.3.2). Changes in SURFACE and GOSAT inversions are also shown separately as the GOSAT inversions are available for 2010–2012. The level of change varied across the countries with the majority of changes lying within 20% except for China (~50%), Arabian Peninsula (~30%) and Venezuela (~30%). For the majority of the countries discussed here, there was an upward change except Russia, Kazakhstan and Venezuela which experienced a downward change between the EDGAR inventory versions. The downward change in emissions for Russia and Kazakhstan were also reported in their recent UNFCCC reports discussed earlier. In regard to average emissions, the direction of change for most inversions is found to roughly follow the corresponding direction present in the priors (i.e., from EDGAR v4.3.2 to EDGAR v6) with either similar or different magnitude of change (in terms of percentage relative to old value) between the inversions and the priors. These could arise mainly from the lack of constraint on posterior emission fluxes due to sparsity of the observation network (Supplementary Figs. S4-S5 and Table S8). For e.g., emissions fluxes over Arabian Peninsula, Iran, Australia, Turkmenistan and Venezuela have lowest sensitivities from the surface network (Supplementary Fig. S6), as the highest sensitivities occur mostly to the fluxes close to the in-situ observation stations (Supplementary Fig. S5) essentially in Northern America and Europe. Additionally, even with better observational constraints (such as for USA and moderately for China; Supplementary Figs. S4-S6), changes in the relative contribution of fossil sectors to total emissions in the priors can also influence subsectoral inversion estimates, as this is the basis for disaggregating

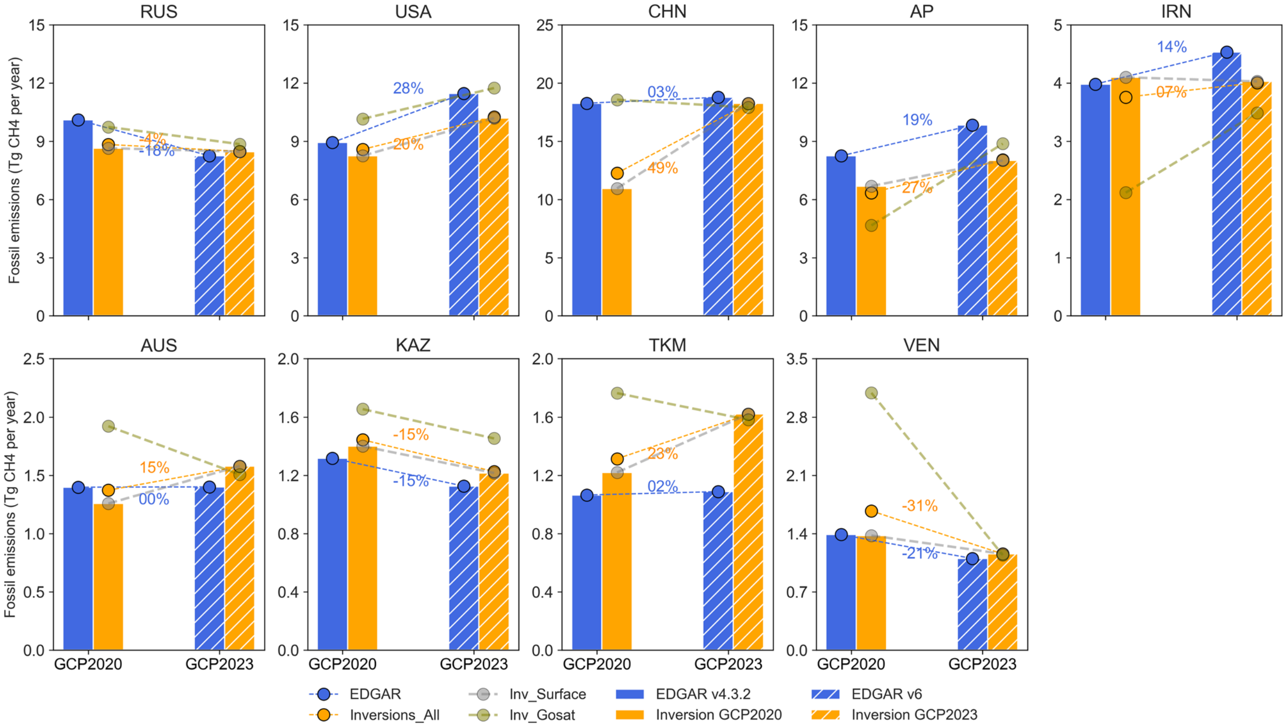

Fig. 5 Comparison of CH_4 emissions from fossil fuels with respect to previous inversions. Changes in mean fossil fuels emissions between previous (GCP2020)[1] and current inversions (GCP2023) are shown for the period 2001–2012 (orange bars). Emissions from the bottom-up inventory used as priors (EDGARv4.3.2 and EDGARv6; blue bars) are also shown for comparison. Percentage values shown represent the change in emissions in the latest versions compared to previous version.

total inversion estimates to sub-sectors[1]. Overall, for both GCP2020 and GCP2023 datasets, estimates from inversions were lower than their respective priors for large emitters including China, Russia, USA, Arabian Peninsula and Iran (Fig. 5) but higher for low emitters such as Australia, Kazakhstan, Turkmenistan and Venezuela (Fig. 5). In regard to the range in emissions values, the new set of inversions (Figs. 1–3) reported a smaller range of magnitude compared to those reported in the previous set of inversions (Supplementary Figs. S1-S2). While several factors can contribute to the difference in magnitude across individual inversions, this reduction in range could be primarily influenced by the harmonization of prior dataset across all inversion simulations for the latest round of inversions. Previous inversions used a mix of priors including EDGARv4.2 and EDGARv4.3.2. (Supplementary Table S2), whereas in the new round of inversions, EDGARv6 was fixed as the common prior dataset.

Discussion

This study consolidates methane emissions from the production of fossil fuels for major emitting countries and various emissions inventories. It evaluates the variability in average annual magnitudes and in trends among different global bottom-up inventories, UNFCCC estimates and global atmospheric inversions. Overall, total fossil emissions averaged over 2011–2020 from bottom-up inventories is within the range estimated by atmospheric inversions for countries examined here. Disagreements largely arise from the oil and gas sector, in both emissions magnitudes averaged over the last decade (2011–2020) and trends from 2000 to 2020. Disagreements exist not only between estimates from bottom-up inventories and inversions but also among the various bottom-up inventories. For Russia, Kazakhstan, Iran and countries under Arabian Peninsula, the spread of the bottom-up inventories is larger than that of atmospheric inversions. Given the large contribution from fossil sectors to global methane emissions, using a single inventory may overestimate or underestimate the evaluation of future emissions reductions under methane pledge.

Disagreements in bottom-up inventories primarily come from the differences in their inputs (i.e., activity data and emission factors). Differences in activity data can arise from using different data sources (e.g., UNFCCC reports or international energy statistics from EIA or IEA) or using different publication versions (Supplementary Table S7). Differences in emissions factors occur from varying data sources (e.g., IPCC[26] or ref. [27] for oil and gas sector), methodology of incorporating country specific information especially for the non-Annex I countries and treatment of emissions sources within the sub-sector, especially in the oil and gas sector (Supplementary Table S7). Besides input data, differences in sectoral coverage and gap-filling strategies for completion of time-series can also introduce disagreement among inventories.

A closer investigation of the sources of input data revealed the level of interdependency among the different global bottom-up inventories. GFEI and EPA obtain emissions directly from UNFCCC reports for Annex I countries, but apply a composite approach for non-Annex I, combining information from available NCs/BURs and international statistics. Only for countries without suitable UNFCCC reporting, an independent estimate is made. GAINS, EDGAR and IEA 2020 are independent from UNFCCC, estimating own emissions for all countries using international energy statistics and emission factors from independent studies (supplemented with additional data from UNFCCC reports). Although international energy statistics also rely on national sources, these can differ in their exact mix and version of data sources. This can potentially influence the trajectory of activity data at specific patches along the time-series, thus making them different from UNFCCC. IEA and CEDS estimates are based on other independent global inventories (i.e., EDGAR and GAINS), thus making them independent from UNFCCC.

UNFCCC reports are a suitable source for country-specific information owing to the detailed sub-sectoral reporting. However, these often undergo revisions following methodological updates, thereby superseding previous estimates. Among selected Annex I countries, we found largest changes (relative difference in the estimate reported in any year with respect to previous year's report) occurred for Russia and Kazakhstan. Maximum changes come from the oil & gas sector for Russia and from both coal and oil & gas sectors for Kazakhstan. Revision in data sources for emission factors is the dominant contributor to these changes followed by revision of activity data and methodology. Besides, some changes also occurred due to corrections in typological errors (such as correction of units, decimal places etc.). Therefore, it is important for inventories dependent on UNFCCC reports, to exercise frequent updates in order to keep up with these revisions. Further, for many major oil and gas producing nations including Iran, Venezuela, countries of the Arabian Peninsula, there is a lack of official estimates from UNFCCC. These countries, being non-Annex I, are not binding to provide regular estimates, leading to either no or very old values (Supplementary Table S5). Thus, it is important that these nations release regular reports to prevent dissemination of obsolete emissions magnitudes.

Finally, this study also reported the influence of priors on inversion estimates. Compared to previous inversions (GCP2020), changes in the new ensemble of inversions (GCP2023) follow the magnitude and direction of change as in their priors EDGARv4.2/EDGARv4.3.2 (previous) and EDGARv6 (new) respectively at the sub-sectoral level. This highlights (i) that inversions do not modify prior values when lacking information from the atmosphere and (ii) a key caveat in the current approach of disaggregating total emissions from inversions into subsectors by using the corresponding sectoral distribution of the prior. For (i), sensitivity to a prior is a function of data sampling and noise from the observations, which includes the density of the surface measurement network (Supplementary Fig. S5) and coverage from satellite (Supplementary Fig. S4 and Table S8). It is difficult to disentangle from adjoint-based global inversions presented here, as these inversions do not have an explicit information content representation, unlike some recent inversions estimates made using analytical approaches[31]. Indeed, for countries lacking of sensitivity of the surface network (Supplementary Fig. S6), the inversions can either stay close to the prior or deviate largely due to insufficient constraint. For (ii), this illustrates that in absence of a more robust approach to evaluate sub-sectoral emissions from inversions, the choice of prior emission inventory is crucial even for countries with higher observational constraints. Increasing resolution and including information from co-emitted species could help better partitioning the sectoral emissions[32,33].

Methods

Methane emissions datasets for the fossil fuel sector. This study uses a new ensemble of fossil fuel CH_4 emissions from top-down inversions and bottom-up inventories (Table 1). The top-down models include 1) a new ensemble of 12 global inversions spanning from the year 2000 to 2020 (10 surface-based inversions for the period 2000–2020 and 2 satellite-based inversions for the period 2010–2020); and 2) 2019–2020 country-wide estimates of CH_4 ultra-emissions from oil and gas sources based on the TROPOMI satellite data[18]. The ensemble of bottom-up inventories consists of national submissions to UNFCCC compiled from different sources[4] and different global inventories, including the Community Emissions Data System (CEDS)[3,19], the Emissions Database for Global Atmospheric Research (EDGARv6)[20], the Greenhouse gas and Air pollutant Interactions and Synergies (GAINS)[21,22], the Global Fuel Exploitation Inventory (GFEI)[8], International Energy Agency (IEA)[23] and the U.S. Environmental Agency (EPA)[24].

Inversion datasets. The new ensemble of inversions from the Global Carbon Project (referred to as GCP2023) from 2000 to 2020 has seven different inverse systems for 12 inversions. The inverse systems include: CarbonTracker-Europe CH4[34], LMDZ-PYVAR[35,36], MIROC4-ACTM[37,38], NICAM-TM[39,40], NIES-TM-FLEXPART[41,42], TM5-CAMS[43] and CIF-LMDz[44]. This ensemble of inversions gathers various chemistry transport models, differing in vertical and horizontal resolutions, meteorological forcing, advection and convection schemes, and boundary layer mixing (see supplementary information[1]). Including these different systems allows to cover different potential uncertainties of the inversion, among them: model transport, set-up issues, and prior dependency. All inversions except four use common prior emission maps for natural and anthropogenic prior emissions divided into 12 sectors, particularly the EDGAR v6 inventory for prior fossil fuel emissions[20] (extrapolated to Jan 1st, 2021). The inversions assimilating surface stations mixing ratios observations provide results since 2000 (hereafter called SURFACE inversions), and those assimilating satellite observations from column CH4 measurements (XCH4) of the GOSAT satellite provide results since 2010 (hereafter referred to as GOSAT inversions), when GOSAT was launched as described in Table S1. Inversion results were gridded into 1° by 1° monthly emission maps. Fossil fuel emissions from the "oil & gas" and "coal" sub-sectors were separated from other sources in each grid cell by taking the fractions that these two sub-sectors represent in each grid cell, based on the prior emission fields. Then, emissions were aggregated nationally using a country mask. The Supplementary information includes an illustrative footprint of the surface network (maps of the station in Fig. S5) based on the global transport model LMDz (Fig. S6) for a typical year 2018. Also included the number of GOSAT XCH4 observation available for a typical year 2018 based on two retrievals product used in the inversions (Fig. S4).

These inversions differ from those used in an earlier study[4], developed for the global methane budget 2020[1]. The previous ensemble of inversions (GCP2020) was based on earlier versions of prior anthropogenic emissions from EDGAR with different versions (EDGAR v4.2 and EDGAR v4.3.2) used among inversion runs. As a result, considerable differences between the previous and new ensembles of inversions are expected.

Complementary to global inversions that solve for all fossil (and other) emissions in a given area, we also used inversions of TROPOMI column CH_4 data using a high-resolution dispersion model that estimated the budget of ultra-emissions in each country where they can be detected[18]. Ultra-emitters are leak events of short duration with high CH_4 release to the atmosphere of more than 25 tCH_4 per hour. Those huge leaks generally constitute a small fraction of national emissions but could also represent a large fraction for certain countries like Turkmenistan[18]. However, these are generally not included in EDGAR and other inventories. The ultra-leak emission budgets aggregated at the national scale were thus added to all inventories estimates and then compared with the results of global inversions. This rationale assumes that global inversion results implicitly have the contribution of ultra-emitters in their national budgets. Still, we acknowledge that the sparse atmosphere sampling by current surface networks and GOSAT soundings could also partly miss their contribution.

Bottom-up inventories. We only considered CH_4 emissions from the fossil fuel sector for all bottom-up inventories. The fossil fuel sector comprises all sources related to the production and distribution of coal, oil, and gas fuels. Emissions of CH_4 from sources involving the combustion of fossil fuels (e.g., electricity generation, chemical industry) are marginal, representing on average 2.6% of the total fossil CH_4 emissions (considering all bottom-up inventories and countries analyzed in this study). Therefore, they are omitted here. Table S3 presents the oil, gas, and coal emission sectors and subsectors from the different bottom-up emission inventories used in this work. Each inventory is briefly described below.

UNFCCC emissions reported per country were extracted for oil, gas, and coal subsectors from the latest inventory accessible in the Greenhouse Gas Inventory Database (https://di.unfccc.int/detailed_data_by_party). Annex I countries (Table 2) report emissions yearly, while non-Annex I countries report less frequently. We use data from National Inventory Reports (NIR) for all Annex I countries and national communications (NCs) / biennial update reports (BURs) for non-Annex I countries (Table S5).

The GFEI inventory[8] reports emissions from 2010 to 2019. The emissions are based on NIR v2021 (UNFCCC report published/as available in 2021) for the Annex I countries but a composite methodology for the non-Annex I countries. For countries with no reported data after 2000 from UNFCCC (i.e., NCs/BURs), a Tier 1 approach was applied. This approach combined default emission factors from IPCC and annual activity data from the US Energy Information Administration (EIA). On the other hand, for those non-Annex I countries that had reported emissions to UNFCCC after 2000, the reported values were adjusted and filled for missing years using the EIA data.

The Community Emissions Data System (CEDS) inventory corresponds to the latest version, CEDS v2021-04-21, released on May 5, 2021. This version contains CH_4 emissions from 1970 to 2019. A description of the methodology can be found in a previous study[19]. CEDS deploys a two-step approach. First, it creates a set of default emissions using activity data from international datasets and emission factors from other global inventories. For the coal sector, default CH_4 emissions are directly taken from EDGAR and interpolated using population data from United Nations and World Bank for missing values. The oil and gas sector's emissions are based on the combination of EDGAR and GAINS datasets with the missing years interpolated using production data from IEA and BP energy statistics. Second, for countries having a regional inventory, the default emissions factors and emissions are scaled to match the corresponding sectoral estimates from that regional inventory. While this is the general methodology, specific revisions have been made over the years for certain countries/sectors[45], which are unclear and beyond the scope of this study.

The GAINS global inventory has yearly emissions from 1990 to 2020. A description of the methodology can be obtained from related studies[21,22]. Activity data (fossil fuel production) is obtained from the International Energy Agency –World Energy Outlook (IEA-WEO) New policies scenario v2018. In regard to emissions factor, values for coal mining are obtained from a combination of national reporting to UNFCCC (either NIR or BUR) where available, IPCC default values, and specific studies for China (Supplementary Table S7). For abandoned mines, it is taken directly from the NIR submitted to UNFCCC for Annex I countries and assumed as 10% of mining emissions for non-Annex I countries. For the oil and gas sectors, emission factors are based on a common source for all countries with updated information for the USA and Russia from specific studies (Supplementary Table S7).

The EDGARv6 inventory reports emissions from 1970 to 2018. It is the prior inventory for the new ensemble of global inversions discussed above. In this version of EDGAR[2], activity data is obtained from international energy statistics from the IEA v2019. The source of emissions factors seems similar to those used in version v4.3.2 except for emissions from venting in oil and gas sectors which are based on updated information from specific studies (Supplementary Table S7). In EDGARv4.3.2[46], activity data is primarily from World Coal Association v2016 and IEA v2014, supplemented with additional region-specific datasets (Supplementary Table S7). Emissions factors are mainly sourced from IPCC default values and UNFCCC reports (Supplementary Table S7).

We used two global datasets from the IEA, one with a time series (1990–2015) of emissions from fossil fuel sources[47] and another one for the year 2020[48]. The first dataset (hereafter referred to as IEA) comprising the time series is available at five years intervals. We interpolated between each timestep to produce yearly emissions. In this dataset, the methane emissions for the fossil sector are directly taken from EDGARv4.3.2[49]. The second dataset (hereafter referred to as IEA_2020) includes emissions only for oil and gas activities. The activity data (i.e., production and consumption) for the oil and gas sector are based on IEA energy statistics. For fugitive emissions (i.e., leakage and venting), the emission factors are based on US emissions intensities from EPA inventory v2021, which are scaled for respective countries using relevant country-specific data[50]. Flaring emissions are estimated based on country-specific combustion efficiencies using country-specific data on production type, company type, wind speed, and regulatory policy[50]. Further, it also includes emissions from ultra-emitters, based on data from the Methane Watch - Kayrros (www.kayrros.com/methane-watch), the same data source as the one we used here. However, their ultra-emitters dataset corresponds to January 2021; here, we present updated data for June 2021[18].

The U.S. EPA inventories also comprise two datasets. The first one contains global emissions every five years from 1970 until 2015, with future projections up to 2050, from which we calculate yearly emissions (up to 2020) by linearly interpolating values between two timesteps[51]. The emissions are directly taken from UNFCCC NIRs v2018 for A-1 and relevant NCs/BURs for NA-I countries[51]. The missing years are filled with activity data from EIA v2018. For countries with no year from UNFCCC, emissions factors are taken from IPCC 2006 default values and combined with the EIA data. For China, coal sector emissions are based on UNFCCC NCs (v1994 and v2005) and other specific studies (Supplementary Table S7). The second dataset contains yearly emissions from 1990–2020 only for the U.S., separating coal, oil and gas sectors and developed using a combination of Tier 3 and Tier 2 approaches[52]. Activity data are primarily based on production data from EIA v2021 for the coal sector and Enverus v2021, supplemented with other national datasets for the oil and gas sectors. Emission factors for the coal sector are based on mine-specific data from EPA's national Greenhouse gas reporting program (GHGRP) for underground mines and older basin-specific datasets for surface mines. For oil and gas, these are sourced from multiple national datasets (Supplementary Table S7). For the U.S., we used this inventory instead of the global EPA dataset.

Selection of countries and regions. The analysis includes eight countries and one group of countries, selected based on average 2010–2020 emission estimates of oil, gas, and coal sources from the bottom-up emission inventories. We selected the top 3 emitters for oil and gas (both sectors grouped together) and for coal: China, Russia, and the United States of America (USA). Then, we added other large emitters to the final list (Australia, Kazakhstan, Turkmenistan, Venezuela, Saudi Arabia, Oman, United Arab Emirates, Kuwait, Bahrain, Iraq, and Qatar). Because the coarse grid resolutions of the global inversions make it challenging to look at emissions from countries with a small area, all the oil and gas-producing countries in the Arabian Peninsula (Saudi Arabia, Oman, United Arab Emirates, Kuwait, Bahrain, Iraq, and Qatar; hereafter referred to as AP) were grouped as a single region. Overall, the selected countries represent, on average, 58 ± 6% of global fossil fuel CH_4 emissions, of which 28 ± 8% come from oil sources, 22 ± 9% from gas sources, and 26 ± 14% from coal sources considering all inventories used here.

Data availability

All data used in the analysis are available in Zenodo archive and can be accessed at https://doi.org/10.5281/zenodo.10277300.

Received: 24 May 2023; Accepted: 20 December 2023;
Published online: 09 January 2024

References

1. Saunois, M. et al. The Global Methane Budget 2000–2017. *Earth Syst Sci Data* **12**, 1561–1623 (2020).
2. Crippa, M. et al. *GHG emissions of all world countries - 2021 Report*. (2021).
3. O'Rourke, P. R. et al. CEDS v_2021_04_21 Release Emission Data. *Community Emissions Data System* Preprint at https://doi.org/10.5281/zenodo.4741285 (2021).
4. Deng, Z. et al. Comparing national greenhouse gas budgets reported in UNFCCC inventories against atmospheric inversions. *Earth Syst Sci Data* **14**, 1639–1675 (2022).
5. International Energy Agency. Methane Tracker. https://www.iea.org/data-and-statistics/data-tools/methane-tracker-data-explorer#comparison-sources (2023).
6. Climate & Clean Air Coalition. Global Methane Pledge. *CCAC* https://www.globalmethanepledge.org/ (2022).
7. United Nations Framework Convention on Climate change. *Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on its third session, held in Glasgow from 31 October to 13 November 2021.* (UNFCCC, 2022).
8. Scarpelli, T. R. et al. Updated Global Fuel Exploitation Inventory (GFEI) for methane emissions from the oil, gas, and coal sectors: evaluation with inversions of atmospheric methane observations. *Atmos. Chem. Phys.* **22**, 3235–3249 (2022).
9. Maasakkers, J. D. et al. Global distribution of methane emissions, emission trends, and OH concentrations and trends inferred from an inversion of GOSAT satellite data for 2010–2015. *Atmos. Chem. Phys.* **19**, 7859–7881 (2019).
10. Shen, L. et al. Unravelling a large methane emission discrepancy in Mexico using satellite observations. *Remote Sens. Environ.* **260**, 112461 (2021).
11. Maasakkers, J. D. et al. 2010–2015 North American methane emissions, sectoral contributions, and trends: a high-resolution inversion of GOSAT observations of atmospheric methane. *Atmos. Chem. Phys.* **21**, 4339–4356 (2021).
12. Zavala-Araiza, D. et al. A tale of two regions: methane emissions from oil and gas production in offshore/onshore Mexico. *Environ. Res. Lett.* **16**, 024019 (2021).
13. Petrescu, A. M. R. et al. The consolidated European synthesis of CH_4 and N_2 O emissions for the European Union and United Kingdom: 1990–2019. *Earth Syst. Sci. Data* **15**, 1197–1268 (2023).
14. Liu, G. et al. Recent Slowdown of Anthropogenic Methane Emissions in China Driven by Stabilized Coal Production. *Environ. Sci. Technol. Lett.* **8**, 739–746 (2021).
15. Sadavarte, P. et al. Methane Emissions from Super emitting Coal Mines in Australia Quantified Using TROPOMI Satellite Observations. *Environ. Sci. Technol.* **55**, 16573–16580 (2021).
16. Palmer, P. I. et al. The added value of satellite observations of methane for understanding the contemporary methane budget. *Philos. Transac. R. Soc. A* **379**, https://doi.org/10.1098/rsta.2021.0106 (2021).
17. Winiwarter, W., Mangino, J., Ajavon, A.-L. N., McCulloch, A. & Woodfield, M. Quality assurance / quality control and verification. in *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme* (eds. Eggleston, H. S, Buendia, L, Miwa, K, Ngara, T. & Tanabe, K.) vol. 1 (Institute for Global Environmental Strategies, 2006).
18. Lauvaux, T. et al. Global assessment of oil and gas methane ultra-emitters. *Science* **375**, 557–561 (2022).
19. Hoesly, R. M. et al. Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). *Geosci Model Dev.* **11**, 369–408 (2018).
20. Crippa, M. et al. EDGAR v6.0 Greenhouse Gas Emissions. European Commission, Joint Research Centre (JRC) [Dataset]. https://data.jrc.ec.europa.eu/dataset/97a67d67-c62e-4826-b873-9d972c4f670b (2021).
21. Höglund-Isaksson, L., Gómez-Sanabria, A., Klimont, Z., Rafaj, P. & Schöpp, W. Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe –results from the GAINS model. *Environ. Res. Commun.* **2**, 025004 (2020).
22. Höglund-Isaksson, L. Global anthropogenic methane emissions 2005–2030: technical mitigation potentials and costs. *Atmos. Chem. Phys.* **12**, 9079–9096 (2012).
23. International Energy Agency. IEA Data and statistics. *IEA* https://www.iea.org/data-and-statistics/data-sets (2021).
24. United States Environmental Protection Agency. Global Greenhouse Gas Emissions Data. *USEPA* https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data (2021).
25. Andrew, R. M. A comparison of estimates of global carbon dioxide emissions from fossil carbon sources. *Earth Syst. Sci. Data* **12**, 1437–1465 (2020).
26. IPCC. *2006 IPCC Guidelines for National Greenhouse Gas Inventories. IGES* vol. 2 https://www.ipcc-nggip.iges.or.jp/public/2006gl/%0A (2006).
27. Höglund-Isaksson, L. Bottom-up simulations of methane and ethane emissions from global oil and gas systems 1980 to 2012. *Environ. Res. Lett.* **12**, 024007 (2017).
28. Qu, Z. et al. Global distribution of methane emissions: a comparative inverse analysis of observations from the TROPOMI and GOSAT satellite instruments. *Atmos. Chem. Phys.* **21**, 14159–14175 (2021).
29. Zhang, Y. et al. Attribution of the accelerating increase in atmospheric methane during 2010–2018 by inverse analysis of GOSAT observations. *Atmos. Chem. Phys.* **21**, 3643–3666 (2021).
30. United Nations Framework Convention on Climate Change. National Inventory Submissions *2022. UNFCCC* https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/national-inventory-submissions-2022 (2022).
31. Worden, J. R. et al. The 2019 methane budget and uncertainties at 1° resolution and each country through Bayesian integration Of GOSAT total column methane data and a priori inventory estimates. *Atmos. Chem. Phys.* **22**, 6811–6841 (2022).
32. Thanwerdas, J. et al. How do Cl concentrations matter for the simulation of CH_4 and $\delta^{13}C(CH_4)$ and estimation of the CH_4 budget through atmospheric inversions? *Atmos. Chem. Phys.* **22**, 15489–15508 (2022).
33. Basu, S. et al. Estimating emissions of methane consistent with atmospheric measurements of methane and $\delta^{13}C$ of methane. *Atmos. Chem. Phys.* **22**, 15351–15377 (2022).
34. Tsuruta, A. et al. Global methane emission estimates for 2000–2012 from CarbonTracker Europe-CH₄ v1.0. *Geosci. Model Dev.* **10**, 1261–1289 (2017).
35. Zheng, B. et al. Rapid decline in carbon monoxide emissions and export from East Asia between years 2005 and 2016. *Environ. Res. Lett.* **13**, 044007 (2018).
36. Zheng, B., Chevallier, F., Ciais, P., Yin, Y. & Wang, Y. On the Role of the Flaming to Smoldering Transition in the Seasonal Cycle of African Fire Emissions. *Geophys. Res. Lett.* **45**, 998–12,007 (2018).
37. Patra, P. K. et al. Improved Chemical Tracer Simulation by MIROC4.0-based Atmospheric Chemistry-Transport Model (MIROC4-ACTM). *SOLA* **14**, 91–96 (2018).
38. CHANDRA, N. et al. Emissions from the Oil and Gas Sectors, Coal Mining and Ruminant Farming Drive Methane Growth over the Past Three Decades. *J. Meteorol. Soc. J. Ser. II* **99**, 2021–015 (2021).
39. Niwa, Y. et al. A 4D-Var inversion system based on the icosahedral grid model (NICAM-TM 4D-Var v1.0) – Part 2: Optimization scheme and identical twin experiment of atmospheric CO2 inversion. *Geosci. Model Dev.* **10**, 2201–2219 (2017).
40. Niwa, Y. et al. A 4D-Var inversion system based on the icosahedral grid model (NICAM-TM 4D-Var v1.0) – Part 1: Offline forward and adjoint transport models. *Geosci. Model Dev.* **10**, 1157–1174 (2017).
41. Wang, F. et al. Methane Emission Estimates by the Global High-Resolution Inverse Model Using National Inventories. *Remote Sens.* **11**, 2489 (2019).
42. Maksyutov, S. et al. Technical note: A high-resolution inverse modelling technique for estimating surface CO2 fluxes based on the NIES-TM–FLEXPART coupled transport model and its adjoint. *Atmos. Chem. Phys.* **21**, 1245–1266 (2021).
43. Segers, A. & Houweling, S. *Description of the CH4 Inversion Production Chain, CAMS (Copernicus Atmospheric Monitoring Service) Report*. https://atmosphere.copernicus.eu/sites/default/files/2018-11/CAMS73_2015SC3_D73.2.5.5-2018_201811_production_chain_v1_0.pdf (2018).

44. Berchet, A. et al. The Community Inversion Framework v1.0: a unified system for atmospheric inversion studies. *Geosci Model Dev.* **14**, 5331–5354 (2021).
45. Smith, S. CEDS Release Notes. *Joint Global Change Research Institute* https://github.com/JGCRI/CEDS/wiki/Release-Notes (2021).
46. Janssens-Maenhout, G. et al. EDGAR v4.3.2 Global Atlas of the three major greenhouse gas emissions for the period 1970–2012. *Earth Syst. Sci. Data* **11**, 959–1002 (2019).
47. International Energy Agency. Greenhouse Gas Emissions from Energy. *IEA* https://www.iea.org/data-and-statistics/data-product/greenhouse-gas-emissions-from-energy (2020).
48. International Energy Agency. Methane Tracker 2021. *IEA* https://www.iea.org/reports/methane-tracker-2021 (2021).
49. International Energy Agency. *Database documentation, Greenhouse Gas Emissions from Energy 2022 Edition*. https://iea.blob.core.windows.net/assets/78ca213f-171e-40ed-bf7e-c053d4376e79/WORLD_GHG_Documentation.pdf (2022).
50. International Energy Agency. *Global Methane Tracker Documentation 2022 Version*. (2022).
51. United States Environmental Protection Agency. *Global Non-CO2 Greenhouse Gas Emission Projections & Mitigation Potential: 2015-2050*. https://www.epa.gov/global-mitigation-non-co2-greenhouse-gases/global-non-co2-greenhouse-gas-emission-projections (2019).
52. United States Environmental Protection Agency. *Inventory of US. Greenhouse Gas Emissions and Sinks: 1990-2020*. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020 (2022).

Acknowledgements
The authors thank Tia Scarpelli for providing 2010-2018 data from GFEI v2 and Nicole Montenegro at LSCE for contributing to figures in the supplementary information. K.T., P.C., X. L., Z.T-S. and M.S. and F.C. acknowledge support of ESA Climate Change Initiative RECCAP2 (ESRIN/4000123002/18/I-NB) and the EU Eastern Mediterranean and Middle East – Climate and Atmosphere Research project (EMME-CARE) grant no. 856612. D.B. and P.K.P. are partly supported by the Environment Research and Technology Development Fund (JPMEERF21S20800).

Author contributions
P.C. and M.S. conceptualized the work. K.T., P.C., M.S., and Z.A.T. performed the analyses. K.T. wrote the manuscript with contributions from P.C., M.S. and Z.A.T. A.M., X.L., J.T., Z.D., F.C., C.G., C.A., P.P., A.T., B.Z., D.B., Y.N., R.J., S.M., A.S. curated the various datasets involved in this study. All authors, along with Ka.T., P.B. and J.S., contributed to the reviewing and writing of the manuscript.

Competing interests
P.P. is an Editorial Board Member for Communications Earth & Environment, but was not involved in the editorial review of, nor the decision to publish this article. All other authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-023-01190-w.

Correspondence and requests for materials should be addressed to Kushal Tibrewal.

Peer review information *Communications Earth & Environment* thanks the anonymous reviewers for their contribution to the peer review of this work. Primary Handling Editors: Clare Davis, Heike Langenberg. A peer review file is available.

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