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Horizon 2020 Societal challenge 5:
Climate action, environment, resource
efficiency and raw materials

VERIFY

Observation-based system for monitoring and verification of greenhouse gases

GA number 776810, RIA

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Internal reviewer:	/

1. Changes with respect to the DoA

The fast-track inversion of the national scale CO_2 anthropogenic emissions was supposed to cover 10 years (2005-2015) of emissions and the whole VERIFY European domain. However, the corresponding deliverable D2.10 covers the period 2012-2015 and Western Europe only. This is due to the much higher cost of the computations compared to what was initially anticipated and to the need to revise and improve the initial system design in order to benefit from recently available products/information (typically updated inventories for the prior knowledge of the inversion system and updated CO/CO_2 and $NO2/CO_2$ emission ratios) for other periods of time.

2. Dissemination and uptake

The results of the fast-track inversion will be used to evaluate and improve the design and potential of the atmospheric inversion in task 2.3 of WP2, and as a support to the assessment of the TNO inventory from task 2.1 of WP2 in the first synthesis of the national estimates in WP5. This public deliverable will thus be used within several WPs of VERIFY and it will be made available to the public via the VERIFY web-site and its catalogue of products.

3. Short Summary of results (<250 words)

In order to provide first inversions of the fossil fuel CO_2 ($ffCO_2$) emissions in Europe during the first years of the project, while the development of the main inversion system for this task 2.3 by LSCE in tasks 2.3.1 to 2.3.3 should last more than 2 years, IAP-RAS has extended the inversions documented in Konovalov et al. (2016), with some modifications of the corresponding inversion system. The inversion targets the annual budgets of $ffCO_2$ emissions over 11 EU countries (Portugal, Spain, France, Belgium, Luxembourg, Netherlands, UK, Germany, Denmark, Italy, Austria) and Switzerland based on the assimilation of total column CO from IASI, and tropospheric column NO_2 from OMI (over a modeling domain slightly larger than the EU 11+ Switzerland domain). The results indicate that the uncertainty in the information from the CO inversion is too high to provide reliable estimates of the $ffCO_2$ emissions when using CO satellite data only, or to provide weight to this information when using $ffCO_2$ estimates from both the CO and NO_x inversions. The estimates based on NO_2 data diverge significantly from that in EDGAR v4.3.2 for the energy, heat and industry production and transport sectors, but they are close to this inventory in terms of total emissions for 2012. These estimates are quite constant over the 4-year period while we assume that the $ffCO_2$ emissions followed a significant negative trend during this period. The analysis shows that the uncertainties in these estimates can explain the difficulty to detect such a trend.

4. Evidence of accomplishment

(report, manuscript, web-link, other)

Maps of annual $ffCO_2$ emissions from the inversion have been sent by IAP-RAS and are available through the VERIFY website, first for the VERIFY partners before a release to the public.

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Version	Date	Description	Author (Organisation)
V0	02/07/19	Creation/Writing	I. Konovalov and D. A. Lvova (IAP-RAS)
V1	25/07/19	Writing/Formatting/Delivery on the Participant Portal	Grégoire Broquet and Philippe Peylin (CEA)

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1. Introduction

1.1. Preamble

The goal of the research work presented in this report was to obtain robust annual estimates of CO_2 emissions from fossil fuel (FF) burning in a western European region including 11 EU countries and Switzerland over a four-year period (2012-2015) by using satellite measurements of NO_2 tropospheric column amounts and CO column amounts. This report contains the description of the data and methodology used in the research work and the obtained estimates of the total annual FF CO_2 emissions along with their uncertainties.

1.2. Background

In recent years, significant efforts have been devoted to developing of methods that could provide observational constraints to available FF emission estimates given by emission inventories and allow independent evaluation of CO_2 emission inventories. However, neither of the available methods has so far been sufficiently generalized to provide reliable observation-based estimates of the budget of FF CO_2 emissions in an arbitrary industrialized region of the world.

A key idea of the method used in this work is to indirectly constrain FF CO_2 emissions by using measurements of "proxy" species, whose sources are mostly collocated in time and space with CO_2 sources. Similar ideas were successfully exploited in several previous studies (e.g., Rivier et al., 2006; Suntharalingam, 2004; Palmer et al., 2006; Brioude et al., 2012; Berezin et al. 2013; Konovalov et al., 2014; 2016). The method includes several major steps, such as: (1) inferring "top-down" estimates of total anthropogenic emissions of NO_x and CO from satellite measurements of the corresponding proxy species by using simulations performed with a mesoscale chemistry transport model (CTM), (2) applying NO_x-to-CO_2 (or CO-to-CO_2) emission conversion factors given by "bottom-up" emission inventories to relate FF CO_2 emissions to the NO_x and CO anthropogenic emissions from the previous step, (3) cross-validation and optimal combination of estimates of the FF CO_2 emission budgets derived from measurements of different proxy species. The main results of the analysis are "hybrid" FF CO_2 emission estimates integrating information coming from measurements and bottom up inventories.

2. Data

2.1. Satellite observations

The analysis described below was based on the same satellite data as in Konovalov et al. (2016). Specifically, we used the Level 2 tropospheric NO_2 column retrievals from measurements of the Earth's back scattered radiation in visible and ultraviolet spectral regions by the OMI satellite instrument (Levelt et al., 2006) onboard the NASA EOS Aura spacecraft. The OMI instrument has a swath width of ~2600 km divided into 60 pixels with a size of 13-26 km. The retrievals used in this study were available from the Royal Netherlands Meteorological Institute (KNMI) as the DOMINO version 2 data product (Boersma et al., 2011) through the TEMIS portal http://www.temis.nl. The initial processing of the original satellite data included their re-

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gridding onto the 0.5º×0.5º grid of a chemistry-transport model (see Sect. 2.2) and application of the recommended screening criteria (only data retrieved for the scenes with the cloud fraction less than 30 % and with the surface albedo less than 0.3 were used). The time series of the daily mean tropospheric NO_2 columns averaged over the study region are shown in Fig. 1a. The maps of the seasonally averaged tropospheric NO_2 columns for the study region are presented below in Appendix 1.

We also used the Level 2 retrievals of total CO column amounts from the measurements performed by the Infrared Atmospheric Sounding Interferometer (IASI) on board the METOP-A satellite (Clerbaux et al., 2009). The IASI instrument provides global coverage twice a day (around 9:30 and 21:30 LST) with a swath of about 2×1100 km and a nominal pixel diameter footprint on the ground of 12 km. The data were pre-selected based on values of the Degree of Freedom of the Signal (DOFS) parameter, which characterizes sensitivity of the spectral observations to the CO concentration in the boundary layer. Taking into account that, on the one hand, distinguishing between the upper and lower troposphere requires this parameter to be about 2 (George et al., 2009), and, on the other hand, that the number of available data with DOFS larger than 2 is very limited, the DOFS threshold was set to be 1.9 (that is, the retrievals with smaller DOFS values were disregarded. Using this value was found to result in more reliable emission estimates than the DOFS threshold of 1.7, which was used by Konovalov et al. (2016). The time series of the daily mean CO columns averaged over the study region are shown in Fig. 1b. The maps of the seasonally averaged CO columns for the study region are presented in Appendix 2.

2.2. Model data

The relationships between NO_x and CO emissions and, respectively, NO_2 and CO column amounts were simulated using the latest available version (version 2017r4) of the CHIMERE chemistry transport model (Mailler et al., 2017). The model configuration (including the spatial resolution, chemical mechanism and boundary conditions) was the same as in Konovalov et al. (2016), except that the top of the model grid was extended from 200 hPa up to 150 hPa pressure level. The CHIMERE model was coupled (off-line) with the WRF-ARW (v3.9) meteorological model which was run with a spatial resolution of 50×50 km^2 and driven with the FNL NCAR reanalysis data.

The model was run with varying anthropogenic emissions (see Sect. 3) for the period from December 21, 2011 to December 30, 2015. The first 11 days of the runs constituted the spin-up period and therefore were withheld from the following analysis. To enable consistency of our simulations with the satellite data employed in this study, the CHIMERE outputs were matched to the observations in space and time (on hourly bases) and were processed (as explained in Konovalov et al., 2016) by using the averaging kernels provided with both the NO_2 and CO satellite data.

2.3. Emission data sets

The CHIMERE runs were forced by the EMEP/CEIP anthropogenic emissions for the year 2014 (updated in 2016), which were originally provided on the same (0.5º×0.5º) grid as the one used

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in CHIMERE. The data were obtained from the EMEP/CEIP website (http://www.ceip.at/ms/ceip_home1/ceip_home). The anthropogenic emissions were aggregated into the same two categories as in Konovalov et al. (2016). Specifically, the first category ("EHI") included the emissions associated mostly with energy and heat production and heavy industries. The second category ("TCO") comprised transport, chemical industry, and all other anthropogenic sources. In the EMEP inventory, the EHI category was defined by aggregating the sources corresponding to the first, second and third sectors of SNAP (combustion in energy and transformation industries, non-industrial combustion plants and combustion in manufacturing industry, respectively), while the TCO category aggregated all other anthropogenic sources considered in the EMEP inventory. For comparison purposes, we also used the national totals that were obtained from the EMEP/CEIP website in August 2018. Note that starting from 2018, the EMEP data are reported for the Gridded Nomenclature for Reporting (GNFR) sectors, which cannot be unambiguously matched to the SNAP sectors.

The analysis involved also the national and gridded data from the EDGAR v4.3.2 inventory (http://edgar.jrc.ec.europa.eu/overview.php?v=432_GHG, http://edgar.jrc.ec.europa.eu/overview.php?v=432_AP) for 2012 (the latest year for which the data were publicly available in August 2018), as well as the national estimates from the Carbon Dioxide Information Analysis Center (CDIAC) (http://cdiac.ess-dive.lbl.gov/trends/emis/overview_2014.html) for the years 2012-2014. The EDGAR data for the sectors "1A1a-c" (public electricity and heat production; other energy industries), "1A2" (manufacturing industries and construction) and "1A4" (fuel combustion in residential and other sectors) were allocated into the EHI emission category, and the TCO category aggregated anthropogenic emissions reported for all other sectors. Note that attribution of the emission sectors used in the EDGAR inventory to the EHI or TCO categories involved some degree of uncertainty. Furthermore, some emission gridmaps provided by EDGARv4.3.2 inventory aggregate the data for several original sectors; taking this into account, we attributed a part of the gridded data which could not be unambiguously split between the EHI and TCO categories into the special "MIX" category.

3. Method

Similar to Konovalov et al. (2016), we first estimated annual totals of anthropogenic emissions, E_c^s, from the two categories of sources, *c,* for a given proxy species (NO_x or CO), *s*, in a study region by assuming a linear relationship between the NO_2 or CO column amounts and the corresponding anthropogenic emissions. The annual emission estimates for the individual source categories, E_c^s, constitute the control vector of the inverse problem considered. The optimum estimate of $\boldsymbol{E^s}$ was obtained by minimizing the sum of the squared differences between the observations and simulations:

$$\widehat{\boldsymbol{E}}^{\boldsymbol{s}} = argmin\{(C_o^s - C_m^s + \Delta^s)^T (C_o^s - C_m^s + \Delta^s)\}\,, \qquad (1)$$

where $\widehat{\boldsymbol{E}}^{\boldsymbol{s}}$ is the optimal estimate of the control vector, Δ^s denotes the systematic discrepancies between the simulations and observations of a given proxy species *s,* and the components of the vectors C_o^s and C_m^s represent available values of the observed and simulated column amounts of NO_2 and CO in different grid cells and / or different hours in the region and period considered.

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The systematic discrepancies (the bias) for a given data point *i* was estimated as the average difference between the simulated and observed columns of a species *s* for the month *m* in which the data point *i* lies:

$$\Delta_i^s \cong \left[\sum_j \theta_j^s(m)\right]^{-1} \sum_j \left[\theta_j^s(m)\left(C_{\boldsymbol{mj}}^{\boldsymbol{s}} - C_{\boldsymbol{oj}}^{\boldsymbol{s}}\right)\right], \tag{2}$$

$$\begin{cases} \theta_j^s = 1, \ j \in \Omega_m \\ \theta_j^s = 0, \ j \notin \Omega_m \end{cases},$$

where Ω_m denotes the subset of the available data for a given month *m,* and $i \in \Omega_m$ is the index of a component (a point in time and space) of the vector $\boldsymbol{\Delta^s}$ and $\boldsymbol{C_m^s}$ is dependent on the control vector, $\boldsymbol{E^s}$. Eqs. (1) and (2), specify a linear optimization problem that was resolved numerically by using a combination of outputs from a "base" model run performed with the "standard" EMEP emissions and two special model runs performed after increasing the annual gridded EMEP emission values for the respective (EHI or TCO) source categories in the study region by 10%. For analysis purposes, one more model run ("bgr") was performed without anthropogenic emissions in the study region. Effectively, information about optimal values of the emission vector was inferred from spatial and temporal variations of the observations and simulations within each month. The simulations corresponding to the "base" and "bgr" cases are presented below in Fig. 1 and in Appendices 1 and 2.

Summing up the optimal emission estimates for the different source categories provided the estimate of total emissions, $\hat{E}_{sum}^s$, of the species *s* in the study region. Alternatively, the estimate of the total emissions could be obtained by applying the same estimation procedure to the special case where all the emission sources are aggregated together. The corresponding optimal emission estimates are denoted below as $\hat{E}_{tot}^s$.

Once the emissions of the proxy species had been estimated, the "hybrid" CO_2 emission estimates, E_{sc}^{CO2}, were obtained as follows.

$$\hat{E}_{sc}^{co2} = F_c^s \hat{E}_c^s. \tag{3}$$

where F_c^s are the conversion factors, F_c^s. In this work, the conversion factors were estimated as follows:

$$F_c^s = \frac{\tilde{E}_c^{CO2}}{\tilde{E}_c^s}, \tag{4}$$

where $\tilde{E}_c^{CO2}$ and $\tilde{E}_c^s$ are the annual estimates of total anthropogenic FF CO_2 emissions and of anthropogenic emissions for a species *s* for a given emission source category (sector) *c* in the study region according to the EDGARv4.3.2 inventory for the year 2012.

Using Eq. (3), the total CO_2 emissions were estimated as follows:

$$\hat{E}_{s,sum}^{co2} = \sum_c F_c^s \hat{E}_c^s \ . \tag{5}$$

The alternative total CO_2 emission estimate, $\hat{E}_{c,tot}^{CO2}$, was inferred directly from an estimate of the total emissions for a proxy species:

$$\hat{E}_{s,tot}^{co2} = F_{tot}^s \hat{E}_{tot}^s, \tag{6}$$

where F_{tot}^s is the conversion factor evaluated similar to Eq. (4) but by using the total annual emission estimates from the EDGARv4.3.2 emission inventory and $\hat{E}_{tot}^s$ are the corresponding estimates inferred from satellite measurements.

The hybrid CO_2 emission estimates derived from measurements of the different proxy species were combined by taking into account the uncertainty of the individual estimates. Specifically,

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the combined (maximum likelihood) estimate of the CO_2 emissions, $E^{CO2}_{comb,c}$, was calculated as follows:

$$\hat{E}^{CO2}_{comb,c} = \left(\sum_{s=1}^{s=2}(\sigma_{sc}^{CO2})^{-2}\right)^{-1}\sum_{s=1}^{Ns}\hat{E}^{CO2}_{sc}(\sigma^{CO2}_{sc})^{-2}, \quad (7)$$

where σ^{CO2}_{sc} are the uncertainties (the standard deviations) of $\hat{E}^{CO2}_{sc}$ which were estimated as explained below.

A combined estimate for the total emissions, $\hat{E}^{CO2}_{comb,sum}$, was then obtained by summing up values of $\hat{E}^{CO2}_{comb,c}$ for the different source categories *c*. An alternative estimate for the total CO_2 emissions, $\hat{E}^{CO2}_{comb,tot}$, was obtained in a similar way by using values of $\hat{E}^{CO2}_{s,tot}$.

The combined CO_2 emission estimates inferred from the satellite measurements were then used to correct the spatial distribution of CO_2 emissions from the EDGARv4.3.2 inventory. To do that, we first computed the correction factors, F^g, as follows:

$$F^g_c = \hat{E}^{CO2}_{comb,c} / \tilde{E}^{CO2}_c \ , \quad (8)$$

$$F^g_{tot} = \hat{E}^{CO2}_{comb,tot} / \tilde{E}^{CO2}_{tot} \ . \quad (9)$$

The EDGAR emissions, $\tilde{E}^{g,CO2}_i$, for each grid cell *i* in the study region were then corrected by applying the factors F^g_c:

$$E^{g,CO2}_i = F^g_1\tilde{E}^{g,CO2}_{i,EHI} + F^g_2\tilde{E}^{g,CO2}_{i,TCO} + F^g_{tot}\tilde{E}^{g,CO2}_{i,MIX} \ . \quad (10)$$

Following Konovalov et al. (2016), the confidence intervals for the emission estimates were evaluated by using the subsampling approach. Specifically, the original set (sample) of the input data for a given proxy species *s* was divided into n_d subsets (subsamples) defined as explained below. From each subset, a "partial" independent emission estimate, $\hat{E}^s_{c,i}$ ($i \in [1,n_d]$) was inferred. The partial estimates were used to evaluate the standard error, σ^s_c, of $\hat{E}^s_c$ as follows:

$$\sigma^s_c \cong \sqrt{\frac{1}{n_{d(n_d-1)}}\sum_{i=1}^{nd}\left(\hat{E}^s_{c,i} - \hat{E}^s_{c(\square)}\right)^2}, \quad (11)$$

where ($\square$) denotes the mean over all the partial estimates. The standard errors in our estimates, $\hat{E}^s_{sum}$ and $\hat{E}^s_{tot}$, for the total emissions of proxy species were evaluated in the same way (that is, by substituting $\hat{E}^s_{sum}$ and $\hat{E}^s_{sum(\square)}$ or $\hat{E}^s_{tot}$ and $\hat{E}^s_{tot(\square)}$ into Eq. (11) instead of $\hat{E}^s_{c,i}$ and $\hat{E}^s_{c(\square)}$).

The original dataset was divided into 4 subsets in the temporal domain and 4 subsets in the spatial domain. Each of the subsets in the temporal domain included data for only one season but for the full spatial domain. The spatial subsets were defined such that each of them included approximately the same number of data points. The standard error was estimated in accordance to Eq. (11) independently for both "temporal" and "spatial" subsets (that is, n_d was equal 4 in the both cases), and the maximum of the two estimates of σ^s_c was selected as the final estimate of the standard error.

The standard error for the conversion factors, σ^F_{sc}, was also estimated using the subsampling technique:

$$\sigma^F_{sc} = \sqrt{\frac{1}{(N_k-1)N_k}\sum_{k=1}^{N_k}\left(F^s_{c,k} - F^s_{c,k}{}' - F^s_{c(\square)} + F^s_{c(\square)}{}'\right)^2 + (F^s_c - F^{s\prime}_c)^2} \ , \quad (12)$$

where $F^p_{s,k}$ are the conversion factors evaluated individually for each of the 12 countries considered by using the EDGARv4.3.2 inventory, $F^p_{s,k}{}'$ are the alternative conversion factor estimates obtained by combining the CDIAC, EDGAR and EMEP inventories (as explained below), *c* is the country index, N_k is the total number of the countries considered, and ($\square$) denotes the

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means over the countries. The country scale is used in Eq. (12), because the CDIAC data had not been provided on a spatial grid, and thus we could not consider the same spatial subsamples as those with the data for NO_2 and CO columns. To evaluate $F_{s,k}^{p}{}'$, we used the EMEP inventory data for NO_x and CO emissions and the CDIAC data for FF CO_2 emissions. As the CDIAC emission data had not been originally distributed among individual emission sectors, the fractions of the two categories of the CO_2 sources were taken to be the same as in the EDGAR v.4.3.2 inventory.

The standard error, σ_{sc}^{CO2}, representing the uncertainty in our hybrid estimates of anthropogenic CO_2 emissions was estimated by assuming that uncertainties in the estimates of a proxy species emissions and in the estimates of the conversion factors are independent:

$$\sigma_{sc}^{CO2} = \hat{E}_{sc}^{co2} \sqrt{\left(\frac{\sigma_c^S}{\hat{E}_c^S}\right)^2 + \left(\frac{\sigma_{sc}^F}{F_c^S}\right)^2}. \qquad (13)$$

The standard error, $\sigma_{s,tot}^{CO2}$, for a corresponding total CO_2 emission estimate, $\hat{E}_{s,tot}^{CO2}$ (see Eq. 6), was evaluated in the same way. The standard error, $\sigma_{s,sum}^{CO2}$, of $\hat{E}_{s,sum}^{CO2}$ (see Eq. 9) was given by a similar equation:

$$\sigma_{s,sum}^{CO2} = \sqrt{\sum_c \left(\hat{E}_c^S \sigma_{sc}^F\right)^2 + \left(\sigma_{s,sum}^{CO2|F}\right)^2}, \qquad (14)$$

where $\sigma_{s,sum}^{CO2|F}$ represents the standard error of $\hat{E}_{s,sum}^{CO2}$ under the condition that the conversion factors are known exactly (that is, the errors included in $\sigma_{s,sum}^{CO2|F}$ are associated with only uncertainties of our top-down emission estimates for the proxy species); $\sigma_{s,sum}^{CO2|F}$ was evaluated by using the same subsampling technique as described above for the case of estimation of uncertainties in $\hat{E}_c^S$. The standard errors given by Eq. (13) or (14) allowed us to combine the estimates based on the measurement of NO_2 and CO columns by using Eq. (7).

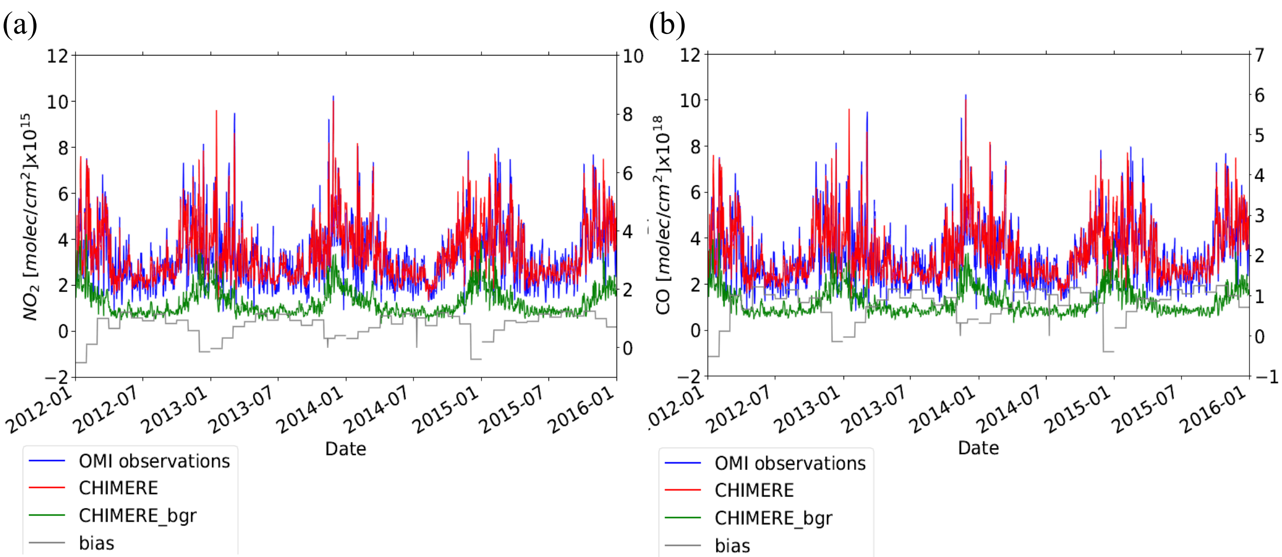

Figure 1. Daily time series of the spatially averaged NO_2 (a) and CO (b) columns retrieved from satellite measurements (see blue curves) and simulated using the CHIMERE CTM both with and without anthropogenic emissions in the study region (see red and green curves, respectively). The simulated data shown have been debiased: the differences (see grey lines) between the monthly averages of the simulation and

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measurement data were subtracted from the original simulation data and are plotted using the right-hand axes.

4. Results

The NO_x and CO emission estimates derived from the OMI NO_2 and IASI CO satellite measurements are reported below in Table 1 in comparison (wherever feasible) with the corresponding EMEP/CEIP and EDGARv4.3.2 data. The estimates of the conversion factors along with their uncertainties are given in Table 2. Finally, the CO_2 emission estimates, their uncertainties and the corresponding available values from the EDGARv4.3.2 and CDIAC inventories are listed in Table 3 and are also shown in Fig. 2. In addition, the gridded CO_2 emission estimates based on the EDGARv4.3.2 and corrected using both the NO_2 and CO observations are presented in Figs. 3 and 4.

Table 1. The optimal estimates of the anthropogenic NO_x and CO emissions (Tg NO_2 and Tg CO, respectively) from the study region. The numbers in brackets represent the 68.3% confidence intervals.
*** Estimates based on the national emission estimates updated in 2018**
**** Estimates based on the gridded emission data updated in 2016**

Species	Year	EHI			TCO			Totals			
		E_1^s	EMEP	EDGAR	E_2^s	EMEP	EDGA R	E_{sum}^s	E_{tot}^s	EMEP*	EDGAR
	2012	1.9 (±0.4)		2.6	4.2 (±0.6)		3.1	6.1 (±0.6)	6.0 (±0.6)	6.3	5.6
NO_x	2013	1.9 (±0.5)			4.3 (±0.7)			6.2 (0.5)	6.1 (±0.5)	6.1	
	2014	1.9 (±0.4)	2.0		4.6 (±0.5)	3.6		5.9 (±0.5)	5.9 (±0.4)	5.8 / 5.6**	
	2015	1.8 (±0.3)			4.2 ± (0.7)			6.1 (±0.7)	6.0 (±0.6)	5.7	
	2012	5.6 ±9.6)		6.9	7.5 (±3.2)		4.4	13.1 (±4.4)	13.9 (±5.2)	14.68	11.2
CO	2013	12.5 (±11.8)			7.4 (±14.9)			19.9 (±8.5)	17.5 (±10.5)	14.61	
	2014	3.6 (±18.0)	7.2		4.9 (±8.1)	7.6		8.5 (±11.8)	8.8 (±3.8)	13.3 / 14.7**	
	2015	38.7 (±40.6)			3.6 (±16.2)			42.2 (±22.6)	26.5 (±6.4)	13.5	

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Table 2. The NO_x-to-CO_2 (g CO2 [g NO_2]−1) and CO-to-CO_2 (g CO_2 [g CO]−1) emission conversion factors based on the EDGARv4.3.2 emission inventory along with their uncertainties given in brackets.

Sectors	NO_x-to-CO_2	CO-to-CO_2
EHI	741.4 (90.1)	279.6 (46.1)
TCO	270.5 (83.4)	101.3 (53.5)
TOTAL	486.4 (82.2)	244.5 (74.0)

Table 3. The estimates of the fossil-fuel CO_2 emissions (Pg CO_2) from the study region in comparison with corresponding data (when available) of the EDGAR v4.3.2 and CDIAC emission inventories. The numbers in brackets represent the 68.3% confidence intervals.

Inversion settings	Year	EHI		TCO		Totals			
		$E_{s,1}^{CO_2}$	EDGAR	$E_{s,2}^{CO_2}$	EDGAR	$E_{s,sum}^{CO_2}$	$E_{s,tot}^{CO_2}$	CDIAC	EDGAR
NO_x-based	2012	1.4 (0.31)		1.1 (0.38)		2.5 (0.4)	2.9 (0.6)		
	2013	1.4 (0.41)		1.2 (0.41)		2.6 (0.4)	3.0 (0.5)		
	2014	1.4 (0.33)		1.1 (0.37)		2.5 (0.3)	2.9 (0.5)		
	2015	1.4 (0.30)		1.1 (0.40)		2.5 (0.3)	2.9 (0.6)		
CO-based	2012	1.6 (2.69)		1.4 (0.97)		3.0 (2.9)	3.4 (1.6)		
	2013	3.5 (3.36)		1.4 (2.93)		4.9 (3.4)	4.3 (2.9)		
	2014	1.0 (5.04)		0.9 (1.61)		1.9 (4.1)	2.2 (1.1)		
	2015	10.8 (11.47)		0.7 (3.09)		11.5 (13.7)	6.5 (2.5)		
NO_x-and CO-based	2012	1.4 (0.3)	1.91	1.2 (0.4)	0.83	2.6 (0.4)	3.0 (0.5)	2.6	2.74
	2013	1.5 (0.4)		1.2 (0.4)		2.6 (0.4)	3.0 (0.5)	2.5	
	2014	1.4 (0.3)		1.2 (0.4)		2.5 (0.3)	2.7 (0.5)	2.3	
	2015	1.4 (0.3)		1.1 (0.4)		2.5 (0.3)	3.1 (0.6)		

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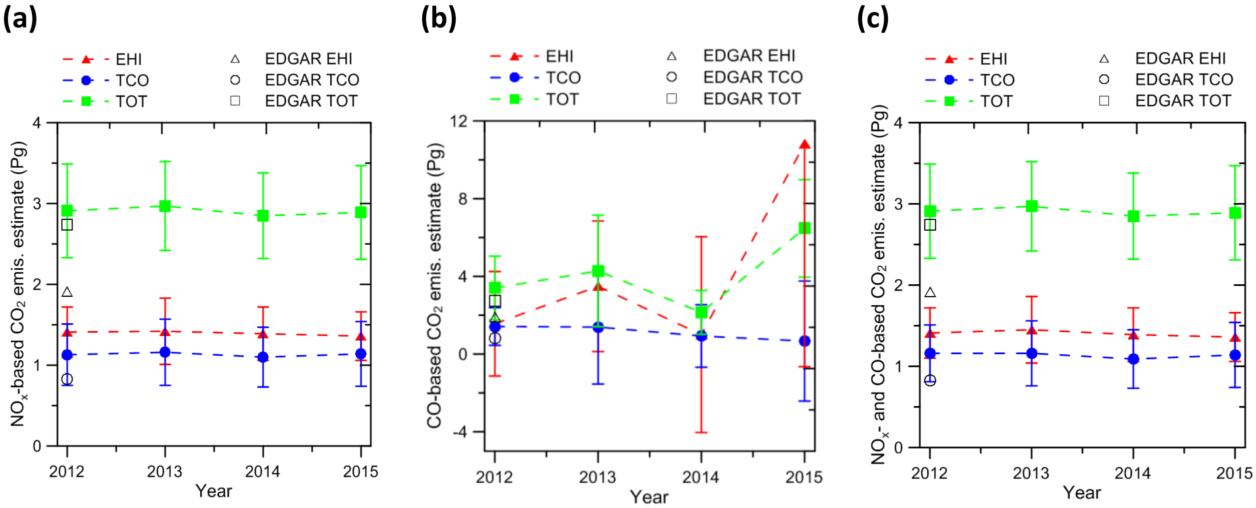

Figure 2. Hybrid estimates of the annual fossil-fuel CO_2 emissions from the study region in comparison with the data of the EDGARv.4.3.2 inventory. The hybrid estimates are based on either (a) only OMI NO_2 measurements, (b) only IASI CO measurements or (c) both NO_2 and CO satellite measurements.

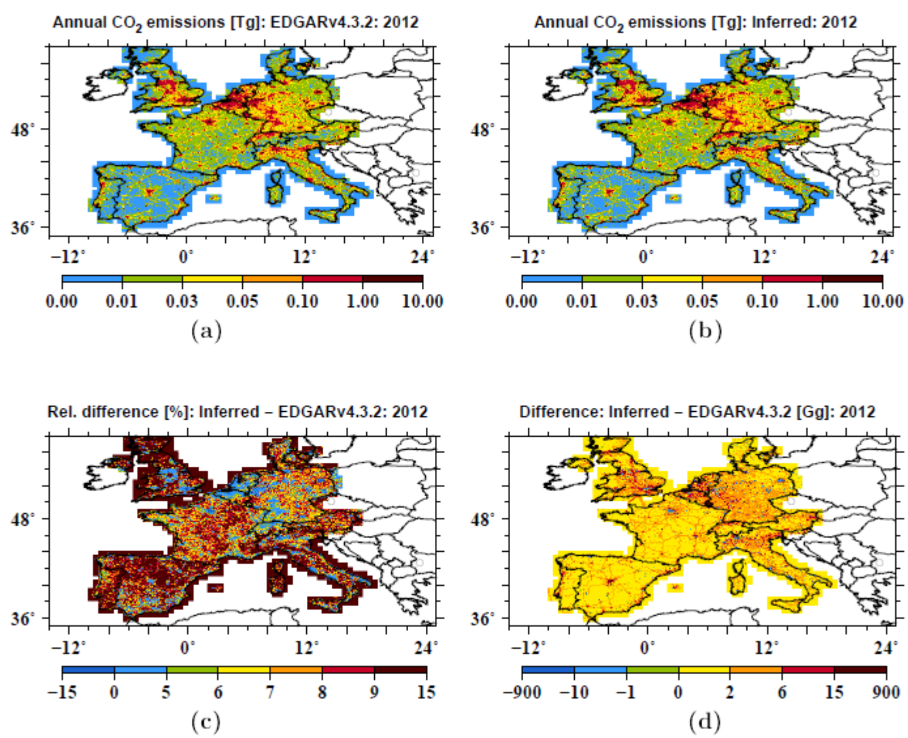

Figure 3: Spatial distribution of the annual FF CO_2 emissions (Tg) in the study region in 2012 according to the EDGARv4.3.2 inventory (a) before and (b) after applying the correction factors inferred from the both OMI NO_2 and IASI CO satellite data. Also shown are the relative and absolute differences between the corrected and original data. The emissions and the differences are shown using the original 0.1× 0.1° EDGAR grid.

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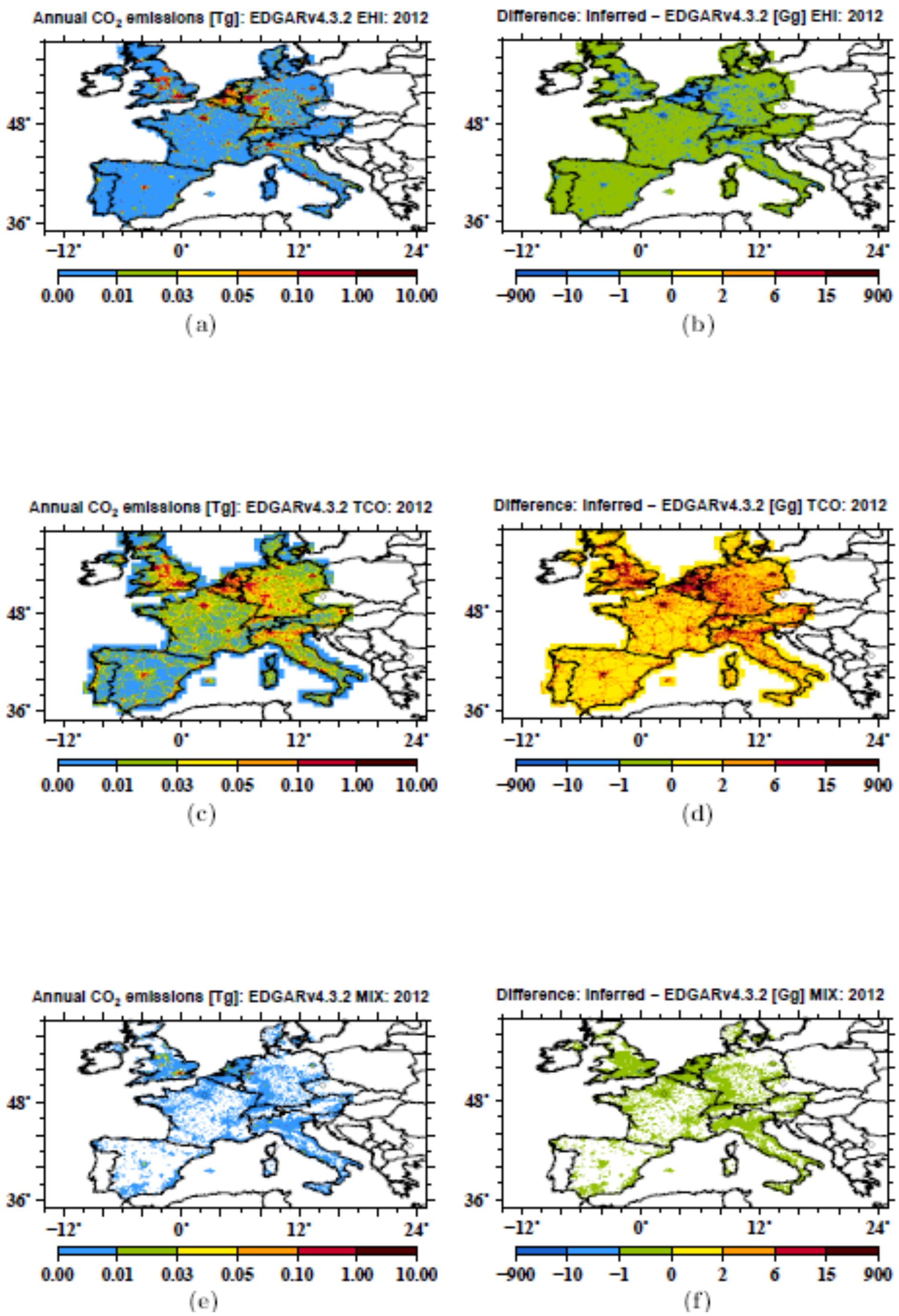

Figure 4: (a,c,e) Spatial distribution of the annual FF CO_2 emissions (Tg) from sources aggregated into the three different categories (EHI, TCO and MIX) according to the EDGARv4.3.2 inventory for 2012 along with (b,d,f) the differences between the corresponding data inferred from satellite measurements and the original EDGARv4.3.2 data.

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5. Dissimination of model results

The estimated gridded fluxes will be available from the VERIFY THREDDS data server (TDS, https://verifydb.lsce.ipsl.fr/thredds/catalog.html), with some limited metadata available from the VERIFY data catalogue (available from the VERIFY web site: http://verify.lsce.ipsl.fr/index.php/products). Note that for the VERIFY partners additional information is available under the password protected share point platform (https://projectsworkspace.eu/sites/VERIFY/).

A filename will be assigned to contain various information about the file itself, including the method, species, institute, region, spatial coverage, temporal resolution and the person who uploaded the file. This information is used to automatically generate a catalogue of available data. The TDS also supports several dataset collection services including some sophisticated dataset aggregation capabilities. This allows the TDS to aggregate a collection of datasets into a single virtual dataset, greatly simplifying user access to that data collection. The TDS also contains viewing tools to facilitate direct user browsing of stored datasets, instead of forcing the user to rely on metadata.

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