CoCO2

Prototype system for a Copernicus CO_2 service

First synthesis of CO_2 and CH_4 observation-based emission estimates

WP8

coco2-project.eu

Co-ordinated by ECMWF

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CoCO2: Prototype system for a Copernicus CO_2 service

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H2020-IBA-SPACE-CHE2-2019 Copernicus evolution – Research activities in support of a European operational monitoring support capacity for fossil CO_2 emissions

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Executive Summary

We present first consistent comparisons of CO_2 and CH_4 emission estimates based on inventories and observations for the top world emitters. We cover fossil CO_2, net land CO_2, and anthropogenic CH_4 emissions. The aim is to identify, quantify and explain divergences between global inventories, atmospheric inversions, process models and national inventories submitted to the UNFCCC. This report is the first of three annual updates. The analysis will be updated every year throughout the CoCO$_2$ project, incorporating the latest data and model results, with more detailed uncertainty assessment included in future reports. Where possible, we include relevant non-CoCO$_2$ estimates from the VERIFY project and satellite inversion results from other studies.

1 Introduction

1.1 Background

Emissions and removals of greenhouse gases (GHG), including both anthropogenic and natural fluxes, require reliable quantification, including estimates of uncertainties, to support credible mitigation action under the Paris Agreement. Reported inventory-based emissions and removals are generally estimated using bottom-up activity data. Top-down observation-based estimates are required by multiple stakeholders and at multiple scales to verify bottom-up emission estimates. These estimates are performed at different scales for a variety of applications: the continental scale for science purposes, country scale for reporting to the UNFCCC, sub-country scale for urban planning, and point sources like large power plants for verification (Pinty et al., 2019).

Inversions combine inventory estimates and a variety of observations to provide invaluable constraints on the inventories (Deng et al., 2021). Since atmospheric concentrations respond to the sum of all emissions and removals, inversion-based estimates are less suited to provide information on individual sectors (unless they are geographically separated), though due to high resolution, observation-based approaches are particularly suited to identify point sources or small geographical areas like cities. Inventories and estimates from atmospheric inversions are therefore complementary and should be used together to improve and build trust in national emission estimates. With dense observation networks and measurements of auxiliary parameters such as isotopic composition of GHG or concentrations of co-emitted gases, additional source-specific information can be gained to support the validation of national emission inventories beyond country totals. Observation-based estimates can be particularly valuable for trace gases with large uncertainties in their emissions (Maksyutov et al., 2019).

In the context of providing recommendations for the implementation of an observation-based operational anthropogenic CO_2 emissions Monitoring and Verification Support capacity (CO2MVS) within the Copernicus programme, one objective of CoCO$_2$ is to provide inputs to the Global Stocktake (GST) process, in the form of anthropogenic CO_2 and CH_4 emission products for the 1st GST (2023), at a spatial scale consistent with GST requirements. For this purpose, CoCO2 identified relevant needs for the periodic GST through the development of a User Requirement Document (URD). The work described in this document represents the starting point for future syntheses to serve future GSTs.

This document is an extension of reconciliation reports and country analysis produced under the VERIFY project (Andrew 2020, Petrescu et al., 2021 a, b), but this time having a global focus. We identify and analyse CO_2 and CH_4 emissions from a subset of the top 10 largest emitters aiming to identify divergences with UNFCCC National GHG Inventories (NGHGI), and thereby identify countries or sectors where observation-based estimates have strong application. This document will be the first in a series of three, with two update reports to follow every year. This report is structured as follows: Chapter 1 presents the background, scope and objectives of this work, Chapter 2 the methodologies, Chapter 3 focuses on the fossil and net land CO_2 fluxes, Chapter 4 presents the CH_4 results both total and sectoral, and the report ends with discussions, conclusions and outlines future needs for research.

1.2 Scope of this deliverable

The scope of this deliverable is to identify and present annual GHG estimates from independent inventory-based estimates, observation-based estimates (drawing on VERIFY and $CoCO_2$ products) and comparing with UNFCCC NGHGIs for a selection of top global CO_2 and CH_4 emitters. We identify divergences between the different estimates and NGHGIs, but for space requirements only report on those of most interest. Finally, we lay the foundation for further reports and improvements.

2 Methodologies

2.1 Anthropogenic CO_2 and CH_4 emissions and removals from UNFCCC

UNFCCC NGHGI (2021) emissions (CO_2 and CH_4) and removals (CO_2) are compiled by individual countries and cover the period 1990-2019. The Annex I Parties to the UNFCCC are required to report emissions inventories annually using the Common Reporting Format (CRF). This annually updated dataset includes all anthropogenic emissions and removals. The reported data is generally for the period 1990 to N-2, but some countries provide data for earlier or later periods. The non-Annex I Parties report their estimates on a voluntary basis via the so called Biannual Updated Reports (BURs)(UNFCCC, n.d.-a). This data comes in irregular formats and requires manual compilation[1] (Deng et al., 2021).

2.2 Fossil CO_2 emissions

The different fossil CO_2 emission data and methods are summarised in Table 1. The inventory-based fossil CO_2 estimates are presented and split per fuel type and reported for the last year when all data products are available, an update to Andrew (2020). The atmospheric inversions fossil CO_2 estimates for the year 2017 are from an inversion assimilating satellite observations. To overcome the current lack of CO_2 observation networks suitable for the monitoring of fossil fuel CO_2 emissions at national scale, this inversion is based on atmospheric concentrations of co-emitted species. It assimilates satellite CO and NO_2 data. While the spatial and temporal coverage of these CO and NO_2 observations is large, the conversion of the information on these co-emitted species into fossil fuel CO_2 emission estimates is complex and carries large uncertainties. In this first report, we have not been able to fully characterise the uncertainty in the inversions, therefore limiting our ability to compare to inventories.

2.3 Net land CO_2 flux

The net land CO_2 fluxes include CO_2 emissions and removals from LULUCF activities, based on inventories, process models and inversion estimates (Table 2). We present the net land CO_2 flux (emissions and removals) from the LULUCF sector reported to UNFCCC, two bookkeeping models (BLUE and H&N), global inventories (FAO), ensemble of dynamic global vegetation models (DGVMs) TRENDYv10 from GCP2021 (Friedlingstein et al., 2021), inverse model results from GCP2021 (Friedlingstein et al., 2021), and an improved CAMS inversion including lateral fluxes and managed land masks (Chevallier et al., 2005; Chevallier, 2021). The TRENDYv10 and GCP2021 do not have a managed land mask applied.

[1]downloaded from https://zenodo.org/record/5089799#.YdRTzGjMJaR

Table 1: Data sources for the fossil CO_2 emissions included in this study

CO_2 anthropogenic				
	Data/model name	**Contact / lab**	**Species / Period**	**Reference/Metadata**
	UNFCCC NGHGI (2021)	UNFCCC	Anthropogenic fossil CO_2 1990-2019	(IPCC, 2006) IPCC Guidelines for National Greenhouse Gas Inventories https://www.ipcc-nggip.iges.or.jp/public/2006gl/, 2006. UNFCCC NIRs/CRFs https://unfccc.int/ghg-inventories-annex-i-parties/2021 (UNFCCC, 2021)
BU	**Compilation of multiple CO_2 fossil emission data sources (Andrew 2020) EDGAR v5.0, BP, EIA, CDIAC, IEA, GCP, CEDS, PRIMAP**	CICERO	CO_2 fossil country totals and split by fuel type 1990-2018 (or last available year)	EDGAR v6.0 https://edgar.jrc.ec.europa.eu/ BP 2021 report(BP, 2021) EIA https://www.eia.gov/beta/international/data/browser/views/partials/sources.html CDIAC https://energy.appstate.edu/CDIAC(Gilfillan and Marland, 2021) IEA https://www.transparency-partnership.net/sites/default/files/u2620/the_iea_energy_data_collection_and_co2_estimates_an_overview__iea__coent.pdf. IEA, 2018d, p. I.17 CEDS https://github.com/JGCRI/CEDS (O'Rourke et al., 2021) GCP (Friedlingstein et al., 2021) PRIMAP-hist(Gütschow et al., 2021) https://doi.org/10.5281/zenodo.4479171
TD	**Fossil fuel CO_2 inversions**	LSCE	Inverse fossil fuel CO_2 emissions 2005-2020	VERIFY Deliverable D2.12 (Fortems-Cheiney and Broquet, 2021a), an as-yet unpublished update of Deliverable D2.11 (Fortems-Cheiney and Broquet, 2021b)

Table 2: Data sources for the land CO_2 emissions included in this study

Product Type / file or directory name	Contact / lab	Variables / Period	References
Inventories			
UNFCCC NGHGI (2021)	UNFCCC	LULUCF Net CO_2 emissions/removals 1990-2019	IPCC, 2006 Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan, https://www.ipcc-nggip.iges.or.jp/public/2006gl/, 2006.(IPCC, 2006) UNFCCC CRFs https://unfccc.int/ghg-inventories-annex-i-parties/2021(UNFCCC, n.d.-b) UNFCCC BURs: https://unfccc.int/BURs(UNFCCC, n.d.-a) (via(Deng et al., 2021))
Bookkeeping and process-based models			
BLUE (GCP) bookkeeping model for land use change	MPI/LMU Munich	Net C flux from land use change, split into the contributions of different types of land use (cropland vs pasture expansion, afforestation, wood harvest) 1990-2020	(Hansis et al., 2015) as updated in(Friedlingstein et al., 2021)
H&N bookkeeping model	Woodwell Climate Research Center	C flux from land use and land cover 1990-2020	(Houghton and Nassikas, 2017) as updated in (Friedlingstein et al., 2021)
FAO	FAOSTAT	CO_2 emissions/removal from LULUCF sectors 1990-2019	FAO, 2022 (accessed February 2022) (Federici et al., 2015) (Tubiello et al., 2021)
TRENDY v10 (2020)	MetOffice UK	Land related C emissions (NBP) from 1990-2020	(Friedlingstein et al., 2021) and references therein.
Inversion models			
GCP 2021 **Global inversions (CTE, CAMS, CarboScope, UoE, CMS-Flux, NISMON-CO2)**	GCP	Total CO_2 inverse flux (NBP) 6 inversions 1979-2020	(Friedlingstein et al., 2021) and references therein.
CAMS via $CoCO_2$	LSCE	CO2 fluxes 1979-2020	(Chevallier, 2021) Includes lateral fluxes and a managed-land mask

2.4 Anthropogenic CH_4 emissions

We present data from three global CH_4 anthropogenic emissions inventories EDGAR v6.0, FAOSTAT and GAINS (Table 3). These estimates are not completely independent from NGHGIs (see Figure 4 in (Petrescu et al., 2020)) as they integrate their own sectorial modelling with the UNFCCC data (e.g. common activity data (AD) and IPCC emission factors (EFs)) when no other source of information is available. We do not report data for the natural CH_4 emissions, but they are available from the VERIFY project as wetlands and "other natural emissions", the latter including geological sources and inland waters (lakes and reservoirs), following (Saunois et al., 2020). The natural emissions were subtracted from inversions (see section 4, following the methodology described in (Deng et al., 2021)).

Atmospheric inversions combine atmospheric observations, transport and chemistry models and estimates of GHG sources with their uncertainties, to estimate emissions. Emission estimates from inversions depend on the data set of atmospheric measurements and the choice of the atmospheric model, as well as on other settings (e.g., prior emissions and their uncertainties). For CH_4, we use 22 global inversions from GCP-CH_4 (Saunois et al., 2020).

Table 3: Data sources for the CH_4 emissions included in this study

Name	**CH_4**	**Contact / lab**	**References**
Inventories (anthropogenic)			
UNFCCC CRFs and BURs	CH_4 emissions 1990-2019	MS inventory agencies	UNFCCC CRFs https://unfccc.int/ghg-inventories-annex-i-parties/2021 UNFCCC BURs:https://unfccc.int/BURs (Deng et al., 2021)
EDGAR v6.0	CH_4 sectoral emissions 1990-2018	EC-JRC	(Crippa et al., 2021) Crippa et al., 2019 EU REPORT (Janssens-Maenhout et al., 2019) (Solazzo et al., 2021)
GAINS	CH_4 sectoral emissions 1990-2015	IIASA	(Höglund-Isaksson, 2012; Höglund-Isaksson, 2017; Höglund-Isaksson et al., 2020) (Gómez-Sanabria et al., 2018)
FAOSTAT	CH_4 agriculture emissions 1990-2019	FAO	FAO, 2021 (accessed October 2021) (Tubiello, 2019)Tubiello, 2019, 2021(Tubiello et al., 2021)
Atmospheric inversions			
GCP-CH_4 2019 anthropogenic partition from inversions	22 models for CH_4 inversions, both *SURF and GOSAT* 2000-2017	LSCE and GCP-CH_4 contributors	(Saunois et al., 2020) and model specific references in Appendix B, Table B4, (Petrescu et al., 2021b)

2.5 Other methodological issues

In the figures presented in this report, we essentially plot the various inversions and inventory methods on the same figure, to allow a visual comparison. There has not been a full uncertainty analysis, that would for example, quantify if one dataset was statistically significantly different to another. This will come in later reports. For some of the datasets we have limited uncertainty information, and it is nevertheless difficult to present all the datasets together with their respective uncertainties on one figure. Methods to present the results, including uncertainties, need to be improved. Additionally, methods are needed to assess for the statistical significance of any differences, given uncertainties.

For the TRENDY and GCP inversions, the median (GCP inversions) or mean (TRENDY) is shown, together with the maximum and minimum values. The median was used for the GCP inversions, as at the time of the initial VERIFY synthesis there were only three inversions. This report shows the results of six inversions. The use of the median and mean should be re-evaluated. Generally, a median is used for small samples or when outliers may be present, and this is likely the case to both the TRENDY and GCP inversion ensembles. Initial tests showed this will not lead to a dramatic difference in results.

System boundary issues are a challenge for all comparisons made here. Independent estimates often have different system boundaries. These can sometimes be minor, but at other times (e.g., land) be significant. Relevant system boundary issues are discussed in each section below.

For a careful comparison with of inversions (gridded) results with UNFCCC NGHGIs (country) several factors needed to be considered. International transport is not included in country totals in NGHGIs, but observational approaches may see this. In some inversion approaches, a correction may be needed for this, particularly in some countries prone to this issue. A related issue is whether the aviation emissions are placed at the correct horizontal and vertical location. Converting gridded data to country totals has issues with borders, including land-sea borders. Whilst these corrections may not be critical for the current comparisons, as operational methods improve, they need to be considered and adjustments potentially made.

3 CO_2 emissions

3.1 Fossil CO_2 emissions

Fossil CO_2 emissions (FCO_2) can be separated into emissions from the oxidation of fossil fuels ($FFCO_2$) and chemical transformation of fossil carbonates into CO_2. Care needs to be taken to ensure consistency in comparisons, as some methods compare FCO_2 and others $FFCO_2$. This is discussed further in the relevant sections.

Inventory-based estimates

Figures 1, 2, 3, and 4 show fossil CO_2 emissions (FCO_2) from global datasets, both globally and for the EU27+UK. ‘Raw’ totals from these datasets have differing system boundaries, meaning they don’t all include the same set of emissions sources. Harmonising is an attempt to remove these differences in coverage to provide more comparable estimates, partly to prevent the false inference of uncertainty relating to the spread of raw estimates. Further details are provided by Andrew (2020). Figures 1 and 3 show unharmonized inventories, while Figures 2 and 4 show harmonised inventories.

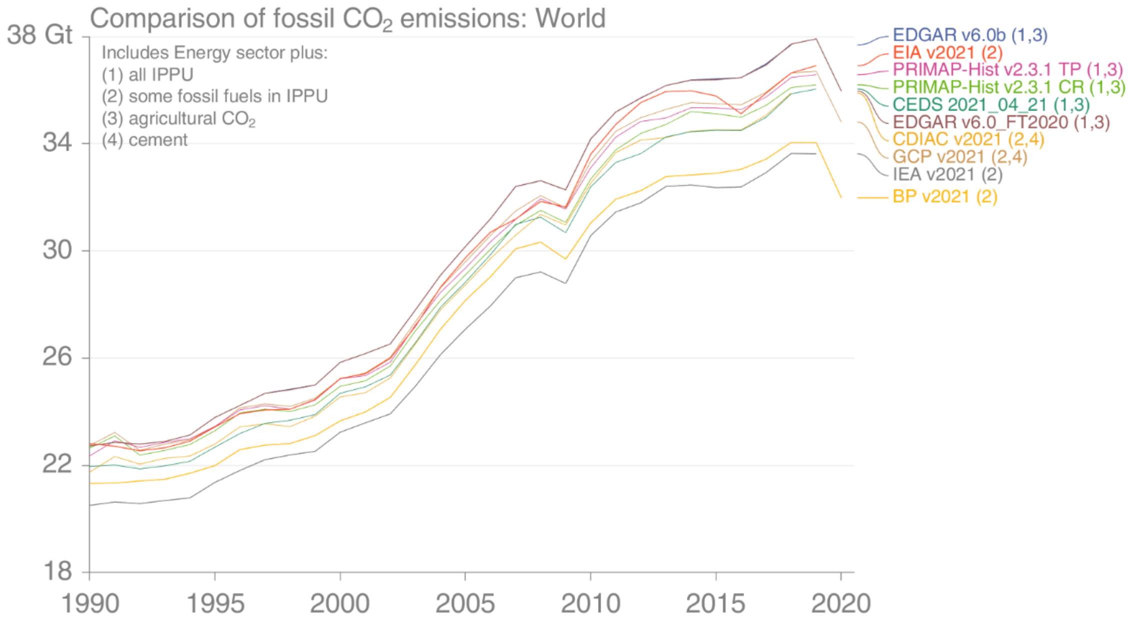


Figure 1: Comparison of unharmonized global fossil CO_2 emissions from multiple inventory datasets.

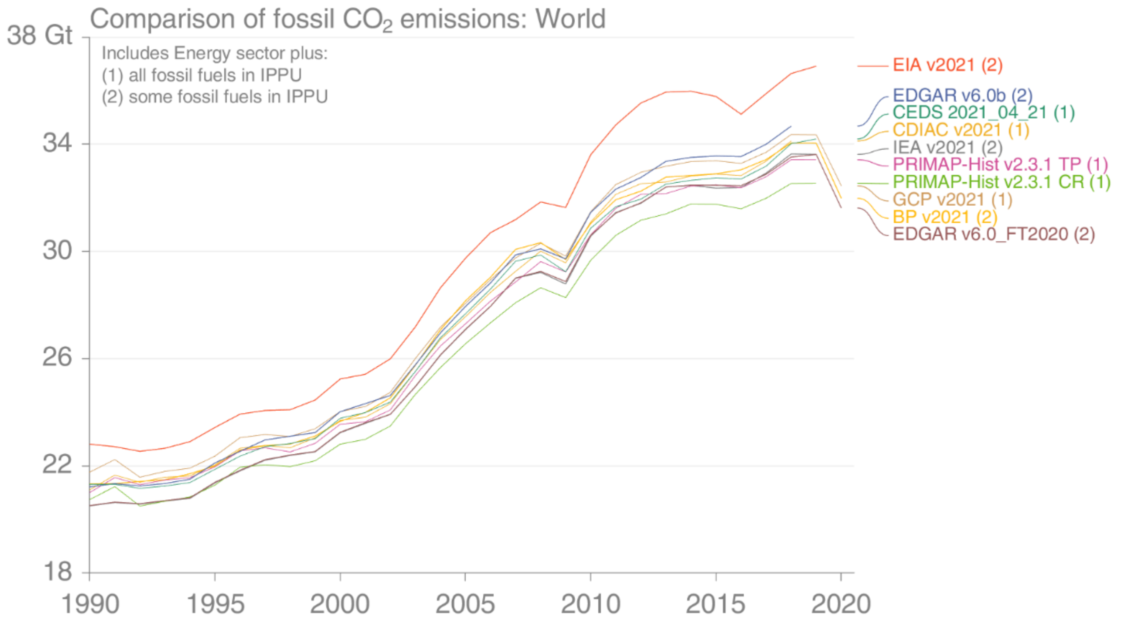


Figure 2: Comparison of global fossil CO_2 emissions from multiple inventory datasets with system boundaries harmonised as much as possible. Harmonisation is limited by the disaggregated information presented by each dataset.

Most datasets agree well within expected system boundary differences (Andrew, 2020), but EIA is an outlier. The reason for the high emissions reported by the EIA remains unknown. Analysis indicates that despite EIA's reported energy consumption data for European countries remaining largely unchanged across several recent releases, CO_2 emissions have grown quite substantially from oil across these same releases. This could be a result of revised emission factors, but could also be a result of errors such as double-counting. Unfortunately

EIA documentation is insufficient and not kept up to date. We have informed the EIA of these discrepancies.

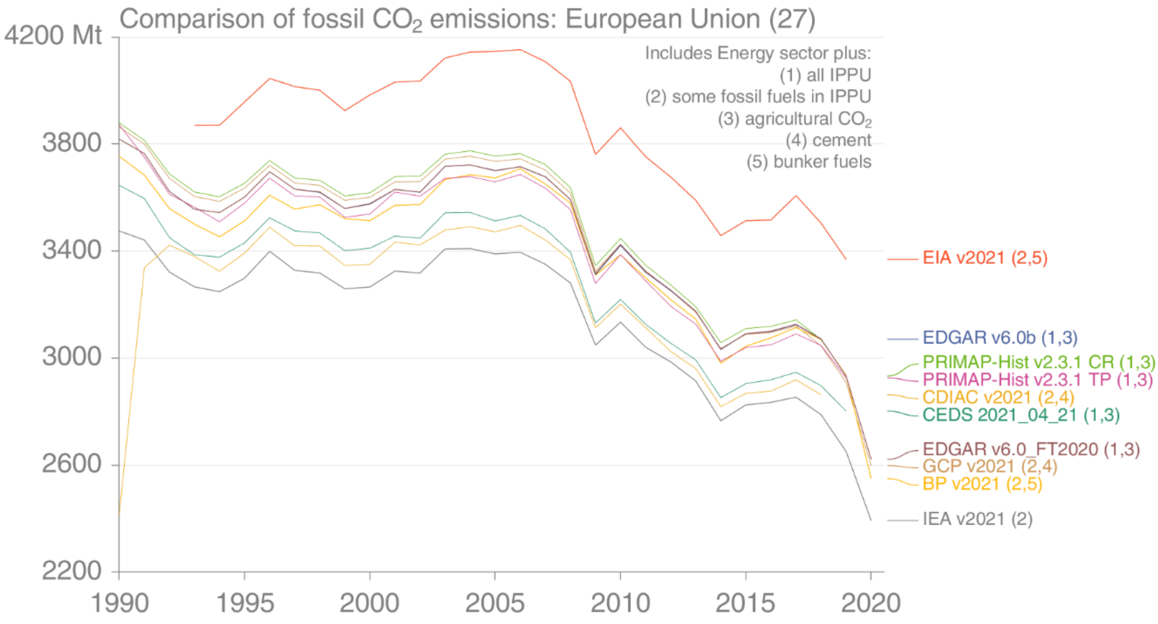


Figure 3: Comparison of EU fossil CO_2 emissions from multiple inventory datasets. CDIAC does not report emissions for countries that did not exist prior to 1992.

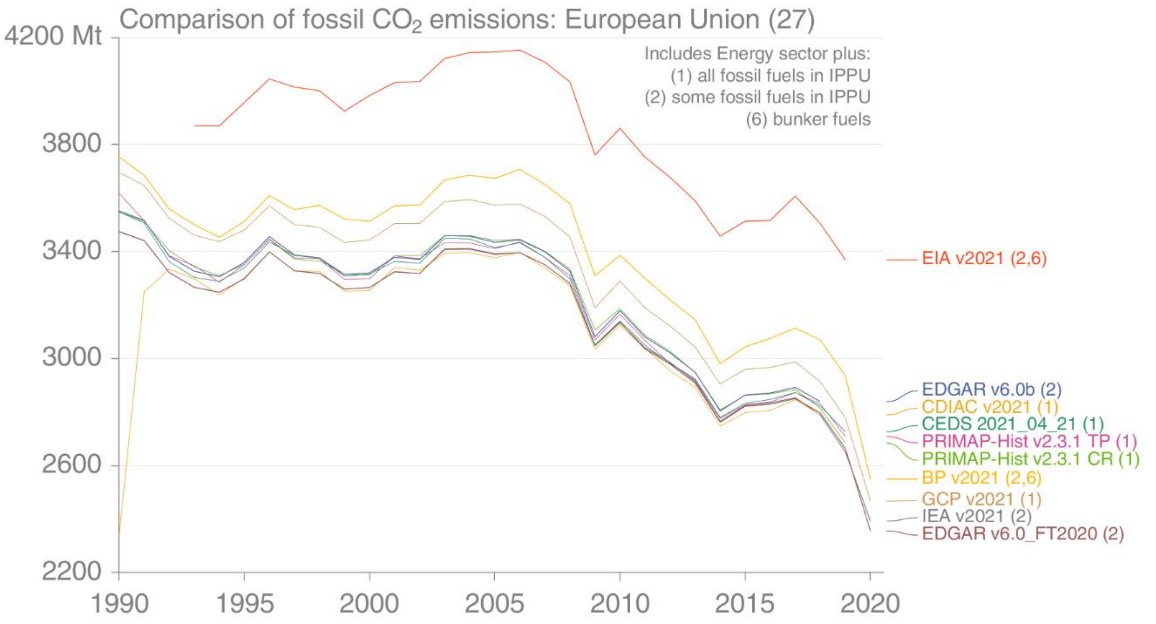
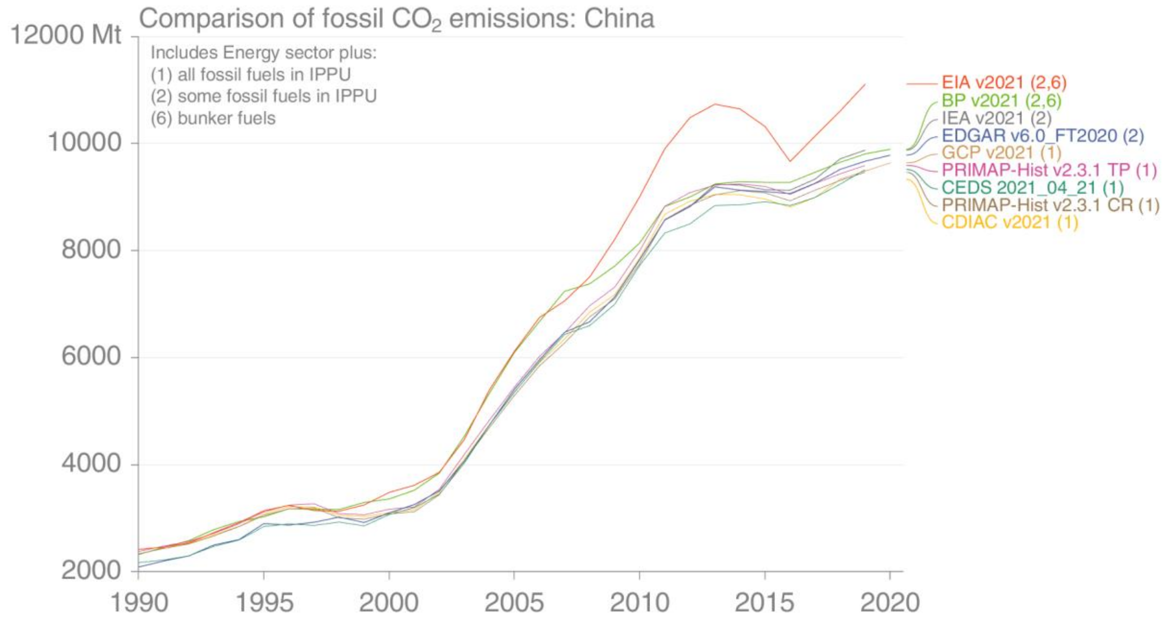


Figure 4: Comparison of EU fossil CO_2 emissions from multiple inventory datasets with system boundaries harmonised as much as possible. Harmonisation is limited by the disaggregated information presented by each dataset. CDIAC does not report emissions for countries that did not exist prior to 1992.

For the inventory-based estimates, it is possible to produce the figures for all countries. Figure 5 repeats the figures for two-largest emitters, China and USA, and Annex 1 additionally contains figures for the next-largest emitters: India, Russia, Japan, Iran, Germany, Saudi Arabia, South Korea, and Indonesia. A general pattern is that the EIA estimates are often higher than all others (see earlier discussion). For China, Andrew (2020) offers some explanation for this. Otherwise, the different datasets are similar in most instances, but further work is required to uncover the reasons for remaining divergences between these datasets.



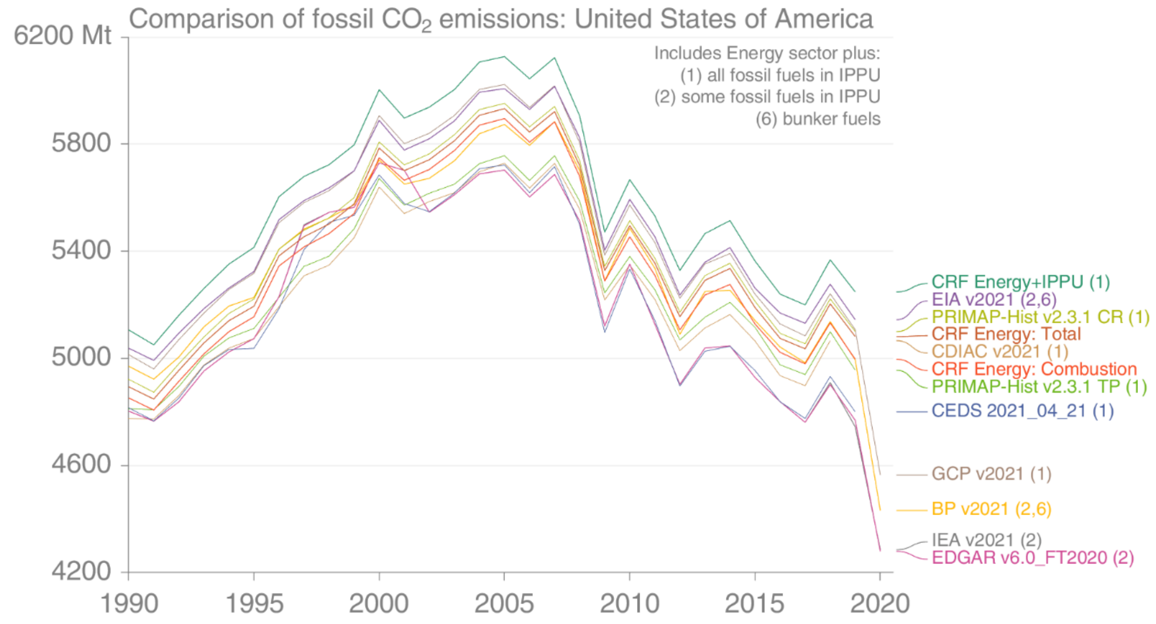


Figure 5: Comparison of China (top) and USA (bottom) fossil CO_2 emissions from multiple inventory datasets with system boundaries harmonised as much as possible.

Atmospheric inversions

The best observation-based constant on national scale estimates of anthropogenic CO_2 emissions in Europe over more than the past decade are satellite measurements of NO_2 and CO, which are "proxy" species co-emitted with CO_2 by fossil fuel combustion ($FFCO_2$). Results from the first atmospheric inversions of the European $FFCO_2$ emissions in VERIFY (Konovalov and Lvova (2018); Petrescu et al. (2021a)), indicated that there were much larger uncertainties associated with the assimilation of CO data than to that of NO_2 data for such a purpose.

In this report we present selected results from outputs from the VERIFY project (deliverable D2.11 and deliverable D2.12), which developed an atmospheric inversion workflow quantifying monthly and annual budgets of the national emissions of $FFCO_2$ in Europe (Fortems-Cheiney and Broquet, 2021b; Fortems-Cheiney et al., 2021). This workflow, implemented in the Community Inversion Framework (CIF; Berchet et al., 2021), estimates the NO_x emissions that when fed into a regional chemical transport model (CHIMERE; Menut et al., 2013)) best match satellite-measured NO_2 concentrations, while simultaneously minimising the difference between these estimated NO_x emissions and those from the prior inventory dataset, TNO-GHGco-v2 or TNO-GHGco-v3 (Denier van der Gon et al., 2020). This is a minimisation of least-squares optimisation process, solved iteratively (Rodgers, 2000; Chevallier et al., 2005). This workflow is applied over the period 2005-2020, on a 0.5°×0.5° grid. Ratios of $FFCO_2$ emissions to NO_x emissions directly derived from TNO-GHGco-v3 for five sectors (energy, industry, residential, road transport and the rest of the sectors), for each country and each month are then used to estimate fossil CO_2 emissions from the NO_x estimates produced by the inversion modelling. Several critical aspects of this workflow need to be highlighted: (i) Fortems-Cheiney and Broquet (2021a) have not reported estimates of the uncertainty in the final $FFCO_2$ emissions yet (ii) the $FFCO_2$ emission budgets provided by the TNO-GHGco-v3 inventory are based on the emissions reported by countries to UNFCCC, which are assumed to be accurate in Europe, therefore the inversion prior estimate (which is also its first guess in the variational inversion framework) is consistent with the inventory estimates.

For the EU27+UK, inversion products (emissions provided by the TNO-GHGco-v2 inventory and the maps of total NOx anthropogenic Emissions) yield credible numbers compared to nine inventory estimates from datasets with global coverage (Figure 6). After modelling was complete it was discovered that the prior fossil emissions estimates provided by TNO included non-combustion emissions (prior estimates were FCO_2, and not $FFCO_2$), the effect of which has not yet been determined.

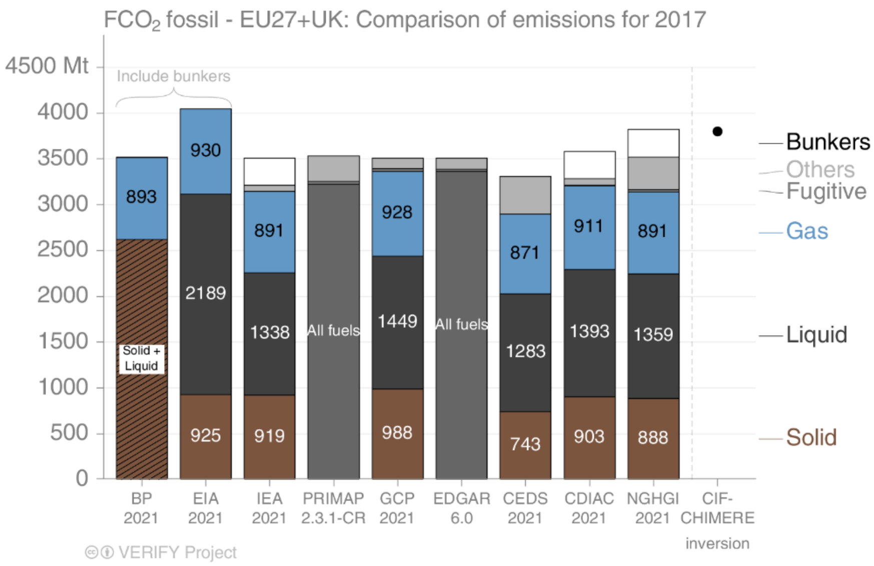


Figure 6: EU27+UK total CO_2 fossil emissions, as reported by nine global inventory data sources: BP, EIA, CEDS, EDGAR, GCP, IEA, CDIAC, PRIMAP-hist and UNFCCC NGHGIs with a top-down, fast-track CIF-CHIMERE atmospheric inversion (black dot) (Fortems-Cheiney and Broquet, 2021b). The data represent EU27+UK for the year 2017 split per fuel type. 'Others' are emissions not categorised by fuel, and international bunker fuels are not usually included in total emissions at sub-global level. Neither EDGAR nor PRIMAP-hist publishes a break-down by fuel type, so only the totals are shown.

Figure 7 shows the annual posterior fossil-CO_2 estimate from Fortems-Cheiney and Broquet (2021b) compared with the prior estimates for the EU27. As discussed above, the similarity of the inversion estimates with the inventory estimates here does not indicate a verification of the inventory estimates, but rather suggests that the workflow functions well and that the inversion was not pulled away from its prior estimate by major lack of fit to the satellite NO_2 data. Further work will be needed to make the inversion outputs more independent and less reliant on (prior) inventory estimates before they can be used for verification, and to derive robust estimates of the posterior uncertainties. Despite the agreement with the inventory estimates, Fortems-Cheiney and Broquet (2021b) indicate that the relative uncertainty in their estimates is likely very high (probably similar to that reported by Konovalov and Lvova, 2018) due to high uncertainties in both the NO_x inversions and the conversion into $FFCO_2$ emission estimates. This work is continuing.

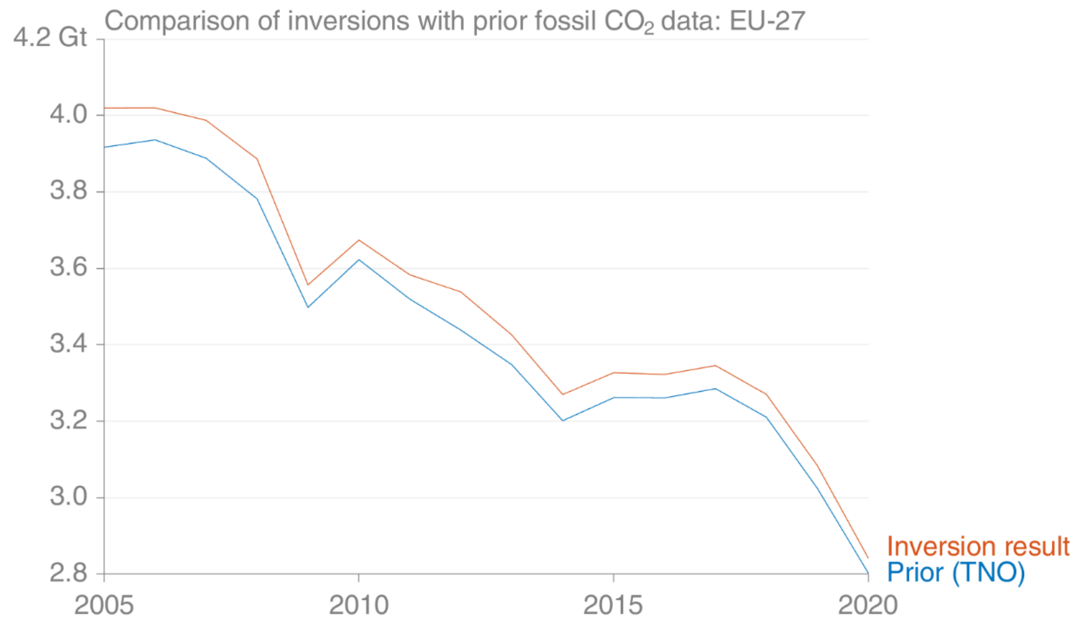


Figure 7: Comparison of inversion results for the EU with prior $FFCO_2$ emissions estimated by the TNO-GHGco-v3 inventory (Fortems-Cheiney and Broquet, 2021b). Note that the proximity of the inversion results to the prior estimates is not a direct indicator of verification, without additional information on the prior and posterior uncertainty and supporting statistical analysis (see discussion in the text).

While we still lack quantified posterior uncertainty estimates, they are currently thought to be high. Therefore, the agreement of the inversion result with inventory estimates is encouraging but is insufficient to confirm either of the estimates. The close agreement tells us that the inversion approach has not found sufficient evidence that the inventories are incorrect. Some reasons for this are lack of spatial coverage, sensitivity to the surface in the data, and the relatively high level of observation uncertainties. Country-level results show in some cases near-perfect agreement between the inversion modelling output and inventory estimates (Figure 8). However, this generally results from insufficient satellite data (because of cloud cover) for these countries, and/or that emissions of NO_2 are low (e.g., rural areas), such that minimal ‘correction’ is obtained to adjust the prior (inventories). Thus far the work involved has been aimed at proving the concepts and building the required modelling infrastructure and workflow. One of the main constraints to reducing uncertainty in this approach is the current lack of observation networks dedicated to the monitoring of $FFCO_2$ emissions, such as the planned constellations of satellite CO_2 spectro-imagers (Fortems-Cheiney and Broquet, 2021b): “the uncertainties in the $FFCO_2$ inversions presented here are still too high to attempt at using these inversions to improve the current knowledge on the $FFCO_2$ national scale emission budgets in Europe, although further progresses are expected”. Focusing on national-scale inversion configurations for European countries and on recent years during which the availability and resolution of CO_2 and pollutant data has significantly increased, $CoCO_2$'s WP4

(T4.4) should make a step forward towards an assessment of national scale FFCO$_2$ emission budgets in Europe.

Inversion results for countries outside of Europe are not yet available from the combined projects VERIFY, CHE, and CoCO$_2$. Some progress has been made in CoCO$_2$ (Task 4.4) for the USA. Given CoCO$_2$'s additional focus on the global top-10 emitters, effort will need to be invested in sourcing inversion results, potentially from collaborators outside of Europe (e.g., Basu et al., 2020).

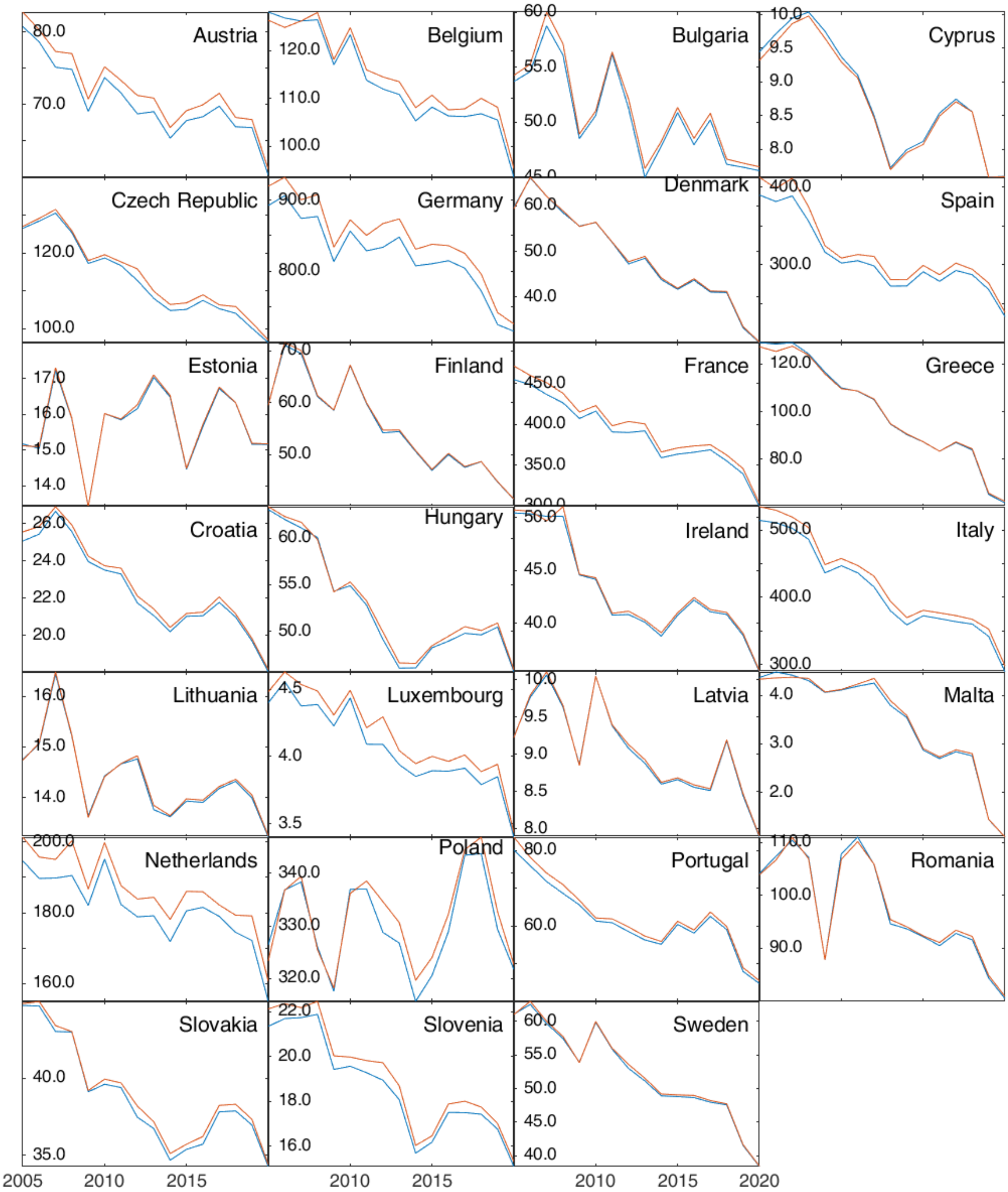


Figure 8: Comparison of inversion results (red lines) for each EU country with FFCO$_2$ prior emissions estimated by the TNO-GHGco-v3 inventory (blue lines), Mt CO$_2$ (Fortems-Cheiney and Broquet, 2021b). Note that the proximity of the inversion results to the prior estimates is not a

direct indicator of verification, without additional information on the prior and posterior uncertainty and supporting statistical analysis (see discussion in the text).

3.2 Net land CO_2 fluxes

The net land CO_2 fluxes are based on inventories, process models, and atmospheric inversions estimates from VERIFY, extended to include a CoCO$_2$ inversion (using CAMS). The inventory datasets include UNFCCC LULUCF and FAOSTAT, two bookkeeping models (BLUE and Houghton & Nassikas), and the TRENDYv10 ensemble. The atmospheric inversions include those from the Global Carbon Budget (GCB), plus a modified inversion using the CAMS framework extending the GCB inversions to include lateral fluxes (CoCO$_2$ activity) and a managed land mask (Chevallier, 2021), the CAMS v20r2 air-sample-driven inversion. The TRENDYv10 ensemble and the inversions are forced by climate and therefore shows a large degree of variability, while bookkeeping models and inventories are based on data or methods that essentially smooth out variability, making comparisons of the different approaches difficult.

System boundary issues plague comparisons of net land CO_2 fluxes. The question of how to define whether these carbon fluxes are anthropogenic is at the core of this issue (Grassi et al., 2018). The carbon cycle and land surface modelling communities (e.g., IPCC assessment reports) define anthropogenic carbon fluxes on land differently to the inventory community (e.g., IPCC guidelines, UNFCCC), though methods are being developed to bridge the differences (Grassi et al., 2021). There are two dimensions to this complex problem: 1) what land areas have anthropogenic changes (what is 'managed land'), and 2) are environmental factors (CO_2 fertilisation, climate, etc) or disturbances anthropogenic? UNFCCC NGHGI have country determined 'managed land' areas and include direct and indirect (environmental) factors. Approaches like BLUE, H&N, and FAO consider direct effects on land reported as having a land use transition. TRENDY and inversions consider all land and all effects. Depending on the share of land managed versus transitioning, and the size of the direct and indirect effects, the differences can be substantial (Grassi et al., 2018; Petrescu et al., 2020). Therefore, comparison of independent estimates of net land CO_2 fluxes need to consider the effect of these system boundary issues. The CoCO$_2$ CAMS inversion includes a managed land mask and therefore provides additional knowledge to aid in comparisons.

Figure 9 shows the comparisons to the UNFCCC NGHGIs in the EU27+UK. For this region, inventories and bookkeeping models indicate relatively constant net removals over the period, in contrast to the high interannual variability displayed by the DGVMs in TRENDYv10 and the inversions. The different datasets are broadly consistent for Europe, with perhaps the exception of CAMS v20r2, and this consistency likely helped since most of the managed land in Europe is transitioning and the indirect effects are small (Petrescu et al., 2020).

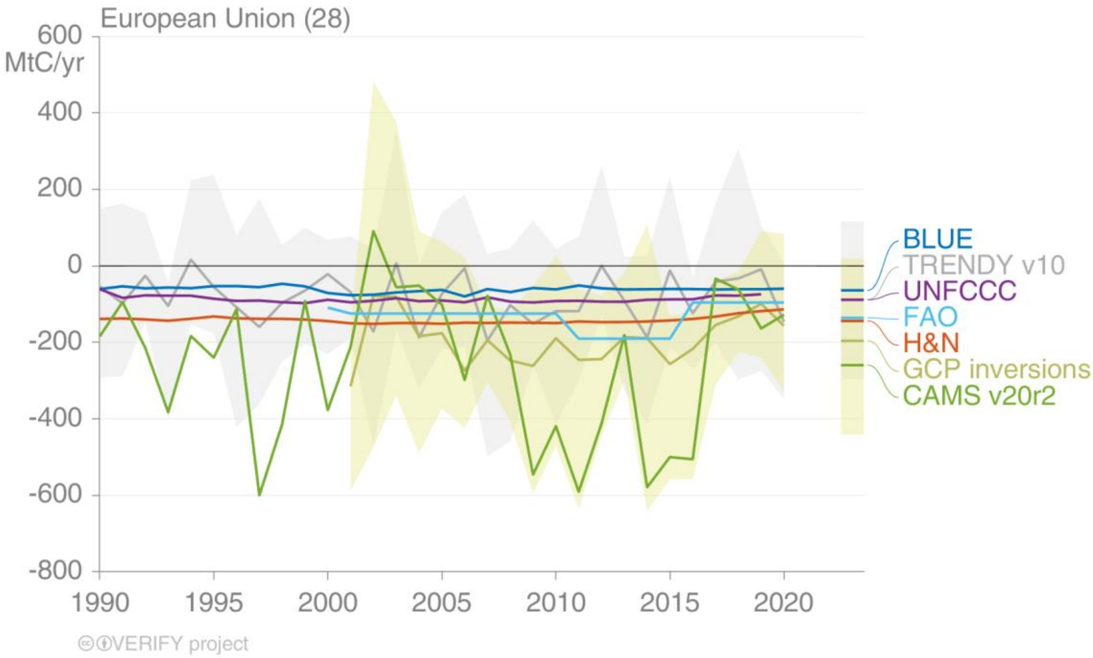
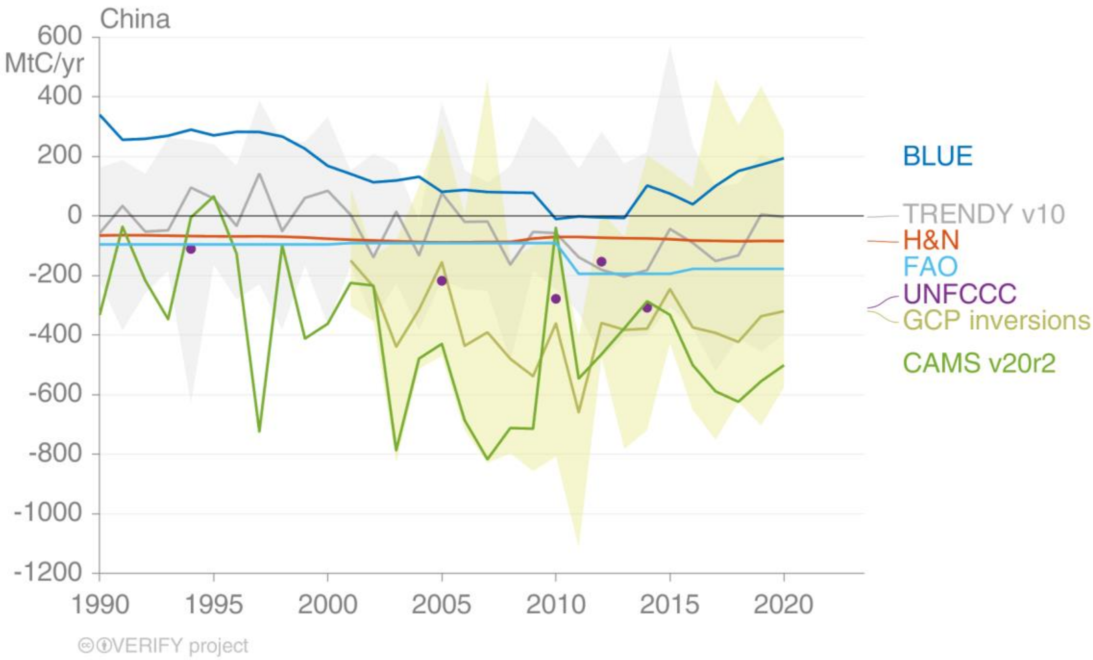


Figure 9: A comparison of inventories and inversions land CO_2 fluxes for the EU28 (EU27+UK).

Figure 10 presents comparisons of the net land CO_2 fluxes for China and Canada. For China, there is a fair amount of scatter in TRENDYv10 ensemble and the inversions, on average, inversions give a larger CO_2 land uptake. The inversions are fairly constrained because they can rely on a couple of stations in China and other stations in neighbouring countries (Russia, Mongolia, Japan, South Korea, India) and in the eastern Pacific Ocean. For Canada, there is a large spread in results, particularly for the GCP inversions. These GCP inversions do not include a managed land mask, and this has a large effect for Canada. The CoCO$_2$ CAMS inversion (v20r2) includes lateral fluxes and a managed land mask, bringing it much closer to the other estimates. As well as spread within datasets, there is divergence between datasets, with both differences in volatility and sign. Canada's official reporting to the UNFCCC is known to differ from most other countries' reporting in the way they account harvested wood products, which may additionally affect the removals shown here.



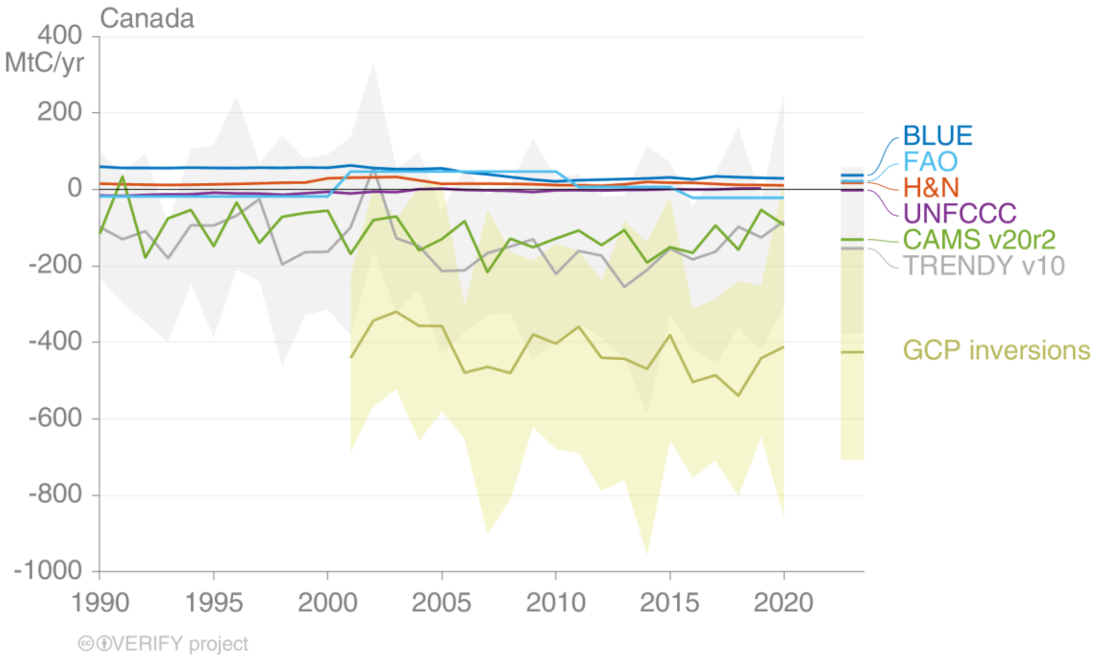


Figure 10: A comparison of inventories and inversions land CO_2 fluxes for China and Canada.

Annex 2 repeats the comparisons for addition countries where the CoCO$_2$ (CAMS) inversion has results: Brazil, Democratic Republic of Congo, India (in addition to Canada, China, and EU shown here). In many cases, the inversions and the TRENDYv10 results show large variability due to climate effects and/or some lack of constraint (in the case of inversions, such a lack of constraint tends to increase as the size of the target country decreases). Studies are ongoing to understand the differences in more details (e.g., within VERIFY).

As discussed above, to permit valid comparisons between UNFCCC inventories and inversions results, corrections can be made for both the land management regime and lateral fluxes to bring the system boundaries of inversion results close to those of the inventories (Chevallier, 2021; Deng et al., 2021). Here we compare the carbon fluxes from CAMS inversions, before (red) and after (blue) these two system boundary corrections (Chevallier, 2021). The results over all 16 regions show relatively small changes due to these corrections (Figure 11), with a root-mean-square error (RMSE) of 4.4% across all regions and years. This small difference confirms the findings of Chevalier et al. (2021) who find that the application of the land mask has a small effect on their results. Deng et al. (2021) also found that the managed land mask did not produce significant differences for regions where forests are mainly managed (e.g., Europe, USA, China), but for some individual countries the application of the land mask yielded large differences (e.g., 16% for Brazil, 30% for Canada). The lateral flux corrections result in changes of either sign depending on the net fluxes. Changes in trends after applying these corrections appear to be relatively small.

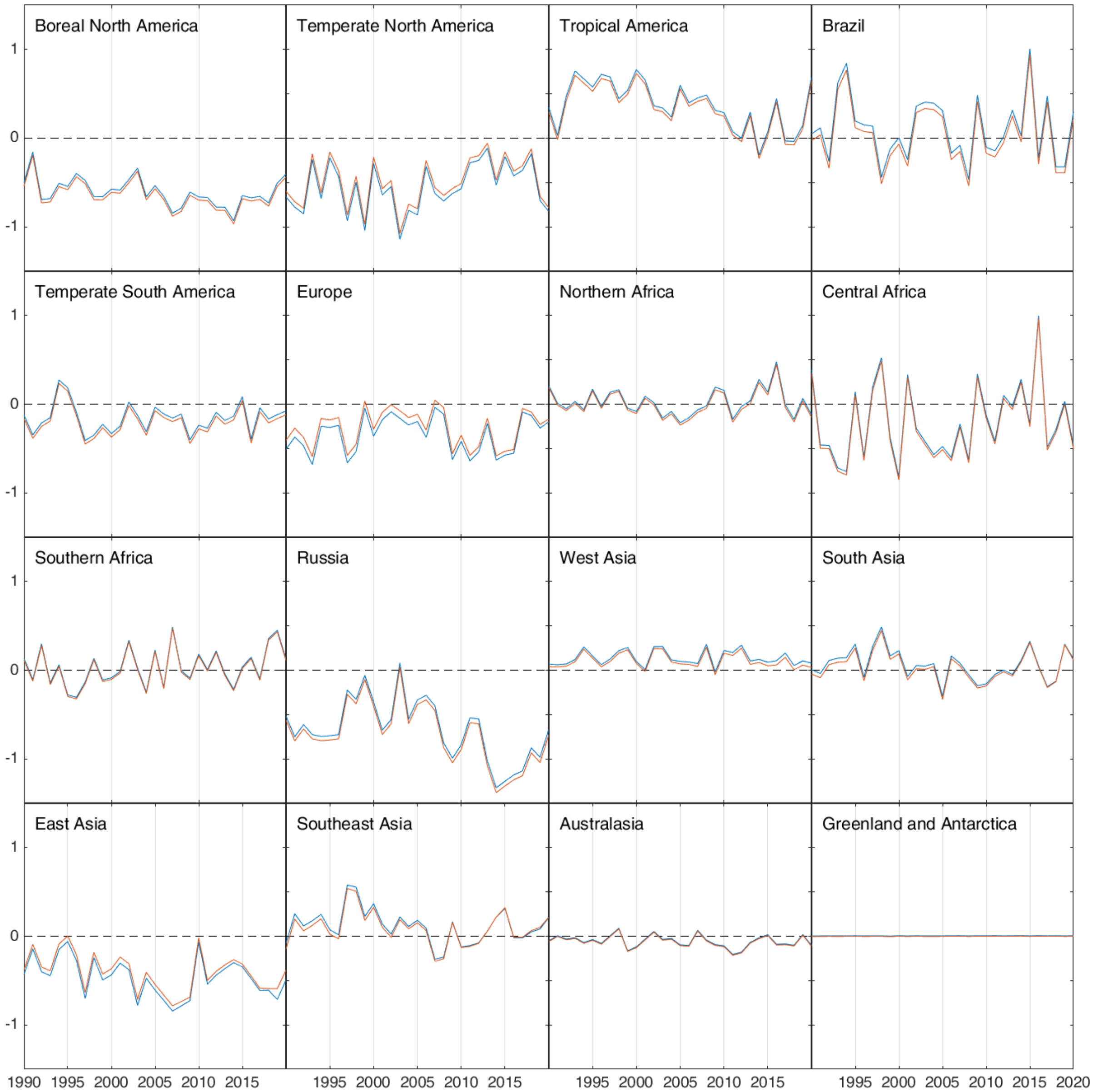


Figure 11: The effects of adjusting for managed land and lateral fluxes to come closer to the system boundary used in UNFCCC reporting. Comparison of unadjusted (red) and adjusted (blue) series from CAMS, in PgC/yr across 16 regions.

4 Total and sectoral CH_4 emissions

Methane is the second most important GHG after CO_2 but more potent because of its radiative forcing (GWP 28 on a 100-year timescale). CH_4 contributes to ~17% of the total global GHGs emissions using a GWP (CO_2-eq), but around 50% of current observed warming (IPCC AR6) due to its potent but short-lived nature. Sector wise, the primary sources of anthropogenic CH_4 emissions are agriculture, fossil fuel production, and waste management. In this report, we analyse and compare data for top CH_4 emitter countries, from bottom-up and top-down sources and compare them to national inventories reported to UNFCCC, from the Common Reporting Format tables (CRFs) for Annex I parties or from the Biannual Updated Reports (BURs) for the non-Annex I parties.

Figure 11 presents the total global anthropogenic CH_4 emissions from seven inventories and all IPCC sectors, while FAO has only emissions for agriculture.

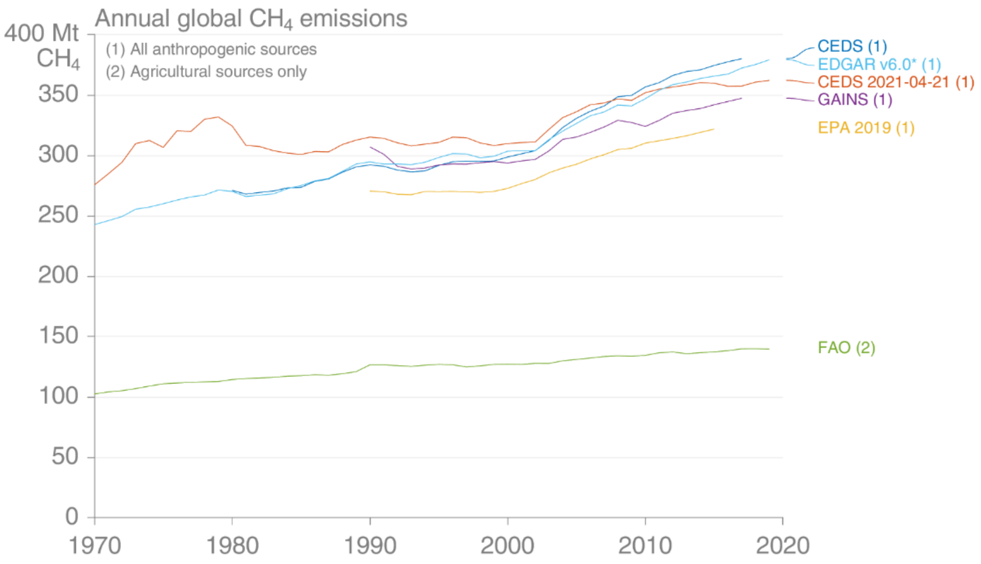


Figure 12: Total global CH_4 anthropogenic emissions from eight inventories, Minx et al., 2021.

All datasets in Figure 12 agree in terms of increasing trends during the last two decades, with differences in absolute emissions values. As summarized by Minx et al., 2021, the differences between inventories are mainly caused by methodologies of producing or using AD, EFs or technological abatement when available. For example, US-EPA inventory uses the reported emissions by the countries to the UNFCCC while other inventories produce their own estimates using a consistent approach for all countries and country-specific AD and/or EFs. FAOSTAT and EDGAR mostly apply a Tier-1 approach to estimate CH_4 emissions, while GAINS uses a Tier-2 approach. CEDS is based on pre-existing emissions estimates from FAOSTAT and EDGAR, which are then scaled to match country-specific inventories, largely those reported to the UNFCCC (Minx et al., 2021). For EU27+UK the use of AD and EFs and linkages between data sources has been summarized in Fig.4, Petrescu et al., 2020.

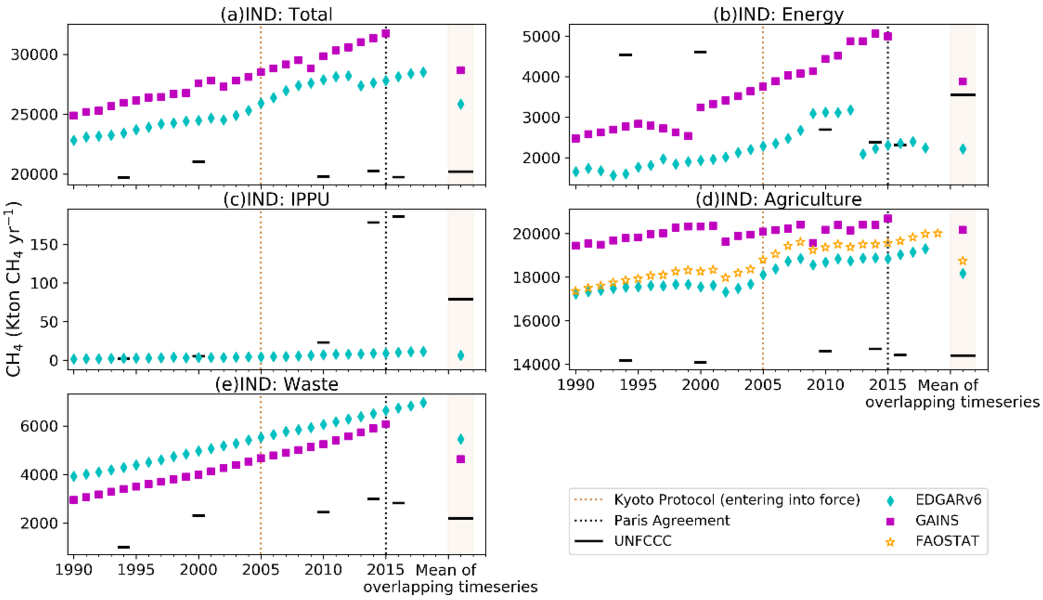
We compare the total anthropogenic CH_4 fluxes in two ways:

Total and sectoral anthropogenic CH_4 fluxes from inventories (Figure 12)

For total CH_4 emissions from the inventory data we compare emissions time series from 1990-last available reported year from EDGARv6.0 which covers all sectors, GAINS model which covers all sectors but Industry Processes and Products (IPPU) which is nevertheless a small flux compared to other sectors and from the UNFCCC CRFs and BURs. For the sectoral emissions we also analyse the data from FAOSTAT (2021). We identified in most inventories, in this or similar order, the following top emitters: China, India, USA, EU27+UK, Brazil, Indonesia, Russia, Mexico, Iran, Australia and Argentina.

For the total and sectoral CH_4 emissions we chose to exemplify India and Australia due to interesting discrepancies we found between the three data sources, both in terms of values and trends. All other country figures are found in the Annex 3.

For India we note that the total CH_4 anthropogenic emissions from both EDGARv6.0 and GAINS agree pretty well on values and trends while UNFCCC BURs are underreported and miss the actual increasing trends shown by the other two inventories. This is mainly seen for Agriculture and Waste which, together, have the highest share of the total emissions (88%, Table 4) and trigger these differences. For Energy, EDGARv6.0 is capturing well the reduction trend (2013-2018) and this is due to the updates and use of Tier 1 default EFs same as India does in their NGHGI.



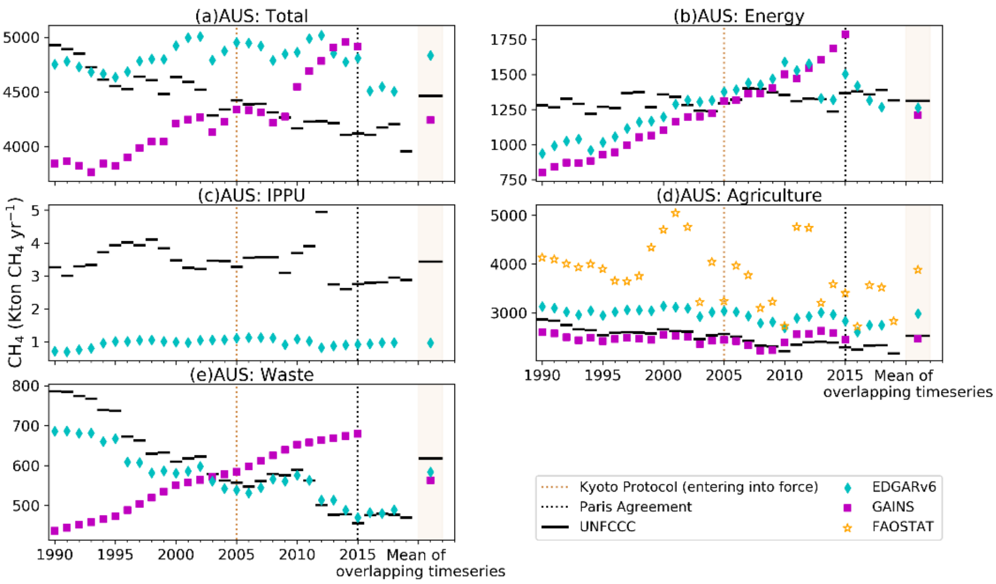


Figure 13: India and Australia total sectoral emissions as: a) total, b) Energy, c) Industry and Products in Use (IPPU), d) Agriculture and e) Waste from UNFCCC (2019) submissions and all sectors excl. LULUCF (EDGAR v6.0, GAINS, FAOSTAT (for Agriculture only)). The means represent the common overlapping period 1990-2015. Last reported year in this study refers to 2019 (UNFCCC and FAOSTAT), 2015 (GAINS) and 2018 EDGARv6.0.

Regarding Australian results, most discrepancies are between GAINS and the other two data sources, mainly for Energy and Waste. Regarding Waste emissions, GAINS' increasing trend, opposed to those of EDGARv6.0 and UNFCCC is mainly caused by the solid municipal waste component which in GAINS is modelled taking into account the socio-economic status of the countries (e.g., the drivers used to project future municipal solid waste generation are GDP per capita and urbanization rate (Gómez-Sanabria *et al* 2018)) which are high in Australia.

EDGAR data is in fair agreement during the last decade mostly for trends, in particular for waste while for Energy we see a better match with UNFCCC starting 2013. This is caused by a drop in the solid, gas and oil use, and it reflects in the decline of the implied EFs for underground coal mines which decreased after 2012 (https://unfccc.int/documents/273478, Vol.1) while for oil wells the trend coincides with the closure of offshore and onshore wells after 2012. Perhaps a smaller contribution to the decrease is the split of oil and gas emissions reported for flaring after 2009. Prior to 2009, the Australian Petroleum Production & Exploration Association (APPEA) data did not provide splits for flaring between oil and gas sources and, therefore, flaring emissions were reported in the oil/gas combined category. With the introduction of the National Greenhouse and Energy Reporting scheme (NGER) for the inventory year 2009, separate emissions data has been available for the individual oil and gas flaring categories and therefore the flaring emissions have been reported for 2009 onwards in those respective categories (https://unfccc.int/documents/273478, Vol.1). GAINS Energy estimates are going upwards and we hypothesize that GAINS continues to take into account the emissions coming from the open holes of the abandoned mines, while the other inventories do not account for it.

For agriculture, FAO reports very fluctuating emissions having a seasonal pattern. We found that this is due to FAO's inclusion of savannah fires into their Agriculture emissions. The other two BU inventories do not report savannah fires as part of their agricultural emissions but into LULUCF (4A Forest land and 4C Grassland).

Table 4 presents the ranking of top world emitter countries by inventory and sectors and their contribution (in %) to the total country emissions. We note that for most of the countries the three BU inventories agree well, except for Indonesia, where EDGARv6.0 and GAINS report as first contribution Energy while UNFCCC Waste. Same we note for Iran and Argentina, where the first bottom-up contribution are Energy for Iran and Agriculture for Argentina while there are shifts between the contribution to the second and third place. The contribution of IPPU is negligible in UNFCCC and EDGARv6.0, while GAINS does not report it.

The contribution (last 10-year average) of these 11 parties (China, India, USA, EU27+UK, Brazil, Indonesia, Russia, Mexico, Iran, Australia, and Argentina) to the total anthropogenic emissions of each inventory is 58**%** for EDGARv6.0 and 61.5 % for GAINS.

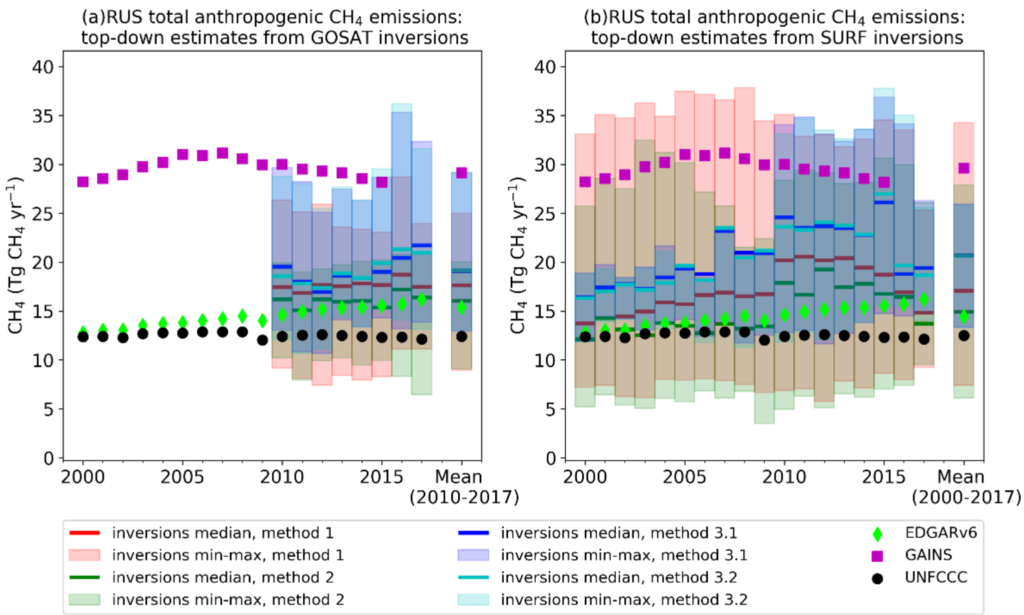
Table 4: Ranking of top world emitter countries by inventory and sectors and their contribution (in %) to the total country emissions.

		Inventory estimates											
		Energy			Agriculture			Waste			IPPU		
1	Countries	UNFCCC	EDGARv6	GAINS	UNFCCC	EDGARv6	GAINS	UNFCCC	EDGARv6	GAINS	UNFCCC	EDGARv6	GAINS
2	China	49%	42%	49%	41%	35%	33%	10%	21%	18%			
3	USA	42%	44%	46%	37%	36%	32%	20%	20%	22%			
4	India	12%	9%	15%	74%	67%	67%	14%	23%	18%			
no data	EU28	19%	21%	17%	51%	47%	54%	30%	31%	29%			
	Brazil	6%	4%	3%	78%	71%	81%	16%	24%	15%			
	Russia	57%	61%	76%	14%	15%	9%	28%	23%	15%			
	Indonesia	14%	43%	51%	30%	38%	34%	56%	19%	15%			
	Mexico	23%	20%	18%	47%	43%	50%	21%	37%	33%			
	Iran	63%	78%	71%	16%	12%	16%	21%	10%	13%			
	Australia	32%	30%	33%	56%	59%	53%	21%	11%	14%			
	Argentina	9%	17%	12.6%	74%	72%	74.6%	17%	11%	12.7%			

SURF and GOSAT atmospheric inversions compared to UNFCCC (Figure 13)

For total inversions CH_4 emissions we compare time series from 1990 to last available reported year from UNFCCC CRFs and BURs against global atmospheric CH_4 inversions from Saunois et al. (2020) separated in those based on the assimilation of surface data (SURF) and those assimilating GOSAT satellite column CH_4 data. All other top emitter country figures are found in the Annex 3.

For the Russian estimates (Figure 13) the inversions presented belong to the four methods described in section 1.4 of Deng et al. (2021), where each of them has a different way of subtracting the natural emissions (inventory or inversions based) from the total emissions, in this way representing the anthropogenic CH_4. Consequently, the anthropogenic emissions are compared with inventories, in a similar manner and methodology developed in the WP5 of VERIFY (Petrescu et al., 2021b). We note that the Russian emissions from GAINS are factor two higher than those from UNFCCC and EDGARv6.0 whereas the mean of atmospheric inversions constrained by a) GOSAT or b) SURF satellite data suggest, on average, stable values closer to the mean of the two inventories. The much lower Russian values reported to the UNFCCC are in part explained by the change in methodologies after the 2018 submissions, which revised the entire time series. In 2018, Russia changed its methodology from a central inventory system to a voluntary-based one done by companies. On top of that, Russia has a regulation which means that companies pay a fine on CH_4 emissions, and we assume that this is why the Russian current CH_4 emissions reported by the companies to the UNFCCC are underreported. Therefore, the main reason for the differences can be referred to as different methods applied in GAINS and NGHGIs. Regarding EDGARv6.0, we hypothesize that EDGARv6.0 relies heavily on EFs and AD from the Russian inventory process, therefore the better agreement is reached.



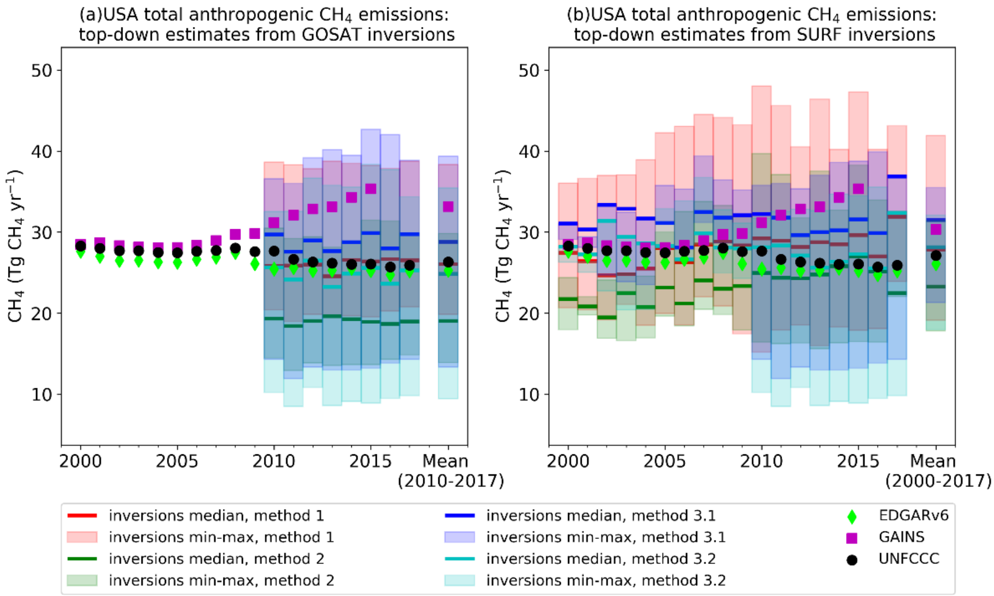


Figure 14: Total anthropogenic CH_4 emissions (Tg CH_4 yr^{-1}) for Russia and USA from inventories (EDGARv6 and GAINS) plotted against UNFCCC national reports (CRFs and BURs) and from global inversion ensembles a) CH_4 emissions based on satellite concentration observations (GOSAT) and b) from global models surface stations (SURF). The inversion ensembles are presented for the 4 methods (1, 2, 3.1 and 3.2) as described in section 1.4 of Deng et al. (2021).

For USA, the CH_4 inventory emissions data reported to UNFCCC (2021) (CRFs) is compared to other emission estimates from global datasets (EDGARv6.0 and GAINS). CH_4 contributes only 10% to the USA GHG total emissions and this share is considerably lower than the global average of 19% (Olivier & Peters, 2020). Recently, CH_4 emissions have increased after a period of stagnation (2.5% increase in 2019 compared to 2018). Natural gas systems in USA provide a 75% share on the CH_4 from oil and gas production (& transmission) and oil systems a 25% share. It is well-known that these emissions are highly uncertain. Over the past 5 years, this sector underwent several revisions, originally a few percent upwards, but in 2017 16% downward and in 2020 another 12% downward (Janssens-Maenhout et al., 2021). In other terms, EDGARv6.0 matches the UNFCCC CRFs but show large difference between themselves when looking at (kt) emissions (e.g., in 2015 the order of factor ~2 between GAINS and EDGAR). We assume that statistics for AD and methodologies (Tiers) are the culprit for these divergences. The increase in GAINS estimates after 2007 is due to the unconventional gas production, shale gas which is not reported by the other inventories. Also, the emissions from oil production in GAINS is ~5 times higher than those calculated by EDGARv6 and UNFCCC. Concerning the USA reported CH_4 emissions, in earlier years of the time series (1990-1992), EPA emissions were estimated. From 2011-on data from GHG reporting are used. To calculate emissions for the intermediate years (1993-2010), EPA calculate a per processing plant with EF for 1992 by dividing the calculated emissions for 1992 by the national count of processing plants in 1992 and then interpolating between that value and the CH_4 per plant value for 2011 developed from the GHG reported data.

Regarding the USA atmospheric inversion estimates, given the uncertain inventory emissions, comparison with inversions seems useful and we note that in general, a stabilising trend is confirmed by the inversions. However, for the CH_4 emissions from oil and natural gas production regions in the USA, some inversions using remote sensing data from TROPOMI on the Sentinel-5P satellite are estimated 45% to 60% higher emissions than reported by US

EPA (Schneising et al., 2020; Weller et al., 2020; Zhang et al., 2020) and those will probably match better the GAINS estimates. However, TROPOMI results are not taken up in the figure, because of the relative short time frame of the TROPOMI observations.

Uncertainties

We did not make use yet of $CoCO_2$ WP5 uncertainties. Table 5 presents a summary of uncertainty estimates at the global scale and for different sectors (Minx et al., 2021).

Table 5: Uncertainties estimated for CH_4 sources at the global scale: based on ensembles of inventories and inversion estimates, national reports, and specific uncertainty assessments of EDGAR. Note that this table provides uncertainty estimates from some of the key literature based on different methodological approaches. It is not intended to be an exhaustive treatment of the literature (Minx et al., 2021).

	Estimated uncertainty in USA inventories[a]	Janssens-Maenhout et al. (2019) EDGARv4.3.2 uncertainty at 2σ	Solazzo et al. (2021) EDGARv5 uncertainty at 2σ	Global inventories uncertainty range[b]	Saunois et al. (2020) BU uncertainty range[c]	Saunois et al. (2020) TD uncertainty range[c]
Total global anthropogenic sources (incl. Biomass burning)					±6 %	±6 %
Total global anthropogenic sources (excl. Biomass burning)		±47 %	−33 % to +46 %	±8 %	±5 %	
Agriculture and Waste					±8 %	±8 %
Rice		±60 %	31 %–38 %	±22 %	±20 %	
Enteric fermentation	±10 to 20 %			±5 %	±8 %	
Manure management	±20 % and up to ±65 %					
Landfills and Waste	±10 % but likely much larger	±91 %	78 %–79 %	±17 %	±7 %	
Fossil fuel production & use					±20 %	±25 %
Coal	−15 % to +20 %	±75 %	65 %	±40 %	±28 %	
Oil and gas	−20 % to +150 %		93 %	±19 %	±15 %	
Other		±100 %	±100 %	±64 %	±130 %*	
Biomass and biofuel burning					±25 %	±25 %
Biomass burning					±35 %	
Biofuel burning		Included in "Other"	147 %	±24 %	±17 %	

a Based on (NASEM, 2018)

b Uncertainty calculated as ((min-max)/2)/mean*100 from the estimates of year 2017 of the six inventories plotted in Figure 1. This does not consider uncertainty on each individual estimate.

c Uncertainty calculated as ((min-max)/2)/mean*100 from individual estimates for the 2008-2017 decade. This does not consider uncertainty on each individual estimate, which is probably larger than the range presented here.

* Mainly due to difficulties in attributing emissions to small specific emission sector.

5 Deviations and counter measures

At the time this report was written, except for CAMS WP6 contribution, we did not receive data/uncertainties from $CoCO_2$ WPs. We based our analysis on data already processed in the VERIFY project. For the next two updates of this report (M24 and M36), next to available updates from the VERIFY project (synthesis for 2021 to continue under $CoCO_2$ WP6, D6.2) we will make use of all available $CoCO_2$ products.

6 Conclusion

This deliverable presents comparisons of inventory-based and observation-based inventory approaches, building on earlier work in VERIFY (Petrescu et al., 2021a; Petrescu et al., 2021b), and applied here to top global GHG emitters. It highlights the differences and discrepancies between UNFCCC NGHGI, independent inventories, process-based models, and atmospheric inversion estimates. The analysis focused on the fossil CO_2 emissions, net land CO_2 fluxes, and CH_4 total and sectoral anthropogenic emissions.

For fossil CO_2 emissions the analysis was focused on Europe and European countries, as we did not have data on global CO_2 inversions. The results show a general consistency between inventories and NO_2 based inversions, but without additional analysis of prior and posterior uncertainties it is not possible to assess the consistency quantitively. Future work will focus on improved uncertainty analysis, and additionally, expand to cover other key fossil CO_2 emitters.

For net land CO_2 fluxes, a variety of datasets are available to provide country-level estimates, both inventory and inversions-based estimates. There is generally a low level of confidence in inventory approaches at the country level, for example, the GCP still does not widely disseminate country level estimates from the bookkeeping (BLUE, H&N) or land-surface model (TRENDYv10) datasets, even though they exist. In this report, no effort was made to make the bookkeeping models and land surface models comparable with each other, and with UNFCCC inventories. In particular, the fact that bookkeeping models only account for land-use change and harvest (but without any forest demography structure) at constant CO_2 and climate, whereas DGVMs account for all fluxes but generally not for forest disturbances and their impact on forest sinks. An active area of research is understanding the differences between datasets, to provide sufficient confidence to disseminate more broadly. The inversions also exhibit significant uncertainty, partially reflecting a lack of observations. However, a certain consistency with other studies was found for the larger countries, between some results assimilating surface measurements and others assimilating satellite measurements. The CoCO$_2$ CAMS inversions now include lateral fluxes and managed land masks, to properly compare with UNFCCC NGHGIs (Figure 11).

For CH_4 emissions, we observe an increase in emissions during the last three decades, mostly from the energy sector, except for the three Annex I Parties Russia, USA and EU27+UK where more green regulations were put in place (Dauwe et al., 2021; European Commission, n.d.); while for Russia we notice very high CH_4 emissions for 1990 which afterwards show a constant decreasing trend which is best explained by the dissolution of the Soviet Union (1989–1991) and the consequent structural changes in their economy and impacts on the agriculture sector (Petrescu et al., 2020). For USA, GAINS tends to overestimate and show an increasing trend when the other two inventories report a decrease (e.g., Energy sector). Overall, we see relatively good agreements between EDGARv6.0, GAINS and UNFCCC (see absolute values in Table 5, Annex 3). For the non-Annex I countries, from the Annex 3 figures, we see that trend wise the three data sources match well albeit the few BUR reported values (e.g. Iran, China). We also note that for Mexico there is the worst agreement from all three data sets. The largest discrepancy between the three data sources is the contribution of sectors to the total emissions. This was the case of Indonesia, Iran, and Argentina, where inventories do not agree on which is the highest contributor (Table 4). We conclude that this is due to the very different methodology and Tiers used by each of the investigated BU inventories: uniform global Tier-1 EDGARv6.0, scenario model Tier-2 GAINS not so much focusing on current emission and trends but on projections and the NGHGI reports from UNFCCC where most of non-Annex 1 countries base their calculations on IPCC default EFs. However, the three agree very well on EU27+UK and leads us to the conclusion that EU has consistent methodologies and statistics put in place (e.g., for AD) which allow bookkeeping models to correctly estimate and agree with the inventories.

Future versions of this report will make more use of $CoCO_2$ products, both in terms of emissions and uncertainties. We will further involve global international emission initiatives (e.g., GEIA) and connect to current work done under RECCAP2. TROPOMI results as well as new developments made in the VERIFY project (CIF intercomparison) should be used.

7 References

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VU Amsterdam	2
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LSCE	2
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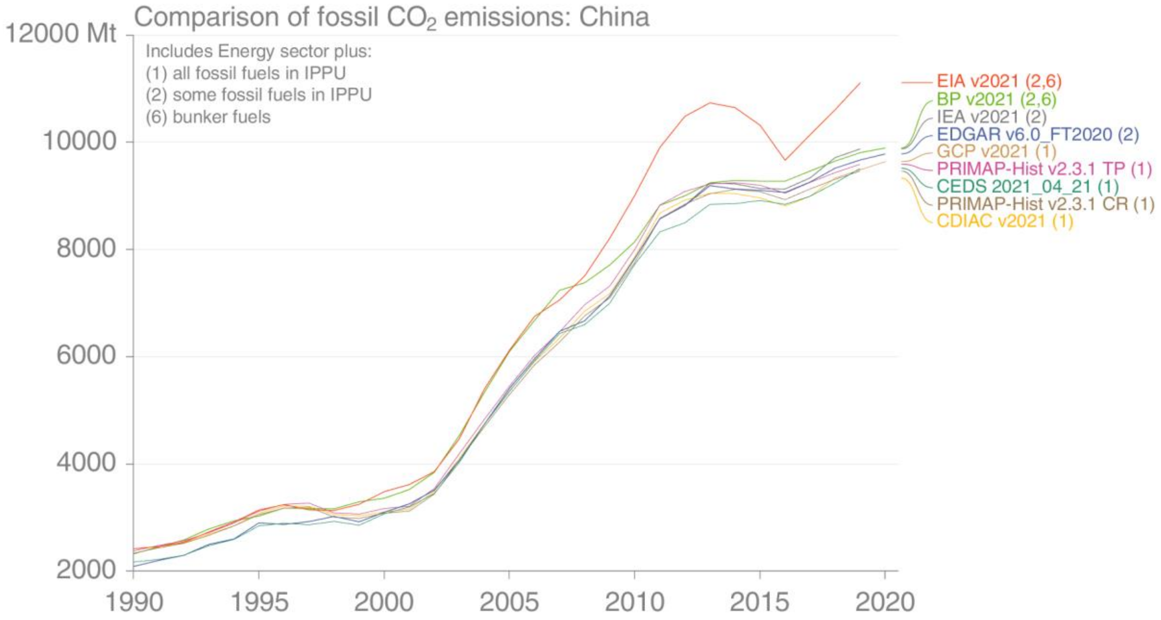
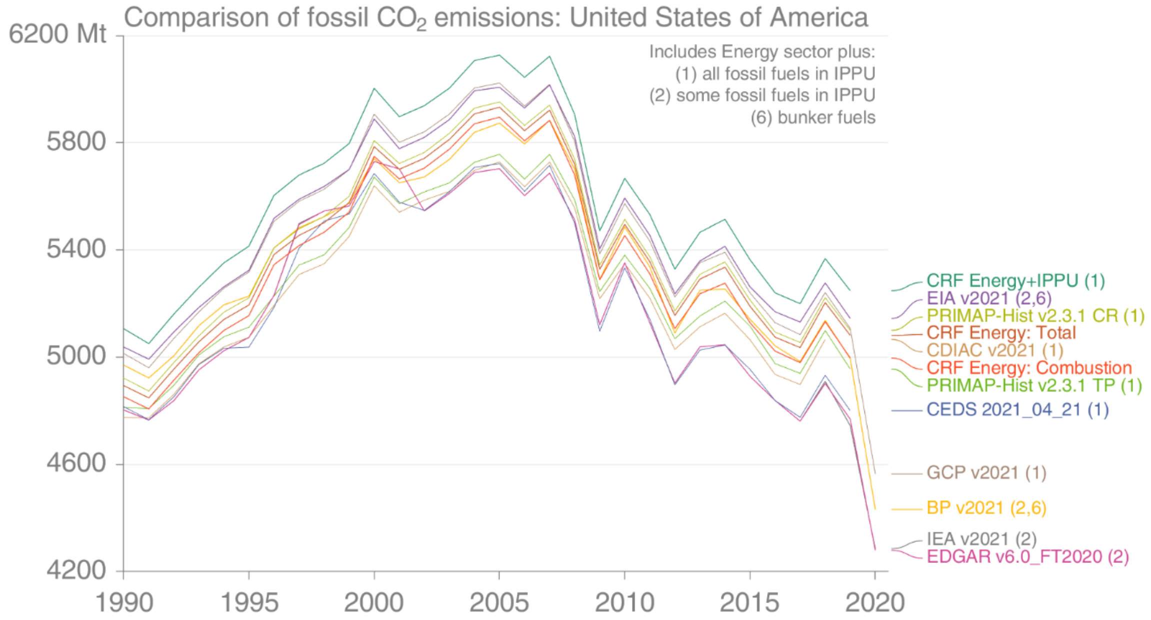
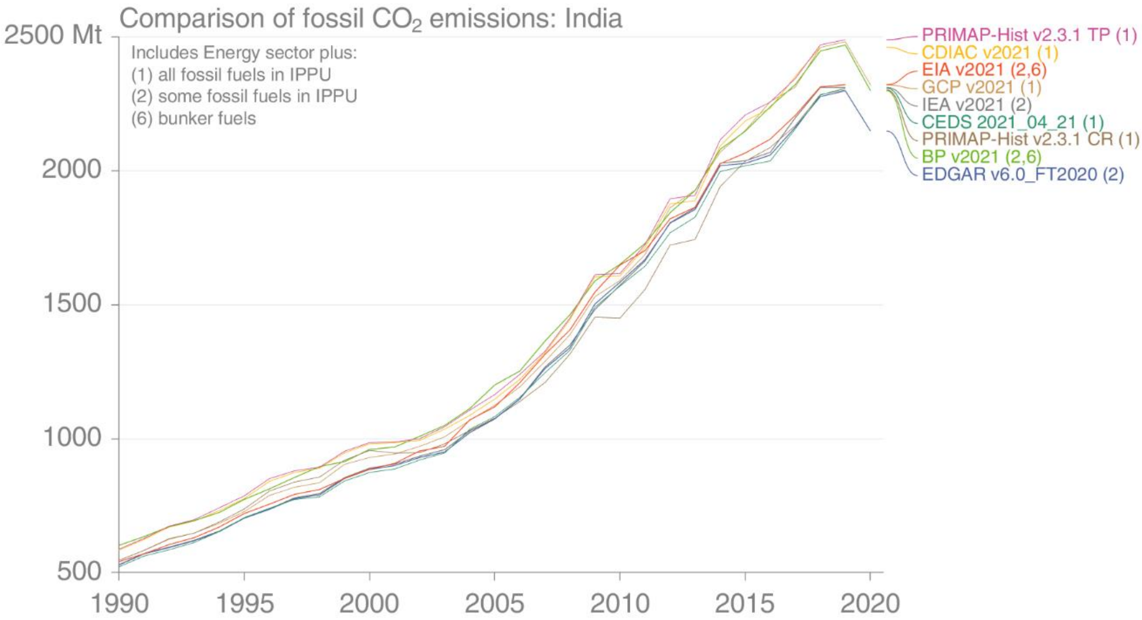
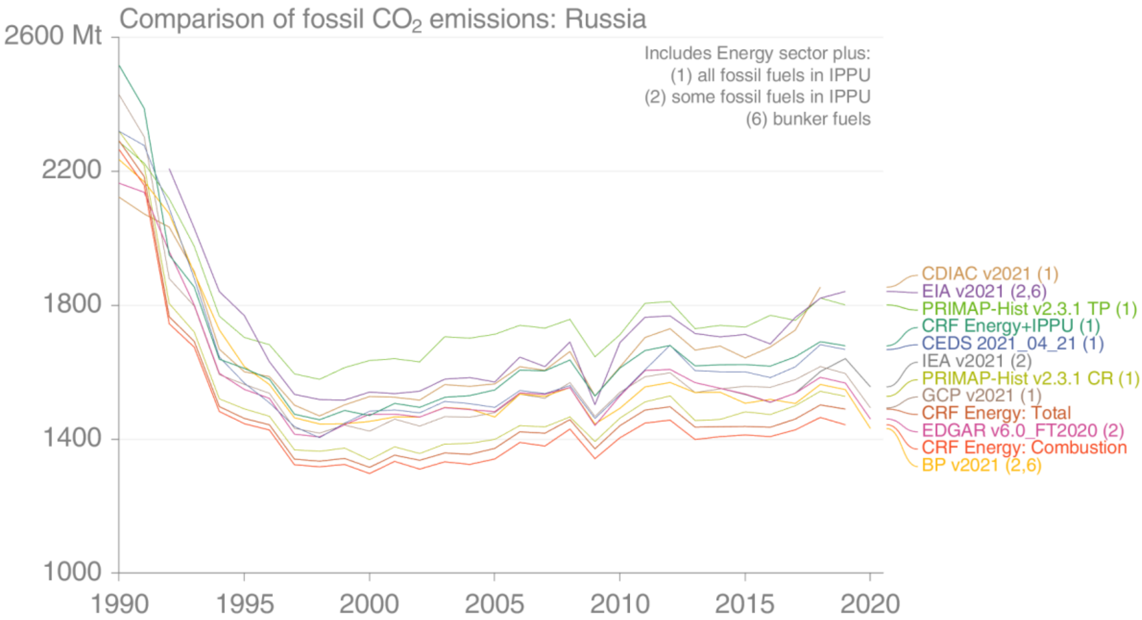
8 Annex 1: Fossil CO_2 figures

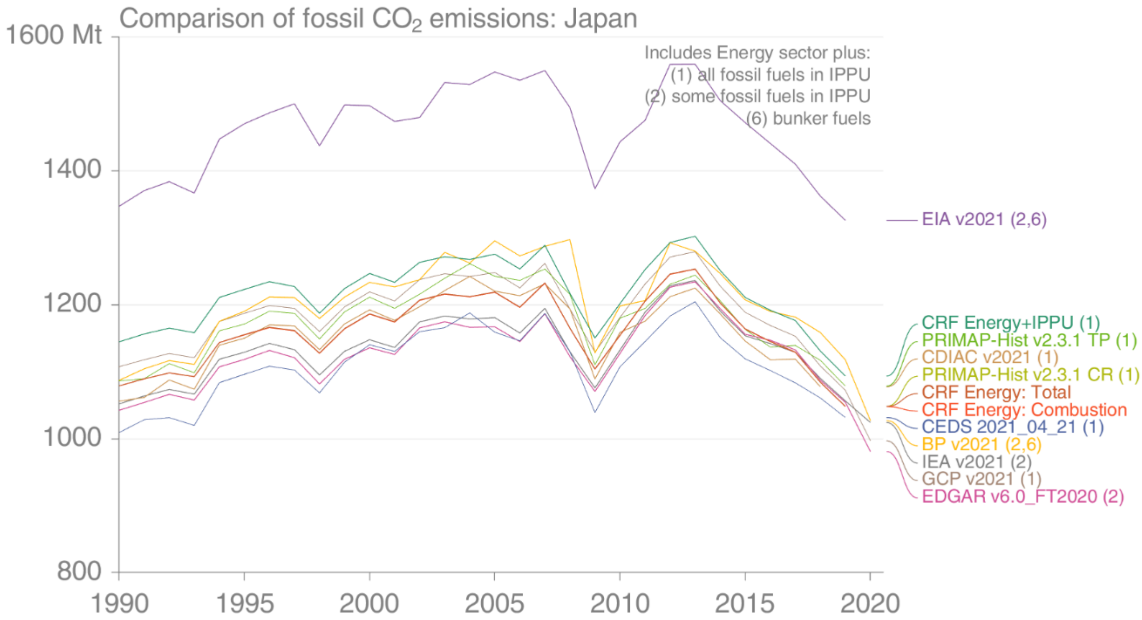
This Annex presents additional figures comparing fossil CO_2 estimates from inventory sources for the top-ten emitters globally.

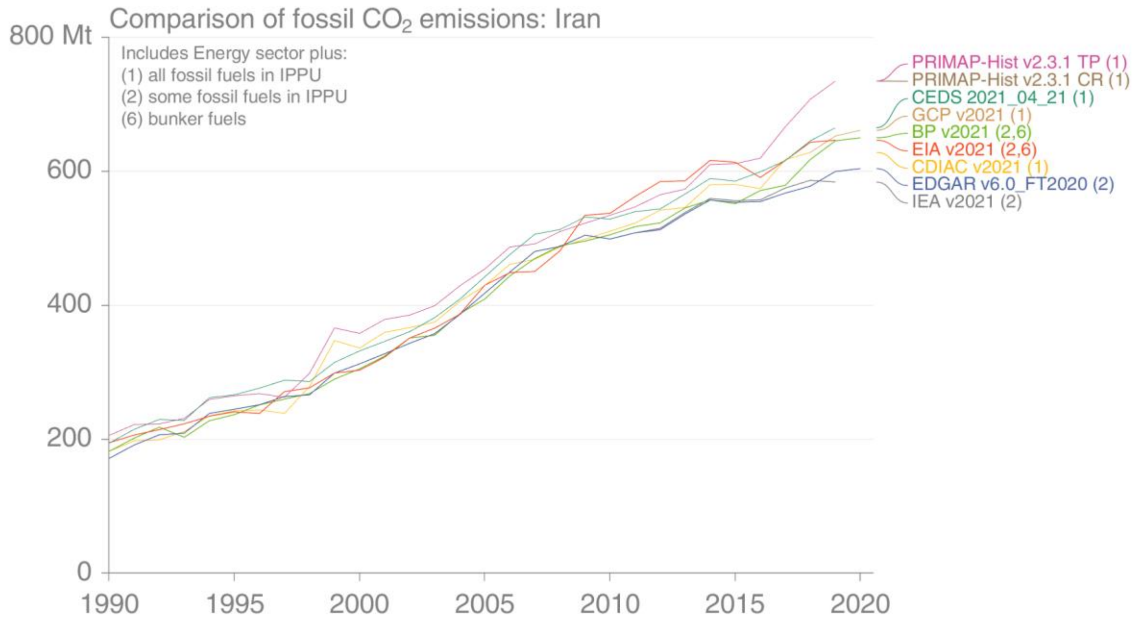


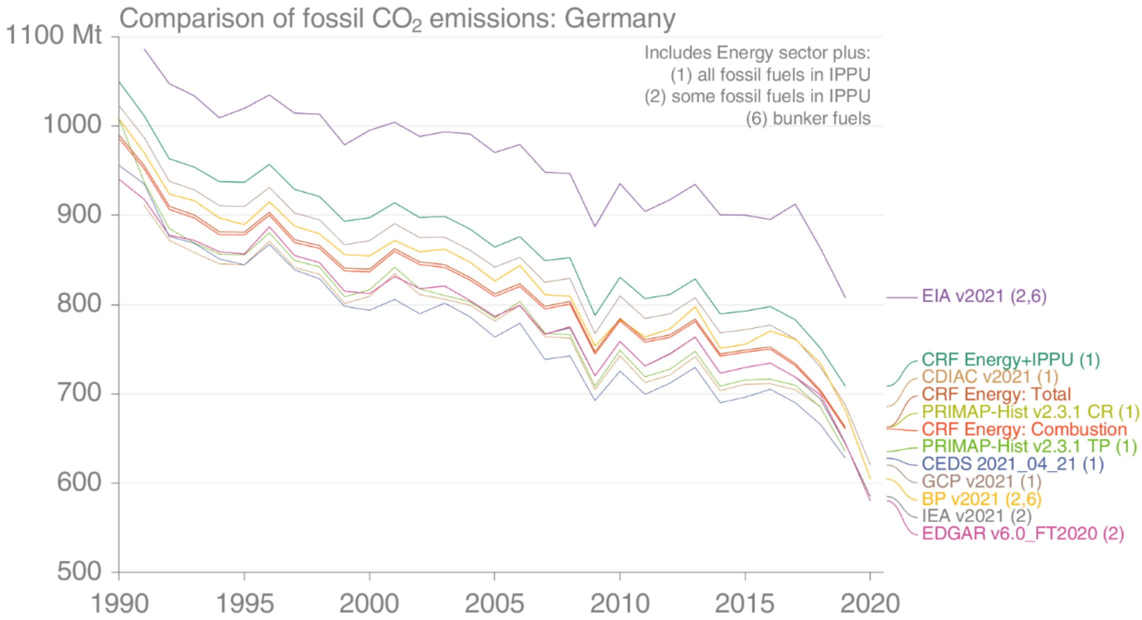


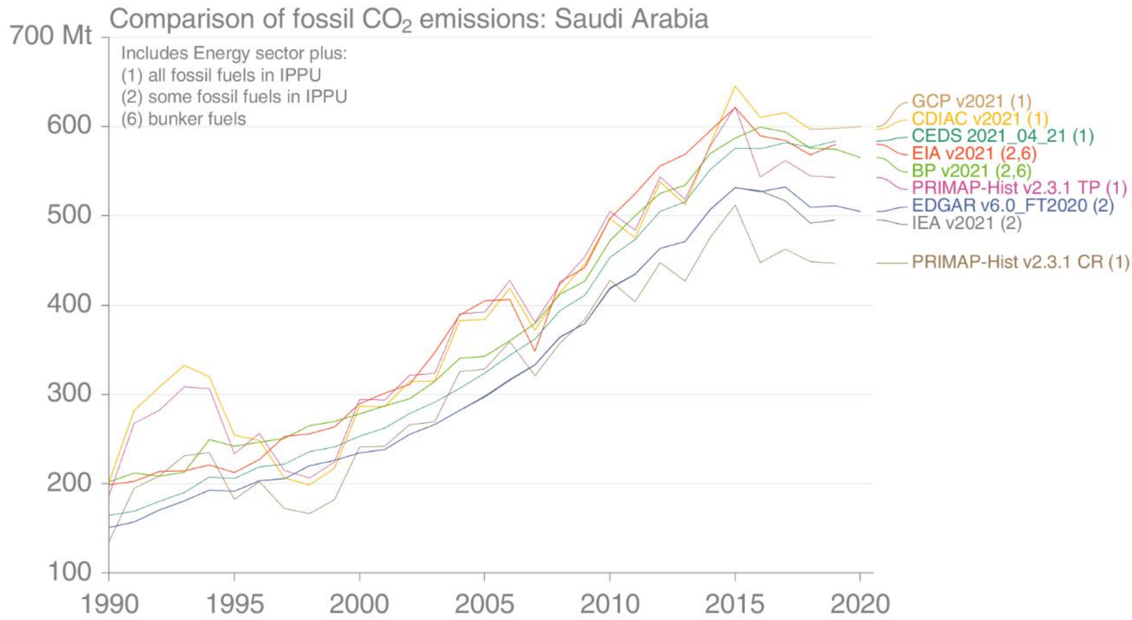

Comparison of fossil CO_2 emissions: India
2500 Mt
2000
1500
1000
500
1990
1995
2000
2005
2010
2015
2020
Includes Energy sector plus:
(1) all fossil fuels in IPPU
(2) some fossil fuels in IPPU
(6) bunker fuels
PRIMAP-Hist v2.3.1 TP (1)
CDIAC v2021 (1)
EIA v2021 (2,6)
GCP v2021 (1)
IEA v2021 (2)
CEDS 2021_04_21 (1)
PRIMAP-Hist v2.3.1 CR (1)
BP v2021 (2,6)
EDGAR v6.0_FT2020 (2)

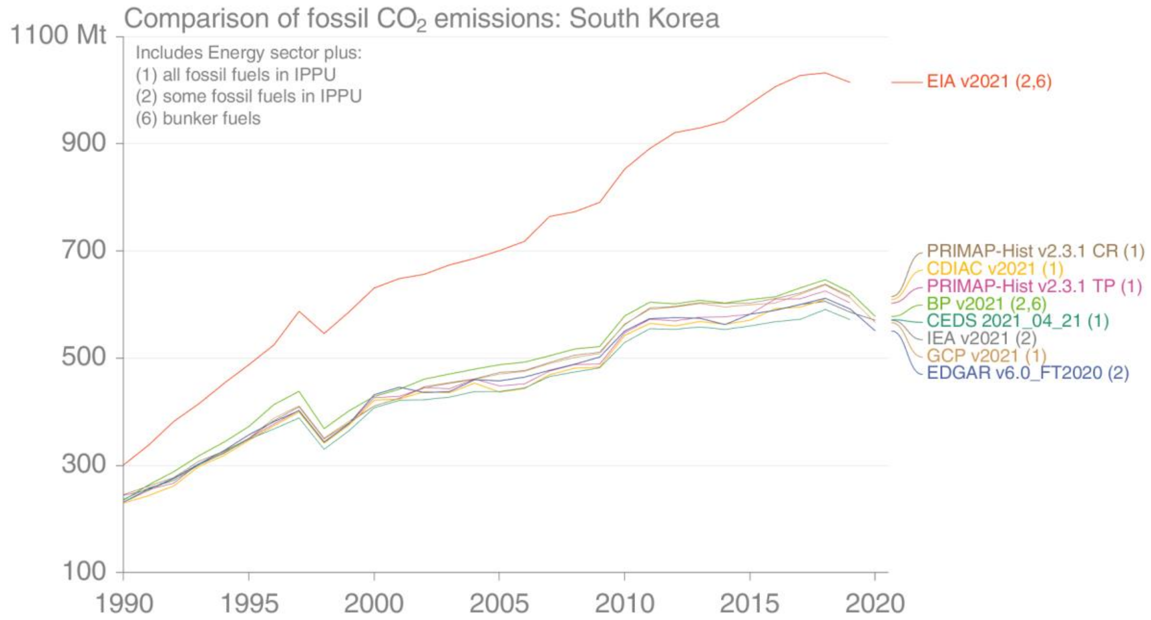

Comparison of fossil CO_2 emissions: Russia
2600 Mt
2200
1800
1400
1000
1990
1995
2000
2005
2010
2015
2020
Includes Energy sector plus:
(1) all fossil fuels in IPPU
(2) some fossil fuels in IPPU
(6) bunker fuels
CDIAC v2021 (1)
EIA v2021 (2,6)
PRIMAP-Hist v2.3.1 TP (1)
CRF Energy+IPPU (1)
CEDS 2021_04_21 (1)
IEA v2021 (2)
PRIMAP-Hist v2.3.1 CR (1)
GCP v2021 (1)
CRF Energy: Total
EDGAR v6.0_FT2020 (2)
CRF Energy: Combustion
BP v2021 (2,6)

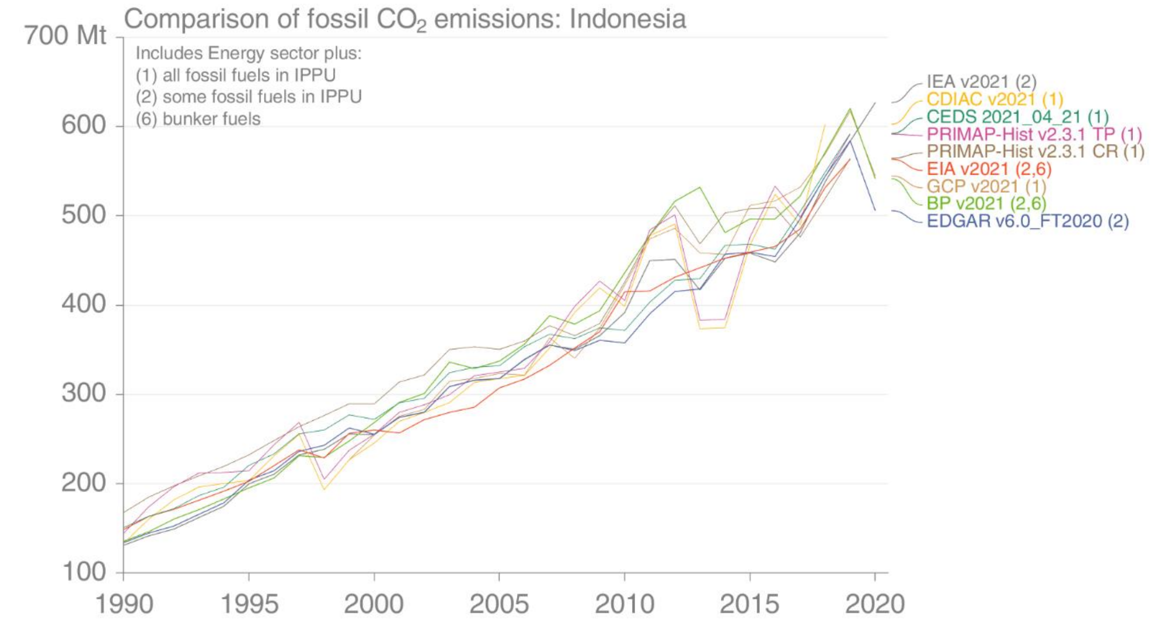

Comparison of fossil CO2 emissions: Japan
1600 Mt
1400
1200
1000
800
1990
1995
2000
2005
2010
2015
2020
Includes Energy sector plus:
(1) all fossil fuels in IPPU
(2) some fossil fuels in IPPU
(6) bunker fuels
EIA v2021 (2,6)
CRF Energy+IPPU (1)
PRIMAP-Hist v2.3.1 TP (1)
CDIAC v2021 (1)
PRIMAP-Hist v2.3.1 CR (1)
CRF Energy: Total
CRF Energy: Combustion
CEDS 2021_04_21 (1)
BP v2021 (2,6)
IEA v2021 (2)
GCP v2021 (1)
EDGAR v6.0_FT2020 (2)


Comparison of fossil CO2 emissions: Iran
800 Mt
600
400
200
0
1990
1995
2000
2005
2010
2015
2020
Includes Energy sector plus:
(1) all fossil fuels in IPPU
(2) some fossil fuels in IPPU
(6) bunker fuels
PRIMAP-Hist v2.3.1 TP (1)
PRIMAP-Hist v2.3.1 CR (1)
CEDS 2021_04_21 (1)
GCP v2021 (1)
BP v2021 (2,6)
EIA v2021 (2,6)
CDIAC v2021 (1)
EDGAR v6.0_FT2020 (2)
IEA v2021 (2)


Comparison of fossil CO2 emissions: Germany
1100 Mt
1000
900
800
700
600
500
1990
1995
2000
2005
2010
2015
2020
Includes Energy sector plus:
(1) all fossil fuels in IPPU
(2) some fossil fuels in IPPU
(6) bunker fuels
EIA v2021 (2,6)
CRF Energy+IPPU (1)
CDIAC v2021 (1)
CRF Energy: Total
PRIMAP-Hist v2.3.1 CR (1)
CRF Energy: Combustion
PRIMAP-Hist v2.3.1 TP (1)
CEDS 2021_04_21 (1)
GCP v2021 (1)
BP v2021 (2,6)
IEA v2021 (2)
EDGAR v6.0_FT2020 (2)

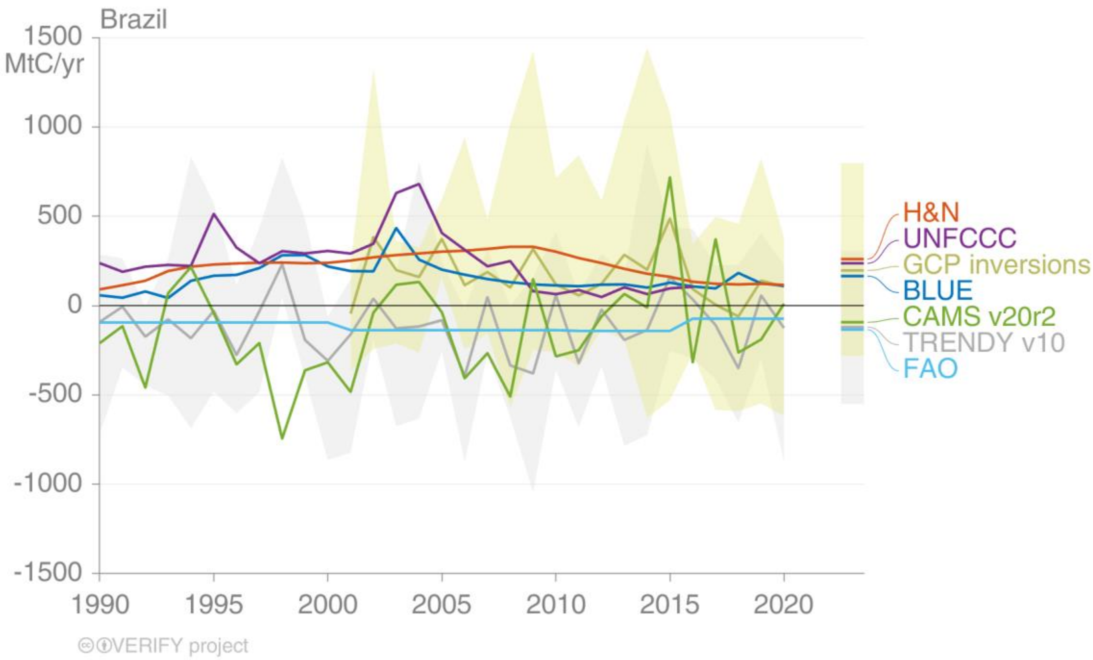

Comparison of fossil CO2 emissions: Saudi Arabia
700 Mt
600
500
400
300
200
100
1990
1995
2000
2005
2010
2015
2020
Includes Energy sector plus:
(1) all fossil fuels in IPPU
(2) some fossil fuels in IPPU
(6) bunker fuels
GCP v2021 (1)
CDIAC v2021 (1)
CEDS 2021_04_21 (1)
EIA v2021 (2,6)
BP v2021 (2,6)
PRIMAP-Hist v2.3.1 TP (1)
EDGAR v6.0_FT2020 (2)
IEA v2021 (2)
PRIMAP-Hist v2.3.1 CR (1)

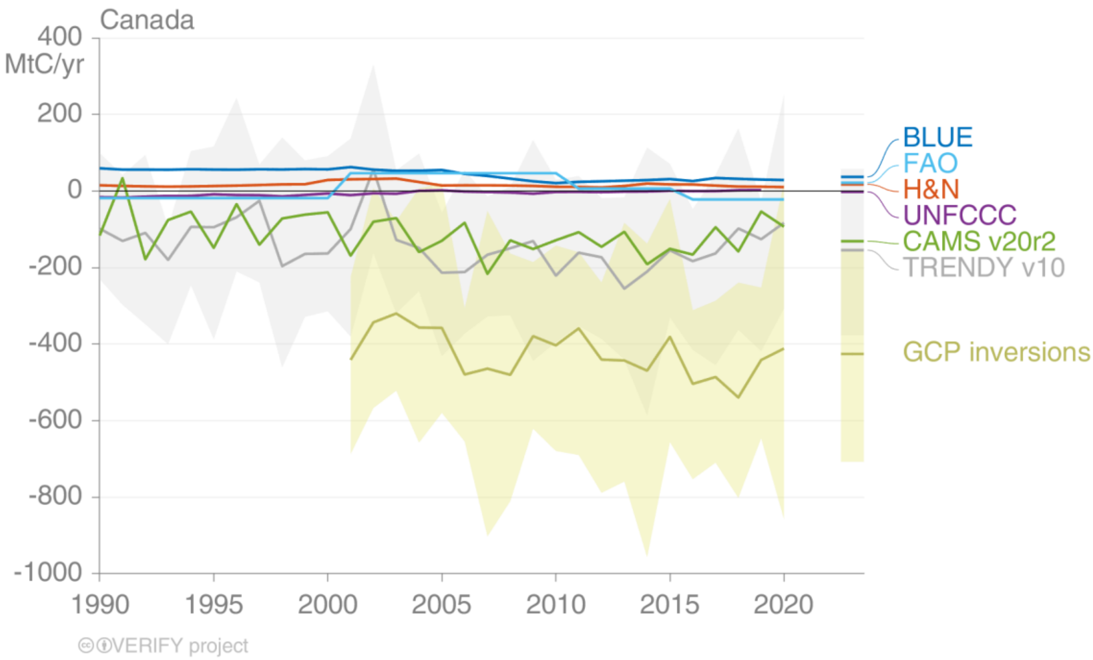

Comparison of fossil CO2 emissions: South Korea
Includes Energy sector plus:
(1) all fossil fuels in IPPU
(2) some fossil fuels in IPPU
(6) bunker fuels
1100 Mt
900
700
500
300
100
1990
1995
2000
2005
2010
2015
2020
EIA v2021 (2,6)
PRIMAP-Hist v2.3.1 CR (1)
CDIAC v2021 (1)
PRIMAP-Hist v2.3.1 TP (1)
BP v2021 (2,6)
CEDS 2021_04_21 (1)
IEA v2021 (2)
GCP v2021 (1)
EDGAR v6.0_FT2020 (2)

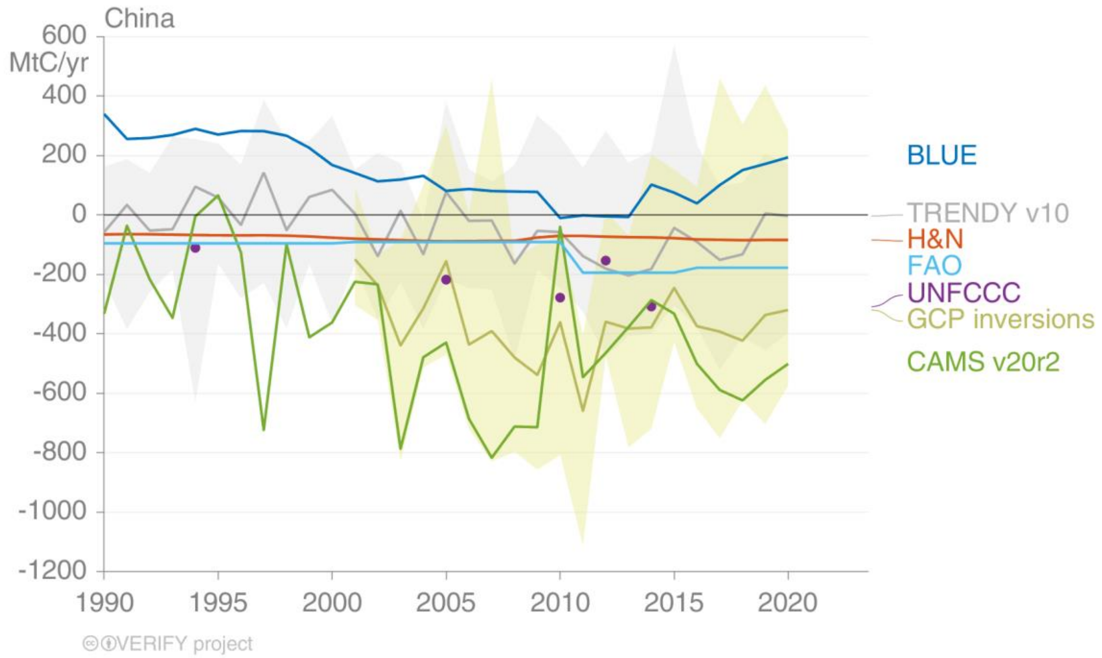

Comparison of fossil CO2 emissions: Indonesia
Includes Energy sector plus:
(1) all fossil fuels in IPPU
(2) some fossil fuels in IPPU
(6) bunker fuels
700 Mt
600
500
400
300
200
100
1990
1995
2000
2005
2010
2015
2020
IEA v2021 (2)
CDIAC v2021 (1)
CEDS 2021_04_21 (1)
PRIMAP-Hist v2.3.1 TP (1)
PRIMAP-Hist v2.3.1 CR (1)
EIA v2021 (2,6)
GCP v2021 (1)
BP v2021 (2,6)
EDGAR v6.0_FT2020 (2)

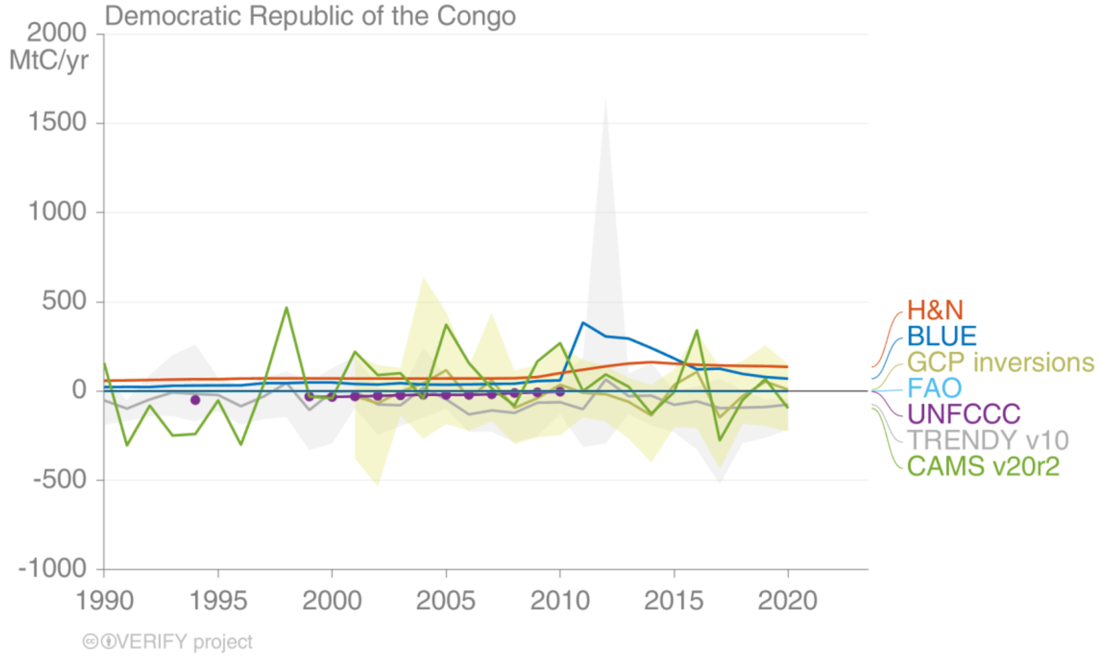
9 Annex 2: Net land CO_2 fluxes figures

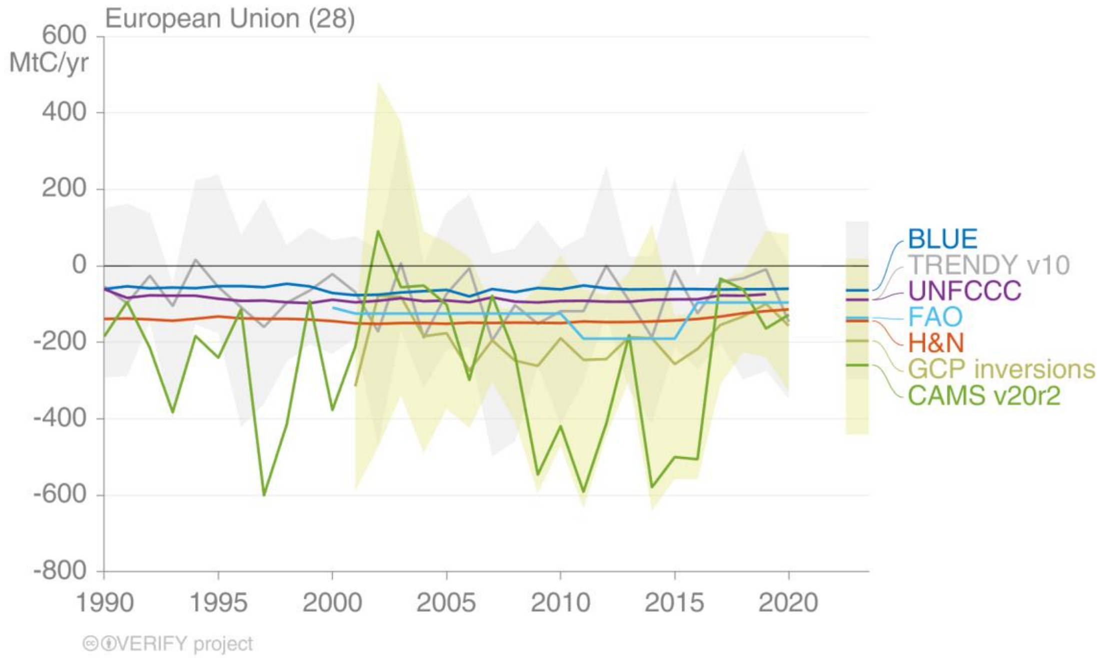
The following figures compare estimates of land-use change emissions from multiple inventories and inversions sources. H&N is Houghton and Nassikas (2017), updated for GCB 2021; BLUE is Hansis et al. (2015) updated for GCB 2021; the GCP inversions are those presented in GCB 2021; TRENDY v10 is the TRENDY set collated for GCB 2021; FAO are FAOSTAT data as downloaded in February 2022; UNFCCC shows estimates officially reported to the UNFCCC, and where these are time-series they are from the most recent submissions (2021 for Annex 1 countries); CAMS v20r2 is from Chevallier (2021). GCB 2021 is presented by Friedlingstein et al. (2021). Means over the period in common between all datasets are shown for countries that report more than point estimates to the UNFCCC (i.e., not for Congo, China, or India).

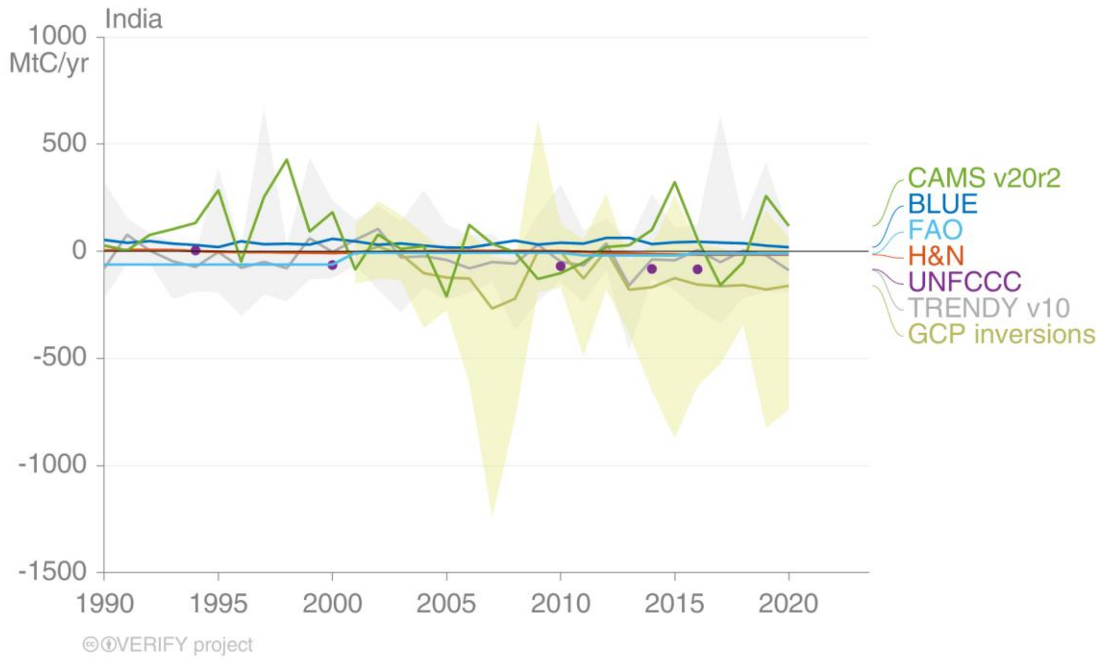


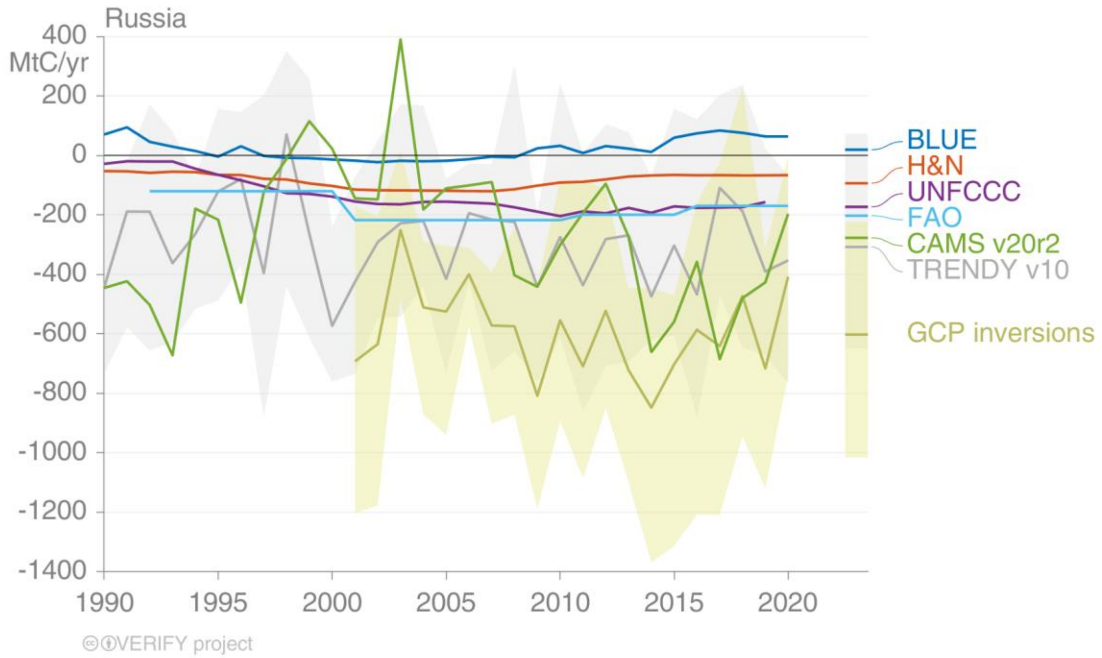


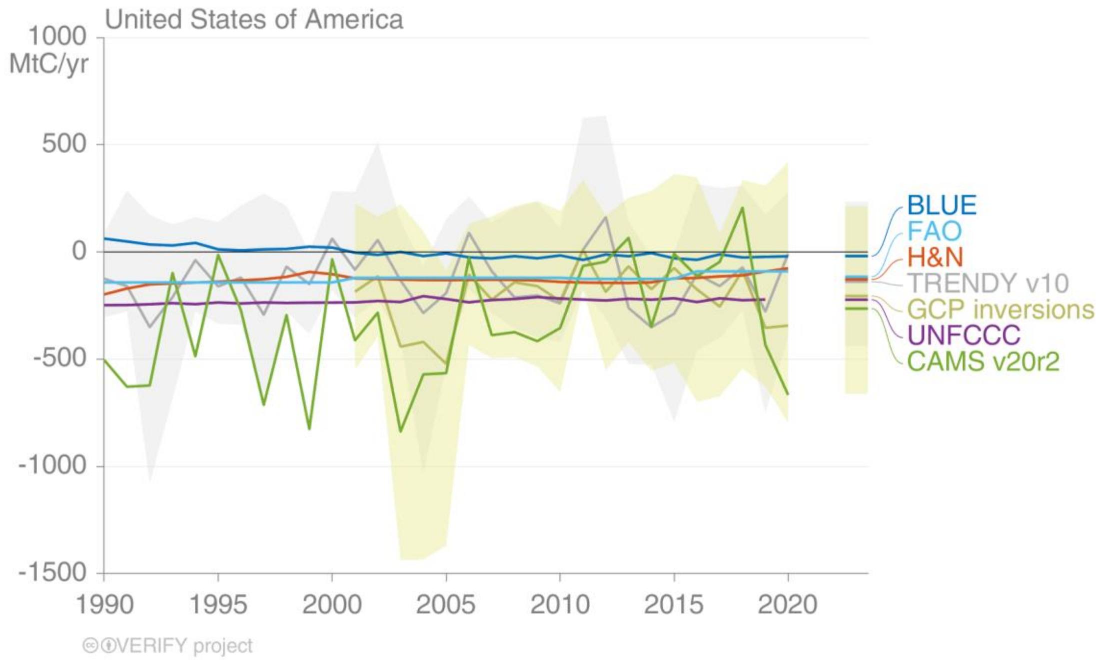

China
600
MtC/yr
400
200
0
-200
-400
-600
-800
-1000
-1200
1990
1995
2000
2005
2010
2015
2020
©VERIFY project
BLUE
TRENDY v10
H&N
FAO
UNFCCC
GCP inversions
CAMS v20r2


Democratic Republic of the Congo
2000
MtC/yr
1500
1000
500
0
-500
-1000
1990
1995
2000
2005
2010
2015
2020
©VERIFY project
H&N
BLUE
GCP inversions
FAO
UNFCCC
TRENDY v10
CAMS v20r2


European Union (28)
600
MtC/yr
400
200
0
-200
-400
-600
-800
1990
1995
2000
2005
2010
2015
2020
BLUE
TRENDY v10
UNFCCC
FAO
H&N
GCP inversions
CAMS v20r2
VERIFY project


India
1000
MtC/yr
500
0
-500
-1000
-1500
1990
1995
2000
2005
2010
2015
2020
CAMS v20r2
BLUE
FAO
H&N
UNFCCC
TRENDY v10
GCP inversions
VERIFY project


Russia
400
MtC/yr
200
0
-200
-400
-600
-800
-1000
-1200
-1400
1990
1995
2000
2005
2010
2015
2020
BLUE
H&N
UNFCCC
FAO
CAMS v20r2
TRENDY v10
GCP inversions
VERIFY project


United States of America
1000
MtC/yr
500
0
-500
-1000
-1500
1990
1995
2000
2005
2010
2015
2020
BLUE
FAO
H&N
TRENDY v10
GCP inversions
UNFCCC
CAMS v20r2
VERIFY project

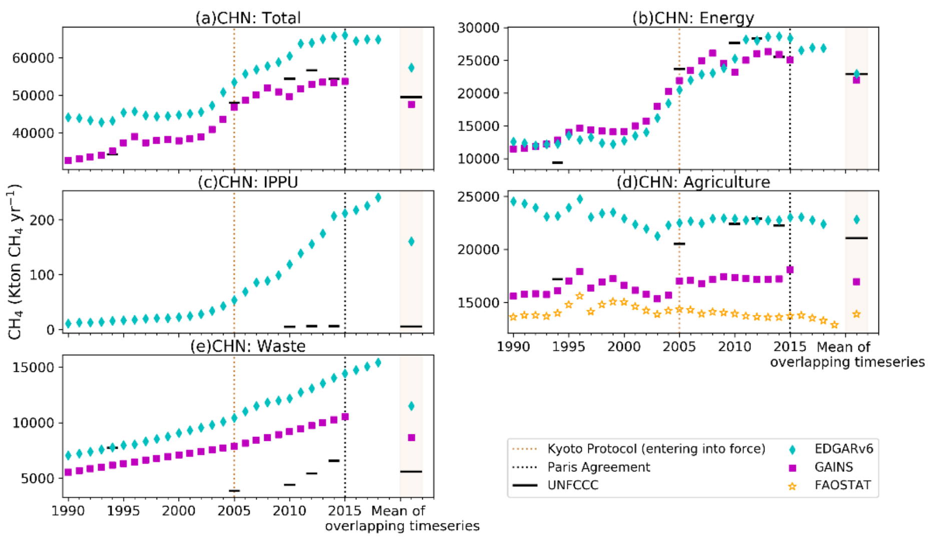
10 Annex 3: CH_4 figures

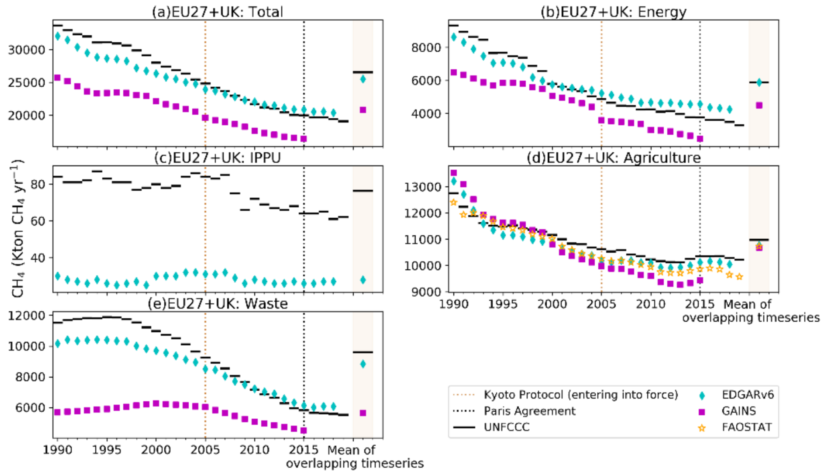
This Annex presents additional figures comparing CH_4 estimates from inventories and inversions sources for the top emitters globally.

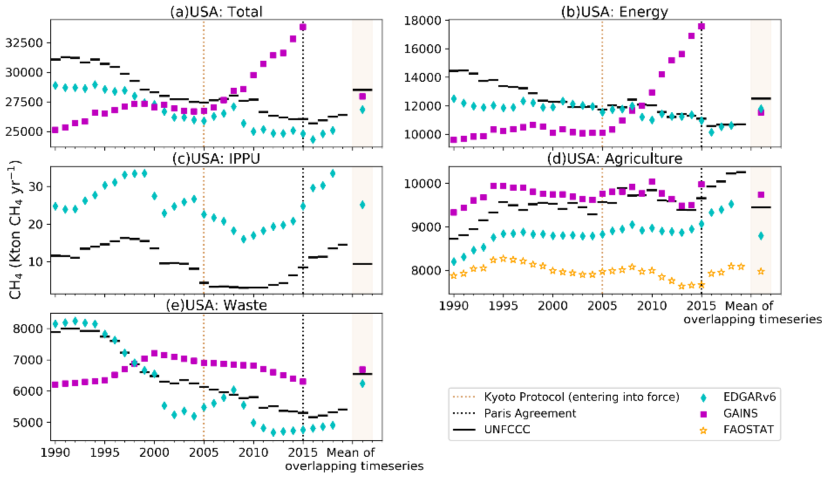
Table 6: Comparison between three inventories and inversion estimates (Deng et al., 2021, SURF and GOSAT inversions, 4 methods) (Tg CH_4 yr^{-1})

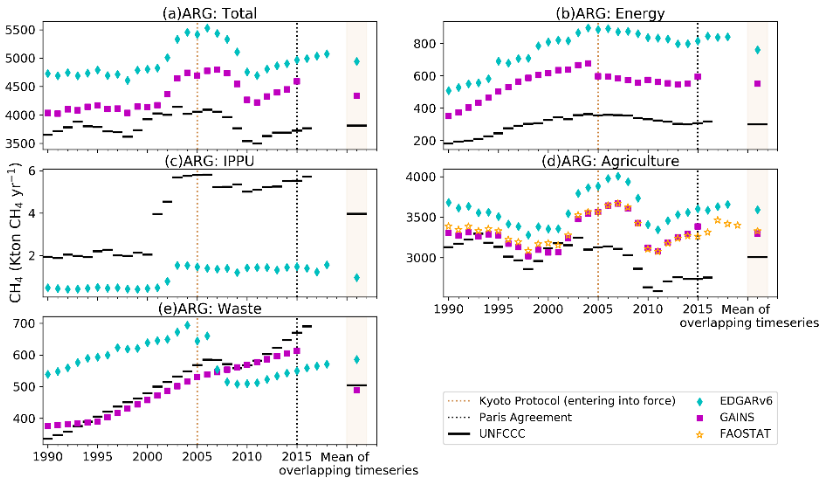
			Inversions estimates (Tg CH4 yr-1)							
Total anthropogenic, inventories (Tg CH4 yr-1)			Deng et al., 2020 method 1		Deng et al., 2020 method 2		Deng et al., 2020 method 3.1		Deng et al., 2020 method 3.2	
UNFCCC	EDGARv6	GAINS	SURF	GOSAT	SURF	GOSAT	SURF	GOSAT	SURF	GOSAT
55.00	64.47	51.67	43.67	53.03	45.89	51.36	51.05	53.55	47.07	49.50
26.32	24.98	30.19	29.02	26.05	24.86	19.04	31.53	28.79	27.61	24.87
19.92	28.01	30.12	31.5	28.02	30.39	28.06	37.69	30.04	34.14	26.48
20.22	21.42	17.69	20.32	20.07	15.54	16.03	16.07	16.37	14.22	14.52
16.37	20.91	16.15	21.8	23.04	21.67	22.65	30.06	38.23	20.56	28.73
12.44	15.27	29.73	18.9	17.6	17.01	16.06	22.8	19.08	22.87	19.16
8.29	12.02	9.91	12.05	10.7	11.78	9.46	7.47	10.72	7.58	10.83
6.42	6.46	4.6	4.95	4.64	5.16	4.36	3.81	3.35	4.51	4.05
6.33	7.04	6.05	6.33	4.86	6.89	4.91	7.03	5.43	7.04	5.44
4.15	4.92	4.59	4.52	4.98	3.62	3.76	2.11	2.55	3.64	4.09
3.65	4.77	4.51	4.28	5.06	3.71	3.91	3.49	3.61	6.25	6.37
average 2010-last year			average 2010-last year							

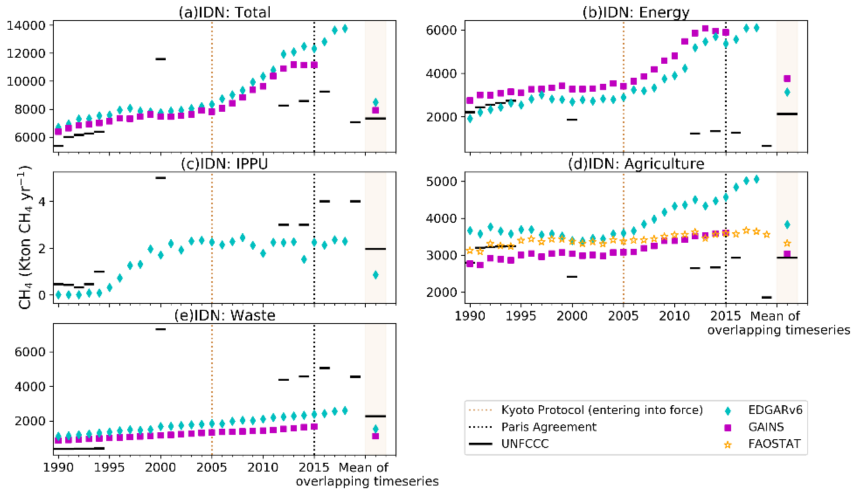
Figures with total and sectoral CH_4 anthropogenic emissions from inventory estimates (Tg CH_4 yr^{-1}), for the top emitter countries:

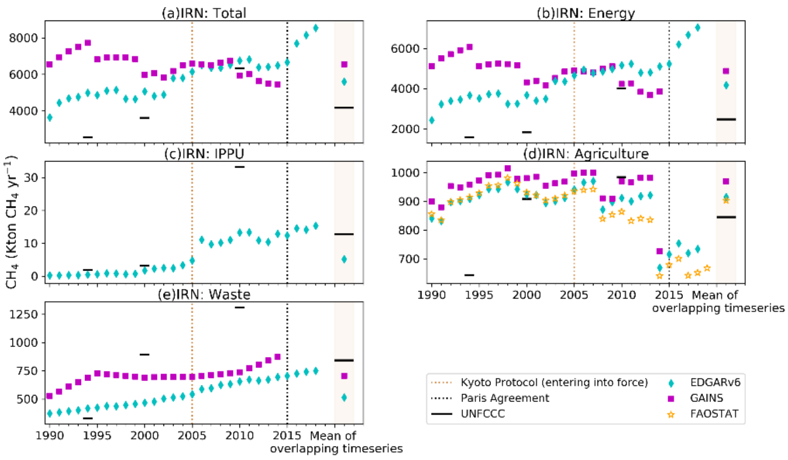


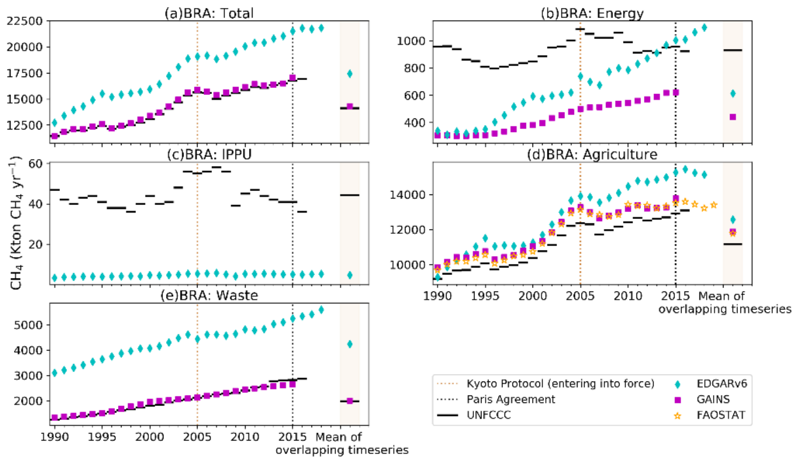

(a)EU27+UK: Total
(b)EU27+UK: Energy
(c)EU27+UK: IPPU
(d)EU27+UK: Agriculture
(e)EU27+UK: Waste
CH$_4$ (Kton CH$_4$ yr^{-1})
1990 1995 2000 2005 2010 2015 Mean of overlapping timeseries
Kyoto Protocol (entering into force)
Paris Agreement
UNFCCC
EDGARv6
GAINS
FAOSTAT

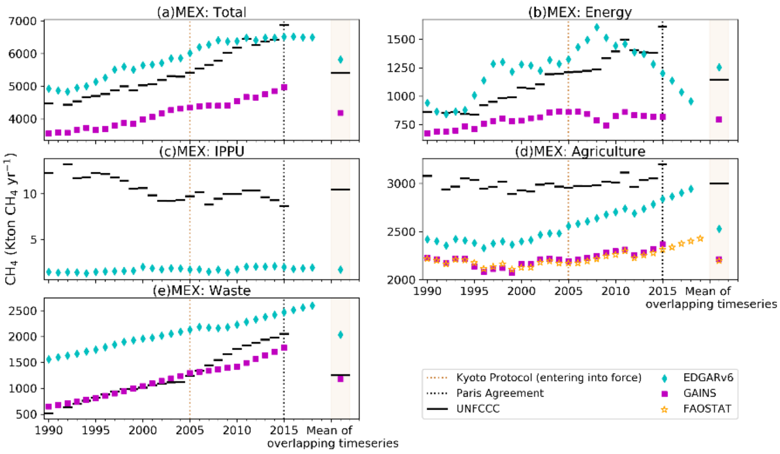

(a)USA: Total
(b)USA: Energy
(c)USA: IPPU
(d)USA: Agriculture
(e)USA: Waste
CH$_4$ (Kton CH$_4$ yr^{-1})
1990 1995 2000 2005 2010 2015 Mean of overlapping timeseries
Kyoto Protocol (entering into force)
Paris Agreement
UNFCCC
EDGARv6
GAINS
FAOSTAT

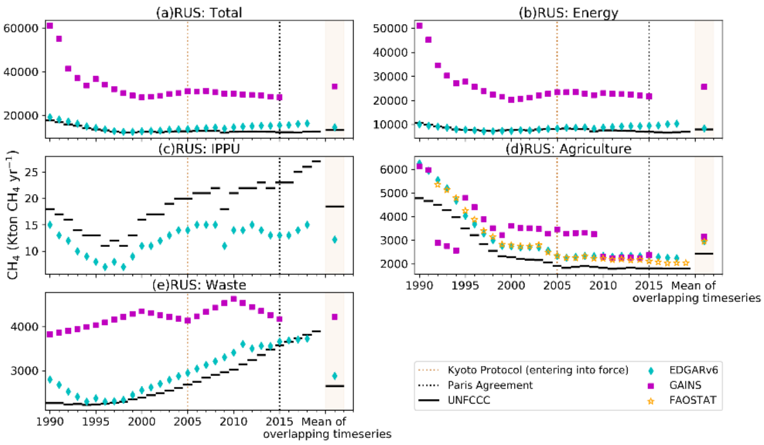

(a)ARG: Total
(b)ARG: Energy
(c)ARG: IPPU
(d)ARG: Agriculture
(e)ARG: Waste
CH$_4$ (Kton CH$_4$ yr^{-1})
1990 1995 2000 2005 2010 2015 Mean of overlapping timeseries
Kyoto Protocol (entering into force)
Paris Agreement
UNFCCC
EDGARv6
GAINS
FAOSTAT


(a)IDN: Total
(b)IDN: Energy
(c)IDN: IPPU
(d)IDN: Agriculture
(e)IDN: Waste
CH$_4$ (Kton CH$_4$ yr^{-1})
1990 1995 2000 2005 2010 2015 Mean of overlapping timeseries
Kyoto Protocol (entering into force)
Paris Agreement
UNFCCC
EDGARv6
GAINS
FAOSTAT

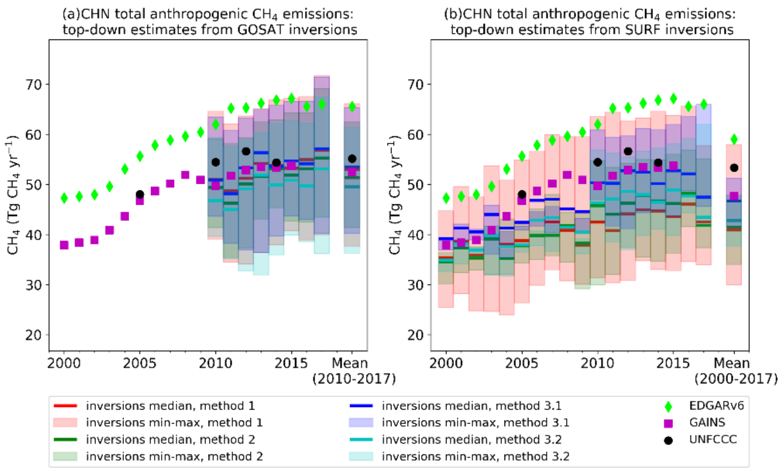

(a)IRN: Total
(b)IRN: Energy
(c)IRN: IPPU
(d)IRN: Agriculture
(e)IRN: Waste
CH$_4$ (Kton CH$_4$ yr^{-1})
1990 1995 2000 2005 2010 2015 Mean of overlapping timeseries
Kyoto Protocol (entering into force)
Paris Agreement
UNFCCC
EDGARv6
GAINS
FAOSTAT

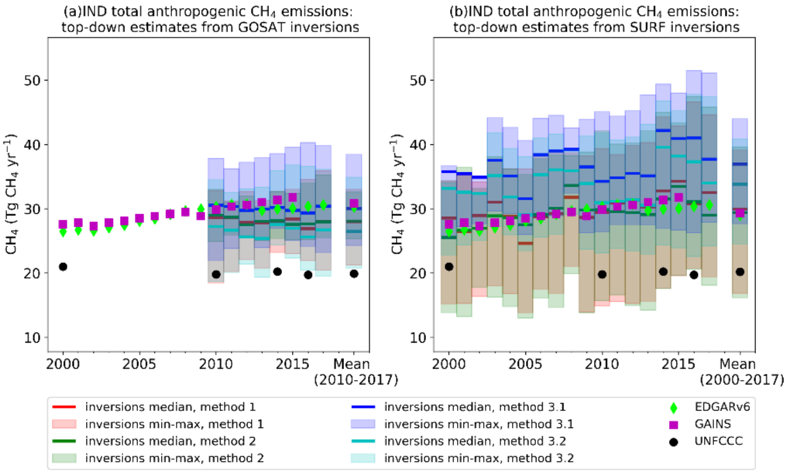

(a)BRA: Total
(b)BRA: Energy
(c)BRA: IPPU
(d)BRA: Agriculture
(e)BRA: Waste
CH$_4$ (Kton CH$_4$ yr^{-1})
1990 1995 2000 2005 2010 2015 Mean of overlapping timeseries
Kyoto Protocol (entering into force)
Paris Agreement
UNFCCC
EDGARv6
GAINS
FAOSTAT

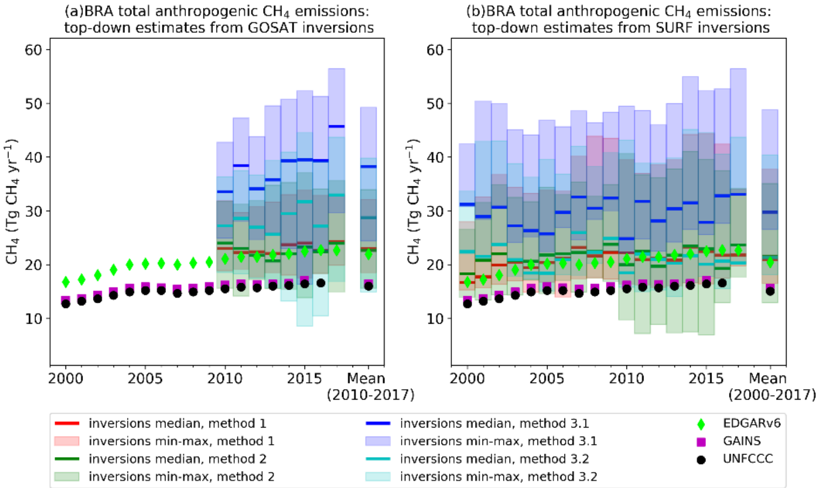


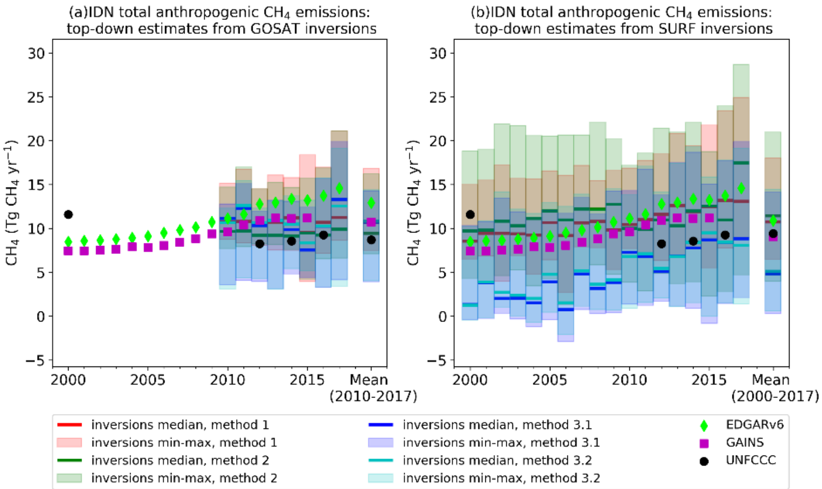


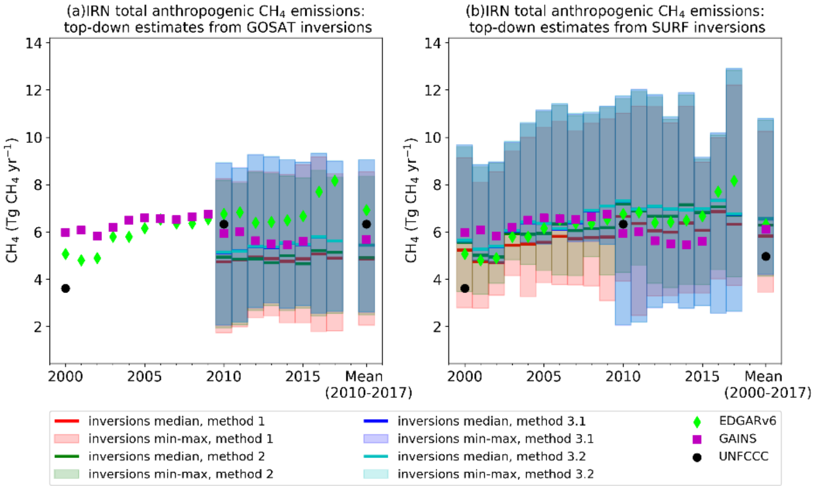
Figures with total anthropogenic CH_4 emissions from inventories vs inversions estimates (Tg CH_4 yr^{-1}), for the top emitter countries:

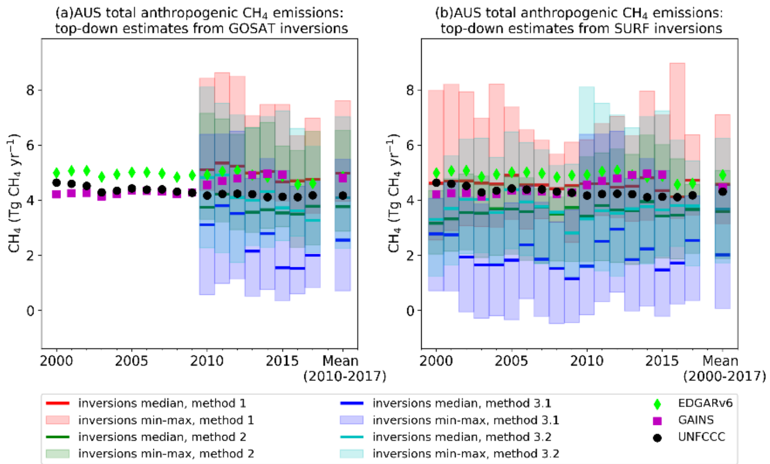


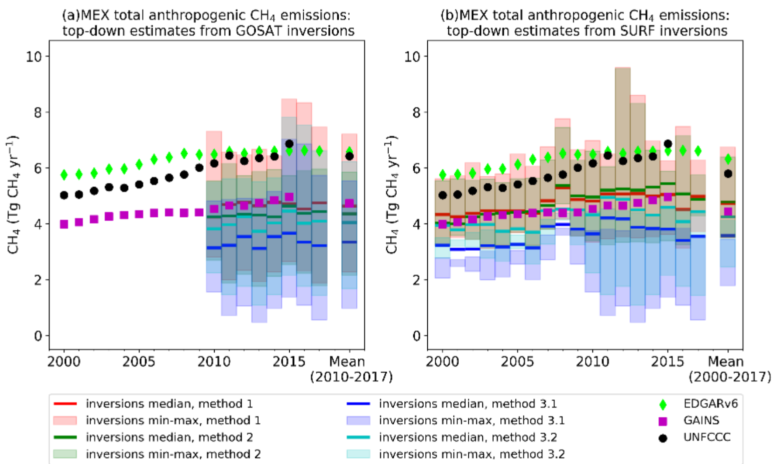

(a)IND total anthropogenic CH4 emissions: top-down estimates from GOSAT inversions
(b)IND total anthropogenic CH4 emissions: top-down estimates from SURF inversions
CH4 (Tg CH4 yr−1)
Mean (2010-2017)
Mean (2000-2017)
inversions median, method 1
inversions min-max, method 1
inversions median, method 2
inversions min-max, method 2
inversions median, method 3.1
inversions min-max, method 3.1
inversions median, method 3.2
inversions min-max, method 3.2
EDGARv6
GAINS
UNFCCC

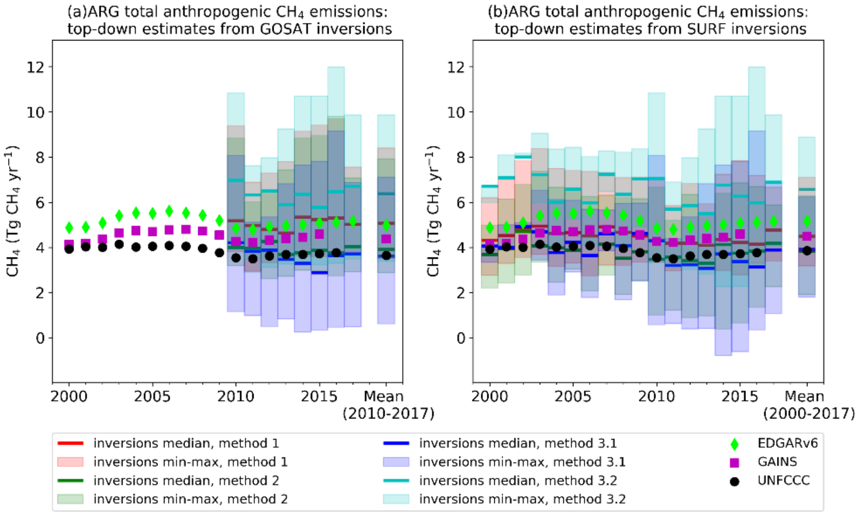

(a)BRA total anthropogenic CH4 emissions: top-down estimates from GOSAT inversions
(b)BRA total anthropogenic CH4 emissions: top-down estimates from SURF inversions
CH4 (Tg CH4 yr−1)
Mean (2010-2017)
Mean (2000-2017)
inversions median, method 1
inversions min-max, method 1
inversions median, method 2
inversions min-max, method 2
inversions median, method 3.1
inversions min-max, method 3.1
inversions median, method 3.2
inversions min-max, method 3.2
EDGARv6
GAINS
UNFCCC


(a)IDN total anthropogenic CH4 emissions: top-down estimates from GOSAT inversions
(b)IDN total anthropogenic CH4 emissions: top-down estimates from SURF inversions
CH4 (Tg CH4 yr−1)
Mean (2010-2017)
Mean (2000-2017)
inversions median, method 1
inversions min-max, method 1
inversions median, method 2
inversions min-max, method 2
inversions median, method 3.1
inversions min-max, method 3.1
inversions median, method 3.2
inversions min-max, method 3.2
EDGARv6
GAINS
UNFCCC


(a)IRN total anthropogenic CH4 emissions: top-down estimates from GOSAT inversions
(b)IRN total anthropogenic CH4 emissions: top-down estimates from SURF inversions
CH4 (Tg CH4 yr−1)
Mean (2010-2017)
Mean (2000-2017)
inversions median, method 1
inversions min-max, method 1
inversions median, method 2
inversions min-max, method 2
inversions median, method 3.1
inversions min-max, method 3.1
inversions median, method 3.2
inversions min-max, method 3.2
EDGARv6
GAINS
UNFCCC


(a)AUS total anthropogenic CH4 emissions: top-down estimates from GOSAT inversions
(b)AUS total anthropogenic CH4 emissions: top-down estimates from SURF inversions
CH4 (Tg CH4 yr−1)
Mean (2010-2017)
Mean (2000-2017)
inversions median, method 1
inversions min-max, method 1
inversions median, method 2
inversions min-max, method 2
inversions median, method 3.1
inversions min-max, method 3.1
inversions median, method 3.2
inversions min-max, method 3.2
EDGARv6
GAINS
UNFCCC


(a)MEX total anthropogenic CH4 emissions: top-down estimates from GOSAT inversions
(b)MEX total anthropogenic CH4 emissions: top-down estimates from SURF inversions
CH4 (Tg CH4 yr−1)
Mean (2010-2017)
Mean (2000-2017)
inversions median, method 1
inversions min-max, method 1
inversions median, method 2
inversions min-max, method 2
inversions median, method 3.1
inversions min-max, method 3.1
inversions median, method 3.2
inversions min-max, method 3.2
EDGARv6
GAINS
UNFCCC


(a)ARG total anthropogenic CH4 emissions:
top-down estimates from GOSAT inversions
(b)ARG total anthropogenic CH4 emissions:
top-down estimates from SURF inversions
CH4 (Tg CH4 yr−1)
Mean
(2010-2017)
(2000-2017)
inversions median, method 1
inversions min-max, method 1
inversions median, method 2
inversions min-max, method 2
inversions median, method 3.1
inversions min-max, method 3.1
inversions median, method 3.2
inversions min-max, method 3.2
EDGARv6
GAINS
UNFCCC