Supplement of Earth Syst. Sci. Data, 13, 5311–5335, 2021
https://doi.org/10.5194/essd-13-5311-2021-supplement


Open Access Earth System Science Data

*Supplement of*

# Global anthropogenic $CO_2$ emissions and uncertainties as a prior for Earth system modelling and data assimilation

**Margarita Choulga et al.**

*Correspondence to:* Margarita Choulga (margarita.choulga@ecmwf.int)

**S.1 Power industry emissions**

Uncertainties calculated in this study are being used in the $CO_2$ Human Emissions (CHE) project to produce an ensemble of simulations with perturbed emissions for emission sensitivity studies (McNorton et al., 2020), and as prior uncertainties in the future carbon dioxide ($CO_2$) Monitoring and Verification Support system (CHE, 2020; Janssens-Maenhout et al., 2020). Correct allocation of emission activity is needed in order to get most of the perturbation (e.g. using random noise) and inverse system techniques. The main source of $CO_2$ emission information in this study is the Emission Database for Global Atmospheric Research (EDGAR) version 4.3.2_FT2015 (Olivier et al., 2016b; Janssens-Maenhout et al., 2019). Based on the comparison with regional data from the Netherlands Organisation for Applied Scientific Research's (TNO) first version of their greenhouse gas (GHG) and co-emitted species emission database (TNO_GHGco_v1.1), EDGARv4.3.2_FT2015 energy sector emissions were divided into autoproducers (energy generated specially for industry) and the rest using percentage value reported by each country (IEA, 2016). Prior implementation percentage values were limited to 30.0 % maximum. The autoproducer emissions were then added to the industry sector, in order to have better sectoral allocation of $CO_2$ emissions.

According to the Intergovernmental Panel on Climate Change (IPCC) 2006 Guidelines for National Greenhouse Gas Inventories and revised information from its refinements (IPCC, 2019), energy sector emission factors are quite well known. Even after taking all the assumptions and activity data uncertainty into account overall emission uncertainty grows only until about ±10.0 %. However, huge power plants operate based on their yearly plan, their construction and maintenance are quite expensive, so normally they operate at full capacity and this upper bound of uncertainty is too high for them. According to the expert knowledge, the upper bound of uncertainty for big power plants can't be more than +3.0 %. In contrast, small plants operate based on day-to-day needs and their upper bound of uncertainty can reach up to +15.0 %. Bearing this in mind, it was decided to separate the modified energy sector (after relocation of autoproducer emissions) into two sub-sectors: (i) energy generated by the super power plants – most emitting single located plant or average emitting and close located (fall into one grid-cell) multiple plants (in total 30 grid-cells), and (ii) energy generated by the remaining (non-super) power plants – average emitting single or few close located plants.

First, all grid-cells of yearly energy sector gridded field were ranked according to the energy flux from the highest to the lowest flux value. Second, all values higher than $7.9 \cdot 10^{-6}$ $kg \cdot m^{-2} \cdot s^{-1}$ were treated as fluxes generated by super power plants, all the rest as fluxes generated by average power plants.

Currently 30 grid-cells from 12 different countries of the initial energy sector were moved to energy generated by super power plants sector, representing 7.1 % (896.7 Mt) of the total energy sector (12705.5 Mt). The top three countries that produce energy using super power plants are China, Russia and India. Usually, the share of energy generated by super power plants for a country is ~15.0 %, exceptions are China where this share is 4.0 %, and Kuwait where this share is 72.4 %. Table S1 shows 30 grid-cell flux values, their ranks and geographical locations. Figure S1 shows the graphical representation of

these ranked 30 grid-cell fluxes, it also shows the possible extension of grid-cell number used based on the step change in the grid-cell values.

**Table S1: List of 30 grid-cells with 2015 $CO_2$ flux values where energy is generated by super power plants, grid-cell ranks, locations and budgets per country**

| Rank | Latitude, ° | Longitude, ° | $CO_2$ flux, $\cdot 10^{-6}$ kg·m$^{-2}$·s$^{-1}$ | Country / Emission budget, Mt |
|---|---|---|---|---|
| 14 | -32.25 | 150.95 | 10.18 | Australia [AUS] / 33.6 |
| 8 | 31.25 | 120.55 | 10.89 | China [CHN] / 169.7 |
| 16 | 48.55 | 119.75 | 9.62 | |
| 17 | 38.15 | 106.35 | 9.54 | |
| 23 | 40.25 | 111.35 | 8.57 | |
| 28 | 31.35 | 121.65 | 8.18 | |
| 30 | 30.65 | 121.05 | 7.92 | |
| 10 | 51.05 | 6.55 | 10.53 | Germany [DEU] / 46.6 |
| 21 | 51.85 | 14.45 | 8.65 | |
| 24 | 53.75 | 359.15 | 8.56 | United Kingdom [GBR] / 19.7 |
| 12 | 24.15 | 82.75 | 10.42 | India [IND] / 133.5 |
| 18 | 24.05 | 82.65 | 9.17 | |
| 19 | 11.55 | 79.45 | 8.81 | |
| 26 | 21.95 | 83.45 | 8.32 | |
| 11 | 35.45 | 139.65 | 10.47 | Japan [JPN] / 59.4 |
| 27 | 35.65 | 140.15 | 8.23 | |
| 15 | 51.85 | 75.35 | 9.87 | Kazakhstan [KAZ] / 23.8 |
| 7 | 36.75 | 126.25 | 11.37 | Korea South [KOR] / 94.3 |
| 13 | 36.85 | 126.65 | 10.27 | |
| 20 | 37.75 | 128.15 | 8.67 | |
| 9 | 29.45 | 48.25 | 10.71 | Kuwait [KWT] / 36.4 |
| 25 | 51.25 | 19.35 | 8.43 | Poland [POL] / 20.6 |
| 1 | 55.95 | 37.75 | 17.74 | Russian Federation [RUS] / 168.4 |
| 2 | 60.35 | 28.65 | 17.19 | |
| 3 | 55.75 | 52.45 | 14.67 | |
| 5 | 54.75 | 20.55 | 12.44 | |
| 22 | 57.05 | 40.35 | 8.63 | |
| 29 | 55.55 | 37.75 | 8.17 | |
| 4 | 24.25 | 120.45 | 14.17 | Taiwan [TWN] / 50.4 |
| 6 | -26.15 | 29.15 | 11.51 | South Africa [ZAF] / 40.3 |

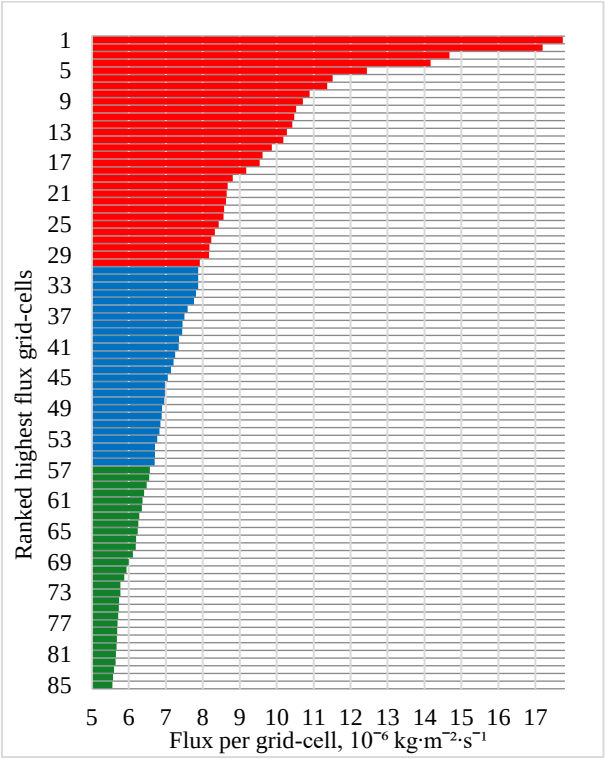


**Figure S1: Ranked highest 2015 $CO_2$ flux values from 85 grid-cells globally (see Table S1), red colour represent grid-cells where energy is generated by super power plants, blue and green colours show possible extension of the new field based on the step change in the grid-cell values**

## S.2 Coal production emissions

Generation of electricity and heat worldwide relies heavily on coal, the most carbon-intensive fossil fuel. In IPCC (2006), it is suggested $CO_2$ emissions from coal production are neglected if prescribed emission factors and activity data (Tier 1 approach) are used, because during this process methane ($CH_4$) is mainly emitted. IPCC (2019) suggests taking $CO_2$ emissions from underground mines into account, as they are already known from the mine filtering equipment. In order to use prescribed emission factor and activity data uncertainties a coal production emission map (COL) was generated. Global grid-maps at 0.1º×0.1º horizontal resolution of $CH_4$ emissions from hard coal and brown coal 2012 production provided by Joint Research Centre of the European Commission (JRC) are used for this purpose. Greet Janssens-Maenhout suggested a possible way of transforming $CH_4$ into $CO_2$ emissions. The main assumption (based on IPCC (2019)) is that $CO_2$ is emitted only during underground mining; $CO_2$ emissions from surface mining are neglected.

First, hard and brown coal $CH_4$ emission global fields had to be separated into underground and surface mining emissions. Surface mines are usually represented by the large area (several touching grid-cells on a grid-map), underground mines are

represented only by the mine entrance (one or maximum two touching grid-cells on a grid-map). For underground mining, only values from grid-cells with 6 to 8 empty neighbouring grid-cells were used. Second, values from hard and brown coal fields are summed together and finally, translated from $CH_4$ into $CO_2$ emissions by multiplication by (5.9/18.0) value, result in $kg \cdot m^{-2} \cdot s^{-1}$.

According to the newly generated $CO_2$ emissions from COL map (Figure S2) 102 countries (105 geographical entities) have $CO_2$ emissions from underground coal mining. Total emissions globally are 7.0 Mt: 50 geographical entities with less than 1.0 kt; 29 geographical entities with 1.0 up to 10.0 kt; 11 geographical entities with 10.0 up to 50.0 kt; and 15 geographical entities with emissions of 50.0 or more kt. Table S2 shows the 15 most emitting countries based on coal production emissions; 95.0 % of all $CO_2$ emissions from coal production globally is emitted by these 15 countries. According to the geographical entity type (see Section S.4 below), i.e., countries with well- and less well-developed statistical infrastructures: 24 geographical entities with well-developed statistical infrastructures emit 70.2 % (4.9 Mt) of global $CO_2$ emissions from coal production versus 81 geographical entities with less well-developed statistical infrastructures that emit only 29.8 % (2.1 Mt) of the global value.

**Table S2: List of 15 most emitting geographical entities based on the $CO_2$ emissions from underground mining coal production map, ranks and budgets per country**

| Rank | ISO Code | Geographical name | Emission budget, kt |
|---|---|---|---|
| 1 | CHN | China | 3044.9 |
| 2 | IDN | Indonesia | 786.5 |
| 3 | USA | United States of America | 645.7 |
| 4 | IND | India | 512.1 |
| 5 | RUS | Russian Federation | 356.4 |
| 6 | UKR | Ukraine | 202.7 |
| 7 | AUS | Australia | 196.6 |
| 8 | VNM | VietNam | 185.2 |
| 9 | KAZ | Kazakhstan | 158.1 |
| 10 | ZAF | South Africa | 139.6 |
| 11 | MNG | Mongolia | 120.4 |
| 12 | PRK | Democratic People's Republic of Korea (North Korea) | 103.9 |
| 13 | COL | Colombia | 62.4 |
| 14 | DEU | Germany | 61.1 |
| 15 | POL | Poland | 50.8 |
| | | TOTAL | 6626.3 |

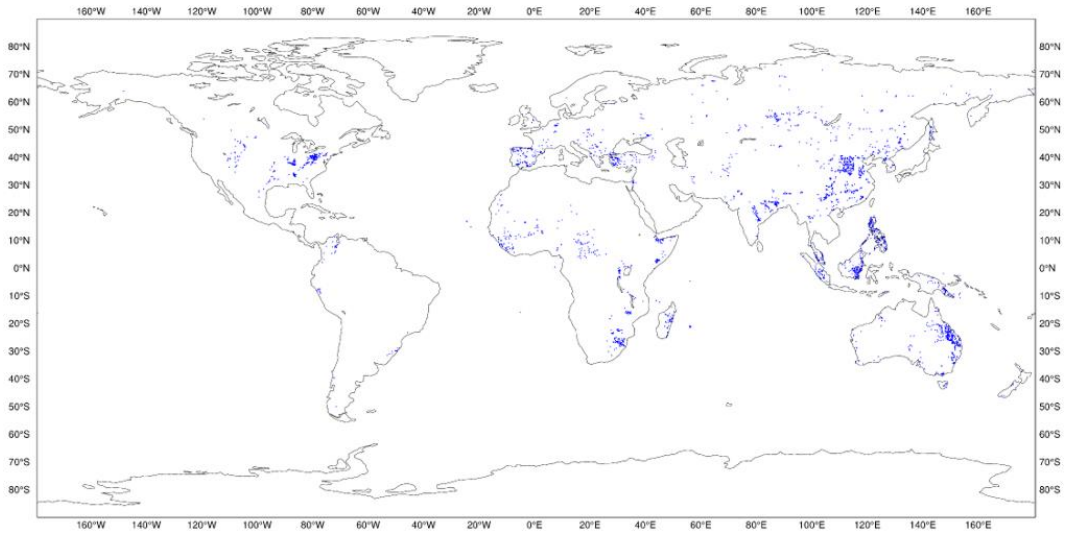


**Figure S2: Global distribution of the $CO_2$ emission sources from coal production based on 2012 $CH_4$ emissions data for brown and hard coal, locations of underground mines are marked with blue dots**

### S.3 Additional explanation on uncertainty computation

After the initial 92 IPCC (2006) activity uncertainties are combined into "sectors" for which the user has emission budget data, and "sector" uncertainties are adjusted to consider a country's statistical system development level and its yearly emission budget, uncertainties also must be forced to be log-normally distributed (emissions can't be negative) in the following way:

$$\mu g_{sector\_j} = exp\left\{ln\left(E_{sector\_j}\right) - \frac{1}{2} \cdot ln\left(1 + \left[\frac{\left(UC_{sector\_j}\right)_{corr}}{200}\right]^2\right)\right\}, \quad (1)$$

$$\sigma g_{sector\_j} = exp\left\{\sqrt{ln\left(1 + \left[\frac{\left(UC_{sector\_j}\right)_{corr}}{200}\right]^2\right)}\right\}, \quad (2)$$

where geometric means $\mu g$ and geometric standard deviations $\sigma g$ per each "sector" $j$ were calculated based on anthropogenic $CO_2$ emissions $E_{sector\_j}$ and the corrected uncertainties $(UC_{sector\_j})_{corr}$ in percent following Frey (2003);

$$\left\{\left[\left(UC_{sector\_j}\right)_{corr}\right]_{low}\right\}_{ln} = \left(\frac{exp\left\{ln\left(\left[\mu g_{sector\_j}\right]_{low}\right) - 1.96 \cdot ln\left(\left[\sigma g_{sector\_j}\right]_{low}\right)\right\} - E_{sector\_j}}{E_{sector\_j}}\right) \times 100, \quad (3)$$

$$\left\{\left[\left(UC_{sector\_j}\right)_{corr}\right]_{high}\right\}_{ln} = \left(\frac{exp\left\{ln\left(\left[\mu g_{sector\_j}\right]_{high}\right) + 1.96 \cdot ln\left(\left[\sigma g_{sector\_j}\right]_{high}\right)\right\} - E_{sector\_j}}{E_{sector\_j}}\right) \times 100, \quad (4)$$

where lower $\left\{\left[\left(UC_{sector\_j}\right)_{corr}\right]_{low}\right\}_{ln}$ and upper $\left\{\left[\left(UC_{sector\_j}\right)_{corr}\right]_{high}\right\}_{ln}$ uncertainty half-ranges corrected for the error propagation method underestimation per each "sector" $j$ were calculated when the corrected lower half-range uncertainty $\left[\left(UC_{sector\_j}\right)_{corr}\right]_{low}$ was ≥ 50 % following Frey (2003) with a logarithmic transformation *ln* using anthropogenic $CO_2$ emissions $E_{sector\_j}$, geometric means $\left[\mu g_{sector\_j}\right]_{low}$, $\left[\mu g_{sector\_j}\right]_{high}$ and geometric standard deviations $\left[\sigma g_{sector\_j}\right]_{low}$, $\left[\sigma g_{sector\_j}\right]_{high}$ respectively to preserve as much accuracy (extra knowledge) as possible in the calculations and not to inflate uncertainty upper or lower bounds artificially. According to this methodology (with constants for 2.5th and 97.5th percentiles, -1.96 and +1.96 respectively, from the Z-table[1]), the lower uncertainty half-range $\left\{\left[\left(UC_{sector\_j}\right)_{corr}\right]_{low}\right\}_{ln}$ will always be less than 100.0 %. The upper uncertainty half-range $\left\{\left[\left(UC_{sector\_j}\right)_{corr}\right]_{high}\right\}_{ln}$ is approximately symmetric relative to the zero value (Gaussian distribution) up to ~20.0 %, then has rather rapid growth until ~500.0 % (which with logarithmic transformation results in ~486.0 %), maxima at ~1350.0 % (which with logarithmic transformation results in ~582.6 %) and further gradual decrease. Further corrected "sector" uncertainties are combined into "group" uncertainties for modelling/comparison purposes.

"Group" upper and lower uncertainty half-range values are descriptive, but not straightforward to use in numerical modelling, so both mean $\mu^{ln}$ and standard $\sigma^{ln}$ deviation of the "group" log-normal distribution are calculated. It is assumed that the lower and upper bounds of the 95 % probability range, which are the 2.5th and 97.5th percentiles respectively, and calculated assuming a log-normal distribution based on a corrected estimated uncertainty half-range from the error propagation approach, are lower and upper uncertainty values. Taking this into account and using the Z-table for 2.5th and 97.5th percentiles $p$, mean $\mu^{ln}$ and standard deviation $\sigma^{ln}$ of log-normal distribution can be calculated in a following way:

$$Z_p = \frac{ln\left(\left[E_{group\_k}\right]_p\right) - \mu^{ln}_{group\_k}}{\sigma^{ln}_{group\_k}}, \quad (5)$$

where the following variables are known:

$$p = 2.5 \Rightarrow Z_{2.5} = -1.96, \left[E_{group\_k}\right]_{2.5} = E_{group\_k} \cdot \left(1 + \frac{\left[UC_{group\_k}\right]_{low}}{100\%}\right), \quad (6)$$

$$p = 97.5 \Rightarrow Z_{97.5} = 1.96, \left[E_{group\_k}\right]_{97.5} = E_{group\_k} \cdot \left(1 + \frac{\left[UC_{group\_k}\right]_{high}}{100\%}\right), \quad (7)$$

where combined uncertainties $UC_{group\_k}$ and total emissions $E_{group\_k}$ per "group" $k$ are used in percent and kilotonne respectively.

Then by applying Eq. (6) and Eq. (7) to Eq. (5) the simple system Eq. (8) can be composed and solved:

[1] The Z-table is a mathematical table for the values of the cumulative distribution function of the normal distribution.

$$\begin{cases} -1.96 = \dfrac{ln(E_{group\_k}) + ln\left(1 + \dfrac{\left[UC_{group\_k}\right]_{low}}{100\%}\right) - \mu^{ln}_{group\_k}}{\sigma^{ln}_{group\_k}} \\ 1.96 = \dfrac{ln(E_{group\_k}) + ln\left(1 + \dfrac{\left[UC_{group\_k}\right]_{high}}{100\%}\right) - \mu^{ln}_{group\_k}}{\sigma^{ln}_{group\_k}} \end{cases}. \quad (8)$$

## S.4 Uncertainty calculation tool

The uncertainty calculation tool CHE_UNC_APP (Choulga et al., 2021) enables a user to compute anthropogenic $CO_2$ emission uncertainties in accordance with the IPCC (2006) Tier 1 approach (i.e. with prescribed Emission Factors and Activity Data and with assigned uncertainty bounds) using emission budgets (yearly and/or monthly) in kilotonne as input data.

The uncertainty calculation tool is designed to be used in the Linux environment. By default, all scripts are executable, pre-compiled and run sequentially one after the other once the main bash script "CHE_Uncertainty" is started. The tool's input information is listed in Table S3, and information on the scripts is summarised in Table S4. The resulting country data files have names ending on the country's three letter ISO-code (a full list of the country codes is available in "data/ CountryGrouping"; additional 4 codes for geographical entities are listed in "data/ CountryGrouping_EXTRA", namely: E28 – 27 European Union countries and the UK, GL1/GL2 – all countries with well-/less well-developed statistical systems, GLB – all countries in the world, including ocean SEA). All generated plots are saved in EPS and PNG formats. The uncertainty generation tool can be easily customised based on specific user needs, see Table S5.

**Table S3: List of uncertainty calculation tool input information**

| File location/ name | Note |
|---|---|
| data/ Budgets2015 (data/ Budgets2015_[1..12] – same but with monthly data) | anthropogenic $CO_2$ emission 2015 yearly budgets, in kt, for 242+1 geographical entities (international aviation and shipping are assigned as ocean SEA); monthly files provide emission budgets for the month in question multiplied by 12 – to get the real monthly emission budget values provided need to be multiplied by the number of days in the month in question and divided by 365 days |
| data/ CountryGrouping (data/ CountryGrouping_EXTRA – same but for additional geographical entities) | list of geographical entities with their statistical system development levels (i.e. countries with well-and less well-developed statistical systems) |
| data/ UncertaintiesIPCC2006 | list of IPCC (2006) activities and their upper and lower uncertainty bounds; the list contains only 92 IPCC (2006) activities which result in anthropogenic $CO_2$ emissions in the yearly budget |

**Table S4: List of uncertainty calculation tool scripts (XXX corresponds to the country's ISO-code)**

| File name | Note | Resulting file location/ name – note |
|---|---|---|
| PART I: combining IPCC (2006) activities into "sectors" for which user has emission budget data | | |
| CombiningUNC_till Budget | combines 92 IPCC (2006) activities into "sectors" for which user has | tmp_data/ UncertaintiesIPCC2006_combined – lower/upper uncertainty bounds (no sign) for countries with well-/less well- |

| | | |
|---|---|---|
| | emission budget data | developed statistical systems per “sector”;<br>tmp_data/ SectorGrouping_Table – “sector” correspondence to certain “group” |
| PART II: adjusting “sector” uncertainties considering country’s statistical system development level and its YEARLY emission budget, and further combination of “sector” uncertainties into “group” uncertainties | | |
| AsymptoticApproach | recalculates “sector” uncertainties by using an asymptotic approach if the lower bound of uncertainty exceeds 100 % (emission budgets are considered) | tmp_data/0/ AsymptoticApproachUncertainty.txt (tmp_data/0/ AsymptoticApproachUncertainty_EXTRA.txt – same but for additional geographical entities) – recalculated lower/upper uncertainty bounds (with sign) per “sector” |
| Combination | combines “sector” uncertainties using an asymptotic approach into user-defined emission “groups” | tmp_data/0/ GroupedAsymptoticUncertainty.txt (tmp_data/0/ GroupedAsymptoticUncertainty_EXTRA.txt – same but for additional geographical entities) – combined lower/upper uncertainty bounds (with sign) per “group” |
| Log-normal_parameters | calculates “group” emission distribution parameters for modelling needs (a log-normal emission distribution is assumed) | res/0/ GroupedDistributionParameters.txt (res/0/ GroupedDistributionParameters_EXTRA.txt – same but for additional geographical entities) – emission budget, lower/upper/average uncertainty bounds (with sign) per “group”/country, log-normal mean & standard deviation per “group”, group’s contribution to country's total uncertainty per “group”;<br>tmp_data/0/ GroupedDistributionParameters_Mu_StDev.txt (tmp_data/0/ GroupedDistributionParameters_Mu_StDev_EXTRA.txt – same but for additional geographical entities) – log-normal mean & standard deviation per “group”;<br>tmp_data/0/ GroupedDistributionParameters_FullList.txt (tmp_data/0/ GroupedDistributionParameters_FullList_EXTRA.txt – same but for additional geographical entities) – emission budget, log-normal mean & standard deviation, mean, median, mode, variance, skewness per “group”;<br>tmp_data/0/ GroupedUncertaintyParameters.txt (tmp_data/0/ GroupedUncertaintyParameters_EXTRA.txt – same but for additional geographical entities) – country’s ISO-code & development level of its statistical system, emission budget, lower/upper/average uncertainty bounds (with sign) per country;<br>tmp_data/0/ UNC_parameters_XXX.txt – emission budget, lower/upper uncertainty bounds (with sign) per “group”/country, group’s contribution to country's total uncertainty, log-normal mean & standard deviation per “group” |
| PlottingGroupedUncertainties | (optional) plots yearly uncertainties per “group” for each country in EPS/PNG formats | tmp_data/0/PLOT/ UNC_parameters_XXX.[eps..png] (tmp_data/0/PLOT/ UNC_parameters_XXX_EXTRA.[eps..png] – same but with the group’s contribution to the country's total uncertainty) – plot per country with emission budgets, lower/upper uncertainty bounds per “group” |
| PlottingGroupedPDF | (optional) plots yearly probability density functions per “group” for each country in EPS/PNG formats (N corresponds to the “group” number) | tmp_data/0/PLOT/ UNC_parameters_XXX_N_PDF.[eps..png] – plot per country per “group” with probability density function, computed from log-normal mean and standard deviation based on emission budgets in kt |
| PART III: adjusting “sector” uncertainties considering country’s statistical system development level and its MONTHLY emission budget – adjusting yearly uncertainties to represent monthly variability (no correlation between months is assumed), and further combination of “sector” uncertainties into “group” uncertainties | | |
| MonthlyUncertainty_Prep | creates initial files with yearly uncertainties adjusting parameter ALPHA, assume ALPHA=1 for all emission “sectors” and countries | tmp_data/ NoCorrelation_Alpha (tmp_data/ NoCorrelation_Alpha_EXTRA – same but for additional geographical entities) – adjusting parameter ALPHA for lower/upper uncertainty bounds per “sector” per country |
| MonthlyUncertainty_AsApp | for each month recalculates the adjusted by the parameter ALPHA “sector” uncertainties using an asymptotic | tmp_data/[1..12]/ AsymptoticApproachUncertainty.txt (tmp_data/[1..12]/ AsymptoticApproachUncertainty_EXTRA.txt – same but for additional geographical entities) – lower/upper |

| | | |
|---|---|---|
| | approach if the lower bound of uncertainty exceeds 100 % (monthly emission budgets are considered) | uncertainty bounds (with sign) per "sector" |
| MonthlyUncertainty_ ALPHA | recalculates yearly uncertainties adjusting parameter ALPHA for all emission "sectors" and countries taking into account yearly and sum of monthly emission budgets & uncertainties, computes maximum difference over all emission "sectors" and countries between current and previous ALPHA | tmp_data/ New_NoCorrelation_Alpha (tmp_data/ New_NoCorrelation_Alpha_EXTRA – same but for additional geographical entities) – updated adjusting parameter ALPHA for lower/upper uncertainty bounds per "sector" per country; tmp_data/ New_NoCorrelation_Alpha_MaxDiff – maximum difference over all "sectors" and countries between current and previous ALPHA computations (single number in the file) |
| Note: scripts "MonthlyUncertainty_AsApp" and "MonthlyUncertainty_ALPHA" are looped until the maximum difference over all "sectors" and countries between the current and previous ALPHA computations is less than a certain threshold (here 0.005) | | |
| MonthlyUncertainty_ Comb | combines monthly "sector" uncertainties using an asymptotic approach into user-defined emission "groups" | tmp_data/[1..12]/ GroupedAsymptoticUncertainty.txt (tmp_data/[1..12]/ GroupedAsymptoticUncertainty_EXTRA.txt – same but for additional geographical entities) – lower/upper uncertainty bounds (with sign) per "group" per country |
| MonthlyUncertainty_ Lg-norm | for each month this calculates "group" emission distribution parameters for modelling needs (log-normal emission distribution is assumed). | res/[1..12]/ GroupedDistributionParameters.txt (res/[1..12]/ GroupedDistributionParameters_EXTRA.txt – same but for additional geographical entities) – emission budget, lower/upper/average uncertainty bounds (with sign) per "group"/country, log-normal mean & standard deviation per "group", group's contribution to country's total uncertainty per "group"; tmp_data/[1..12]/ GroupedDistributionParameters_Mu_StDev.txt (tmp_data/[1..12]/ GroupedDistributionParameters_Mu_StDev_EXTRA.txt – same but for additional geographical entities) – log-normal mean & standard deviation per "group"; tmp_data/[1..12]/ GroupedDistributionParameters_FullList.txt (tmp_data/[1..12]/ GroupedDistributionParameters_FullList_EXTRA.txt – same but for additional geographical entities) – emission budget, log-normal mean & standard deviation, mean, median, mode, variance, skewness per "group"; tmp_data/[1..12]/ GroupedUncertaintyParameters.txt (tmp_data/[1..12]/ GroupedUncertaintyParameters_EXTRA.txt – same but for additional geographical entities) – country's ISO-code & development level of its statistical system, emission budget, lower/upper/average uncertainty bounds (with sign) per country; tmp_data/[1..12]/ UNC_parameters_XXX.txt – emission budget, lower/upper uncertainty bounds (with sign) per "group"/country, group's contribution to country's total uncertainty, log-normal mean & standard deviation per "group" |
| MonthlyUncertainty_ Arrange | (optional) arranges monthly uncertainties per "group" for each country for plotting needs (N corresponds to the "group" number) | tmp_data/0/Monthly_Arranged/ UNC_parameters_XXX_Sector_N – emission budget, lower & upper uncertainty bounds (with sign) per month per "group"/country, group's contribution to country's total uncertainty, log-normal mean & standard deviation per month per "group" |
| PlottingMonthlyGroupedUncertainties | (optional) plots monthly uncertainties per "group" for each country in EPS/PNG formats | tmp_data/0/Monthly_Arranged/PLOT/ UNC_parameters_XXX.[eps..png] – plot per country with emission budgets, lower/upper uncertainty bounds per month for all groups defined by the user |
| PlottingMonthlyGroupedPDF | (optional) plots monthly probability density functions per "group" per month for each country in EPS/PNG formats (N corresponds to the "group" | tmp_data/0/Monthly_Arranged/PLOT/ UNC_parameters_XXX_N_M_PDF.[eps..png] – plot per country per "group" per month with probability density function, computed from log-normal mean and standard deviation based on monthly emission |

| | | |
|---|---|---|
| | number, M – to the month of the year number) | budgets in kt |

**Table S5: List of possible customisations of the uncertainty calculation tool**

| Customisation (change) | User action |
|---|---|
| yearly (monthly) emission budgets | replace the "data/ Budgets2015" ("data/ Budgets2015_[1..12]") values in the third column with the updated emission budget data |
| country's statistical systems development level | replace the "data/ CountryGrouping" ("data/ CountryGrouping_EXTRA" for additional geographical entities) letters in the second column with the updated development level ("A" corresponds to a country with a well-developed statistical system, "N" – to a country with a less well-developed statistical system) |
| IPCC2006 activity uncertainty values | replace the "data/ UncertaintiesIPCC2006" values in columns three to six with the updated uncertainty lower and upper bounds |
| IPCC2006 activity combination into "sectors" | replace the "data/ UncertaintiesIPCC2006" values in the seventh column with the updated numbers (if some activities must be left out from the computation – they should be numbered as 0) |
| "sector" combination into "groups" | replace the "data/ UncertaintiesIPCC2006" values in the eighth column with the updated numbers (if some "sectors" must be left out from the computation – they should be numbered as 0) |

## S.5 Geographical treatment

The whole world in this study is represented as 242 geographical entities (i.e. 232 countries) over the land and 1 residual entity over the ocean (including seas). Each geographical entity represents part of the country (e.g. Isle of Man, Bermuda and Cayman Islands are different parts of the United Kingdom) or several countries merged together (e.g. Sudan and South Sudan or Netherlands Antilles and Bonaire, Sint Eustatius, Saba and Curacao).

Each entity reports its annual GHG inventory with anthropogenic emission budgets, uncertainties and trends. Residual entity emissions are calculated from any activity (e.g. aviation, shipping, etc.) that took place over the ocean based on the global country mask (international aviation and international shipping are explicitly taken into account in the residual entity emissions, not any specific country). The accuracy of these reported values strongly depends on the statistical system development level of the entity. According to IPCC (2006), all entities should be divided into two groups (with well- and less well-developed statistical infrastructures) and can be related to Annex I and Non-Annex I countries respectively, see Figure S3 for schematic representation of all world countries grouping.

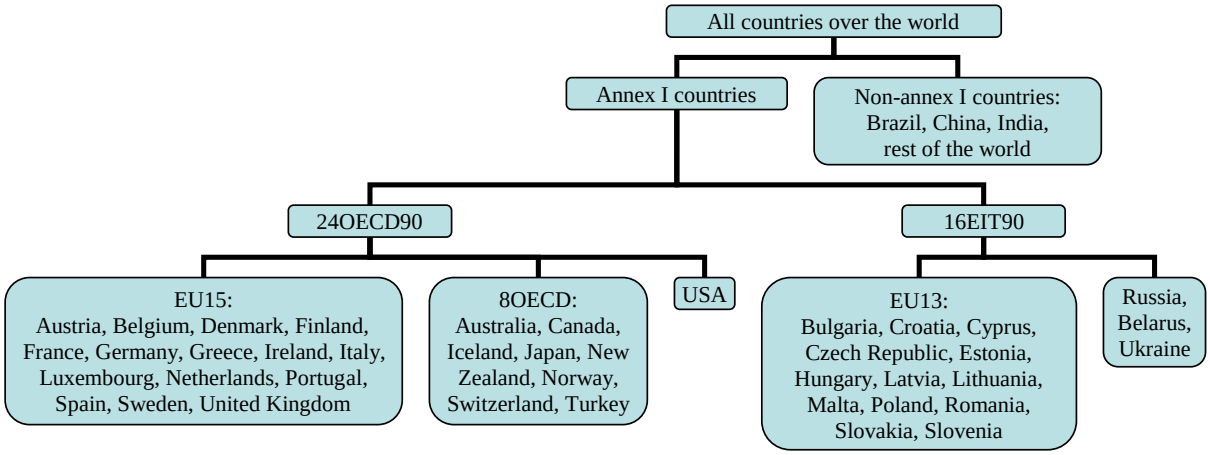


**Figure S3: Schematic grouping of world countries**

Annex I countries must report their GHG inventories annually and consist of the 24 countries of the Organisation for Economic Co-operation and Development of 1990 (24OECD90) and the 16 countries with Economies in Transition (mainly the Commonwealth of Independent States, 16EIT90). The 24OECD90 countries are assumed to be economically stable and to have good statistical infrastructure and thus to have the lowest uncertainties in their inventories. The 16EIT90 countries experienced more economical instability and flaws in the statistical reporting during the early 1990's, but are nowadays assumed to have a good statistical infrastructure. As such, they have slightly higher uncertainties in their inventories than the 24OECD90 countries but are still quite certain. Non-Annex I countries consist of the United Nations Framework Convention on Climate Change (UNFCCC) developing countries (Janssens-Maenhout et al., 2019).

For this study, certain exceptions are made to this grouping: (i) far away territories of Annex I countries are treated as geographical entities with less well-developed statistical infrastructures (e.g. the United Kingdom is Annex I country meaning a country with well-developed statistical infrastructure, Bermuda is its part yet treated as geographical entity with less well-developed statistical infrastructure because of its far away geographical location from the main part of the United Kingdom); (ii) China is treated as a country with a well-developed statistical infrastructure, because the quality of its GHG inventories has recently increased; (iii) India is treated as a country with a well-developed statistical infrastructure, because of its inherited well-developed statistical infrastructure; (iv) the Russian Federation is currently treated as a country with a less well-developed statistical infrastructure, because completion of its GHG inventory has recently decreased. Table S6 shows all geographical entities involved in this study with their statistical system development level and main country. .

**Table S6: Full list of geographical entities, their statistical infrastructure development type (countries with well- (WDS) and less well-developed (LDS) statistical infrastructures), and main country of dependence**

| ISO Code | Geographical name | Type | Main country (dependency) | Full information |
|---|---|---|---|---|
| AFG | Afghanistan | LDS | Afghanistan | Afghanistan |

| ISO Code | Geographical name | Type | Main country (dependency) | Full information |
|---|---|---|---|---|
| ALA | Aland Islands | LDS | Finland | Aland Islands |
| ALB | Albania | LDS | Albania | Albania |
| DZA | Algeria | LDS | Algeria | Algeria |
| ASM | American Samoa | LDS | United States of America | American Samoa |
| AND | Andorra | WDS | Andorra | Andorra |
| AGO | Angola | LDS | Angola | Angola |
| AIA | Anguilla | LDS | United Kingdom | Anguilla |
| ATA | Antarctica | LDS | Antarctica | Antarctica |
| ATG | Antigua and Barbuda | LDS | Antigua and Barbuda | Antigua and Barbuda |
| ARG | Argentina | LDS | Argentina | Argentina |
| ARM | Armenia | LDS | Armenia | Armenia |
| ABW | Aruba | LDS | Netherlands | Aruba |
| AUS | Australia | WDS | Australia | Australia |
| AUT | Austria | WDS | Austria | Austria |
| AZE | Azerbaijan | LDS | Azerbaijan | Azerbaijan |
| BHS | Bahamas | LDS | Bahamas | Bahamas |
| BHR | Bahrain | LDS | Bahrain | Bahrain |
| BGD | Bangladesh | LDS | Bangladesh | Bangladesh |
| BRB | Barbados | LDS | Barbados | Barbados |
| BLR | Belarus | WDS | Belarus | Belarus |
| BEL | Belgium | WDS | Belgium | Belgium |
| BLZ | Belize | LDS | Belize | Belize |
| BEN | Benin | LDS | Benin | Benin |
| BMU | Bermuda | LDS | United Kingdom | Bermuda |
| BTN | Bhutan | LDS | Bhutan | Bhutan |
| BOL | Bolivia | LDS | Bolivia | Bolivia, Plurinational State of |
| BIH | Bosnia and Herzegovina | LDS | Bosnia and Herzegovina | Bosnia and Herzegovina |
| BWA | Botswana | LDS | Botswana | Botswana |
| BVT | Bouvet Islands | LDS | Norway | Bouvet Islands |
| BRA | Brazil | LDS | Brazil | Brazil |
| IOT | British Indian Ocean Territory | LDS | United Kingdom | British Indian Ocean Territory |
| BRN | Brunei Darussalam | LDS | Brunei Darussalam | Brunei Darussalam |
| BGR | Bulgaria | WDS | Bulgaria | Bulgaria |
| BFA | Burkina Faso | LDS | Burkina Faso | Burkina Faso |
| BDI | Burundi | LDS | Burundi | Burundi |
| CPV | Cabo Verde | LDS | Cabo Verde | Cabo (or Cape) Verde |
| KHM | Cambodia | LDS | Cambodia | Cambodia |
| CMR | Cameroon | LDS | Cameroon | Cameroon |
| CAN | Canada | WDS | Canada | Canada |
| CYM | Cayman Islands | LDS | United Kingdom | Cayman Islands |
| CAF | Central African Republic | LDS | Central African Republic | Central African Republic |
| TCD | Chad | LDS | Chad | Chad |
| CHL | Chile | LDS | Chile | Chile |
| CHN | China | WDS | China | China |
| CXR | Christmas Islands | LDS | Australia | Christmas Islands |
| CCK | Cocos Islands | LDS | Australia | Cocos (or Keeling) Islands |
| COL | Colombia | LDS | Colombia | Colombia |
| COM | Comoros | LDS | Comoros | Comoros |
| COG | Congo | LDS | Congo | Congo |
| COD | Congo, Democratic Republic of | LDS | Congo, Democratic Republic of | Congo, Democratic Republic of |
| COK | Cook Islands | LDS | New Zealand | Cook Islands |

| ISO Code | Geographical name | Type | Main country (dependency) | Full information |
|---|---|---|---|---|
| CRI | Costa Rica | LDS | Costa Rica | Costa Rica |
| CIV | Cote D'Ivoire | LDS | Cote D'Ivoire | Cote D'Ivoire |
| HRV | Croatia | WDS | Croatia | Croatia |
| CUB | Cuba | LDS | Cuba | Cuba |
| CYP | Cyprus | WDS | Cyprus | Cyprus |
| CZE | Czechia | WDS | Czechia | Czechia |
| DNK | Denmark | WDS | Denmark | Denmark |
| DJI | Djibouti | LDS | Djibouti | Djibouti |
| DMA | Dominica | LDS | Dominica | Dominica |
| DOM | Dominican Republic | LDS | Dominican Republic | Dominican Republic |
| ECU | Ecuador | LDS | Ecuador | Ecuador |
| EGY | Egypt | LDS | Egypt | Egypt |
| SLV | El Salvador | LDS | El Salvador | El Salvador |
| GNQ | Equatorial Guinea | LDS | Equatorial Guinea | Equatorial Guinea |
| ERI | Eritrea | LDS | Eritrea | Eritrea |
| EST | Estonia | WDS | Estonia | Estonia |
| SWZ | Eswatini | LDS | Eswatini | Eswatini |
| ETH | Ethiopia | LDS | Ethiopia | Ethiopia |
| FRO | Faeroe Islands | WDS | Denmark | Faeroe Islands |
| FLK | Falkland Islands | LDS | United Kingdom | Falkland Islands |
| FJI | Fiji | LDS | Fiji | Fiji |
| FIN | Finland | WDS | Finland | Finland |
| FRA | France | WDS | France | France, merged with: Monaco [MCO] |
| GUF | French Guiana | LDS | France | French Guiana |
| PYF | French Polynesia | LDS | France | French Polynesia |
| MAF | French Saint Martin | LDS | France | French Saint Martin, merged with: Sint Maarten [SXM] |
| ATF | French Southern Territories | LDS | France | French Southern Territories |
| GAB | Gabon | LDS | Gabon | Gabon |
| GMB | Gambia | LDS | Gambia | Gambia |
| GEO | Georgia | LDS | Georgia | Georgia |
| DEU | Germany | WDS | Germany | Germany |
| GHA | Ghana | LDS | Ghana | Ghana |
| GRC | Greece | WDS | Greece | Greece |
| GRL | Greenland | WDS | Denmark | Greenland |
| GRD | Grenada | LDS | Grenada | Grenada |
| GLP | Guadeloupe | LDS | France | Guadeloupe |
| GUM | Guam | LDS | United States of America | Guam |
| GTM | Guatemala | LDS | Guatemala | Guatemala |
| GGY | Guernsey | WDS | United Kingdom | Guernsey |
| GIN | Guinea | LDS | Guinea | Guinea |
| GNB | Guinea-Bissau | LDS | Guinea-Bissau | Guinea-Bissau |
| GUY | Guyana | LDS | Guyana | Guyana |
| HTI | Haiti | LDS | Haiti | Haiti |
| HMD | Heard Island and McDonald Island | LDS | Australia | Heard Island and McDonald Island |
| HND | Honduras | LDS | Honduras | Honduras |
| HKG | Hong Kong | LDS | China | Hong Kong |
| HUN | Hungary | WDS | Hungary | Hungary |
| ISL | Iceland | WDS | Iceland | Iceland |
| IND | India | WDS | India | India |
| IDN | Indonesia | LDS | Indonesia | Indonesia |

| ISO Code | Geographical name | Type | Main country (dependency) | Full information |
|---|---|---|---|---|
| IRN | Iran | LDS | Iran | Iran, Islamic Republic of |
| IRQ | Iraq | LDS | Iraq | Iraq |
| IRL | Ireland | WDS | Ireland | Ireland |
| IMN | Isle of Man | WDS | United Kingdom | Isle of Man |
| ISR | Israel | LDS | Israel | Israel |
| ITA | Italy | WDS | Italy | Italy, merged with: Holy See [VAT] |
| JAM | Jamaica | LDS | Jamaica | Jamaica |
| JPN | Japan | WDS | Japan | Japan |
| JEY | Jersey | WDS | United Kingdom | Jersey |
| JOR | Jordan | LDS | Jordan | Jordan |
| KAZ | Kazakhstan | LDS | Kazakhstan | Kazakhstan |
| KEN | Kenya | LDS | Kenya | Kenya |
| KIR | Kiribati | LDS | Kiribati | Kiribati |
| PRK | Korea, Democratic People's Republic of | LDS | Korea, Democratic People's Republic of | Korea, Democratic People's Republic of (North Korea) |
| KOR | Korea, Republic of | LDS | Korea, Republic of | Korea, Republic of (South Korea) |
| KWT | Kuwait | LDS | Kuwait | Kuwait |
| KGZ | Kyrgyzstan | LDS | Kyrgyzstan | Kyrgyzstan |
| LAO | Lao People's Democratic Republic | LDS | Lao People's Democratic Republic | Lao People's Democratic Republic |
| LVA | Latvia | WDS | Latvia | Latvia |
| LBN | Lebanon | LDS | Lebanon | Lebanon |
| LSO | Lesotho | LDS | Lesotho | Lesotho |
| LBR | Liberia | LDS | Liberia | Liberia |
| LBY | Libya | LDS | Libya | Libya |
| LIE | Liechtenstein | WDS | Liechtenstein | Liechtenstein |
| LTU | Lithuania | WDS | Lithuania | Lithuania |
| LUX | Luxembourg | WDS | Luxembourg | Luxembourg |
| MAC | Macao | LDS | China | Macao |
| MKD | Macedonia | LDS | Macedonia | Macedonia |
| MDG | Madagascar | LDS | Madagascar | Madagascar |
| MWI | Malawi | LDS | Malawi | Malawi |
| MYS | Malaysia | LDS | Malaysia | Malaysia |
| MDV | Maldives | LDS | Maldives | Maldives |
| MLI | Mali | LDS | Mali | Mali |
| MLT | Malta | WDS | Malta | Malta |
| MHL | Marshall Islands | LDS | Marshall Islands | Marshall Islands |
| MTQ | Martinique | LDS | France | Martinique |
| MRT | Mauritania | LDS | Mauritania | Mauritania |
| MUS | Mauritius | LDS | Mauritius | Mauritius |
| MYT | Mayotte | LDS | France | Mayotte |
| MEX | Mexico | LDS | Mexico | Mexico |
| FSM | Micronesia | LDS | Micronesia | Micronesia, Federated State of |
| MDA | Moldova | LDS | Moldova | Moldova, Republic of |
| MNG | Mongolia | LDS | Mongolia | Mongolia |
| MNE | Montenegro | LDS | Montenegro | Montenegro |
| MSR | Montserrat | LDS | United Kingdom | Montserrat |
| MAR | Morocco | LDS | Morocco | Morocco |
| MOZ | Mozambique | LDS | Mozambique | Mozambique |
| MMR | Myanmar | LDS | Myanmar | Myanmar |
| NAM | Namibia | LDS | Namibia | Namibia |
| NPL | Nepal | LDS | Nepal | Nepal |

| ISO Code | Geographical name | Type | Main country (dependency) | Full information |
|---|---|---|---|---|
| NLD | Netherlands | WDS | Netherlands | Netherlands |
| ANT | Netherlands Antilles | LDS | Netherlands | Netherlands Antilles, merged with: Bonaire, Sint Eustatius, Saba [BES], Curacao [CUW] |
| NCL | New Caledonia | LDS | France | New Caledonia |
| NZL | New Zealand | WDS | New Zealand | New Zealand |
| NIC | Nicaragua | LDS | Nicaragua | Nicaragua |
| NER | Niger | LDS | Niger | Niger |
| NGA | Nigeria | LDS | Nigeria | Nigeria |
| NIU | Niue | LDS | New Zealand | Niue |
| NFK | Norfolk Island | LDS | Australia | Norfolk Island |
| MNP | Northern Mariana Islands | LDS | United States of America | Northern Mariana Islands |
| NOR | Norway | WDS | Norway | Norway |
| OMN | Oman | LDS | Oman | Oman |
| PAK | Pakistan | LDS | Pakistan | Pakistan |
| PLW | Palau | LDS | Palau | Palau |
| PSE | Palestine | LDS | Palestine | Palestine, State of |
| PAN | Panama | LDS | Panama | Panama |
| PNG | Papua New Guinea | LDS | Papua New Guinea | Papua New Guinea |
| PRY | Paraguay | LDS | Paraguay | Paraguay |
| PER | Peru | LDS | Peru | Peru |
| PHL | Philippines | LDS | Philippines | Philippines |
| PCN | Pitcairn | LDS | United Kingdom | Pitcairn |
| POL | Poland | WDS | Poland | Poland |
| PRT | Portugal | WDS | Portugal | Portugal |
| PRI | Puerto Rico | LDS | United States of America | Puerto Rico |
| QAT | Qatar | LDS | Qatar | Qatar |
| REU | Reunion | LDS | France | Reunion |
| ROU | Romania | WDS | Romania | Romania |
| RUS | Russian Federation | LDS | Russian Federation | Russian Federation |
| RWA | Rwanda | LDS | Rwanda | Rwanda |
| BLM | Saint Barthelemy | LDS | France | Saint Barthelemy |
| SHN | Saint Helena, Ascension and Tristan Da Cunha | LDS | United Kingdom | Saint Helena, Ascension and Tristan Da Cunha |
| KNA | Saint Kitts and Nevis | LDS | Saint Kitts and Nevis | Saint Kitts and Nevis |
| LCA | Saint Lucia | LDS | Saint Lucia | Saint Lucia |
| SPM | Saint Pierre and Miquelon | LDS | France | Saint Pierre and Miquelon |
| VCT | Saint Vincent and The Grenadines | LDS | Saint Vincent and The Grenadines | Saint Vincent and The Grenadines |
| WSM | Samoa | LDS | Samoa | Samoa |
| SMR | San Marino | WDS | San Marino | San Marino |
| STP | Sao Tome and Principe | LDS | Sao Tome and Principe | Sao Tome and Principe |
| SAU | Saudi Arabia | LDS | Saudi Arabia | Saudi Arabia |
| SEN | Senegal | LDS | Senegal | Senegal |
| SRB | Serbia | LDS | Serbia | Serbia (including Kosovo) |
| SYC | Seychelles | LDS | Seychelles | Seychelles |
| SLE | Sierra Leone | LDS | Sierra Leone | Sierra Leone |
| SGP | Singapore | LDS | Singapore | Singapore |
| SVK | Slovakia | WDS | Slovakia | Slovakia |
| SVN | Slovenia | WDS | Slovenia | Slovenia |
| SLB | Solomon Islands | LDS | Solomon Islands | Solomon Islands |
| SOM | Somalia | LDS | Somalia | Somalia |
| ZAF | South Africa | LDS | South Africa | South Africa |

| ISO Code | Geographical name | Type | Main country (dependency) | Full information |
|---|---|---|---|---|
| SGS | South Georgia and South Sandwich Islands | LDS | United Kingdom | South Georgia and The South Sandwich Islands |
| ESP | Spain | WDS | Spain | Spain, merged with: Gibraltar [GIB] |
| LKA | Sri Lanka | LDS | Sri Lanka | Sri Lanka |
| SDN | Sudan | LDS | Sudan | Sudan, merged with: South Sudan [SSD] |
| SUR | Suriname | LDS | Suriname | Suriname |
| SJM | Svalbard, Jan Mayen | LDS | Norway | Svalbard, Jan Mayen |
| SWE | Sweden | WDS | Sweden | Sweden |
| CHE | Switzerland | WDS | Switzerland | Switzerland |
| SYR | Syrian Arab Republic | LDS | Syrian Arab Republic | Syrian Arab Republic |
| TWN | Taiwan | LDS | China | Taiwan, Province of China |
| TJK | Tajikistan | LDS | Tajikistan | Tajikistan |
| TZA | Tanzania | LDS | Tanzania | Tanzania, United Republic of |
| THA | Thailand | LDS | Thailand | Thailand |
| TLS | Timor-Leste | LDS | Timor-Leste | Timor-Leste |
| TGO | Togo | LDS | Togo | Togo |
| TKL | Tokelau | LDS | New Zealand | Tokelau |
| TON | Tonga | LDS | Tonga | Tonga |
| TTO | Trinidad and Tobago | LDS | Trinidad and Tobago | Trinidad and Tobago |
| TUN | Tunisia | LDS | Tunisia | Tunisia |
| TUR | Turkey | WDS | Turkey | Turkey |
| TKM | Turkmenistan | LDS | Turkmenistan | Turkmenistan |
| TCA | Turks and Caicos Islands | LDS | United Kingdom | Turks and Caicos Islands |
| TUV | Tuvalu | LDS | Tuvalu | Tuvalu |
| UGA | Uganda | LDS | Uganda | Uganda |
| UKR | Ukraine | WDS | Ukraine | Ukraine |
| ARE | United Arab Emirates | LDS | United Arab Emirates | United Arab Emirates |
| GBR | United Kingdom | WDS | United Kingdom | United Kingdom |
| UMI | United States Minor Outlying Islands | LDS | United States of America | United States Minor Outlying Islands |
| USA | United States of America | WDS | United States of America | United States of America |
| URY | Uruguay | LDS | Uruguay | Uruguay |
| UZB | Uzbekistan | LDS | Uzbekistan | Uzbekistan |
| VUT | Vanuatu | LDS | Vanuatu | Vanuatu |
| VEN | Venezuela | LDS | Venezuela | Venezuela, Bolivarian Republic of |
| VNM | Viet Nam | LDS | Viet Nam | Viet Nam |
| VGB | Virgin Islands British | LDS | United Kingdom | Virgin Islands British |
| VIR | Virgin Islands United States | LDS | United States of America | Virgin Islands United States |
| WLF | Wallis and Futuna | LDS | France | Wallis and Futuna |
| ESH | Western Sahara | LDS | Western Sahara | Western Sahara |
| YEM | Yemen | LDS | Yemen | Yemen |
| ZMB | Zambia | LDS | Zambia | Zambia |
| ZWE | Zimbabwe | LDS | Zimbabwe | Zimbabwe |
| SEA | Ocean | LDS | Ocean | Ocean, merged with: Nauru [NRU] |

In addition, for comparison reasons, four extra geographical entities were introduced; i.e. Europe (28 members until end 2019) [E28], all countries with well-/less well-developed statistical systems [GL1/GL2], and all world countries (including ocean) [GLB]. For several geographical entity uncertainty aggregations (e.g. Europe (28 members until end 2019)) emissions are considered to be fully uncorrelated, following the suggestion from IPCC (2006).

### S.6 Fuel specific information

The EDGAR dataset with incorporated fuel-specific activity data, emission factor uncertainties and Tier 1 approach for uncertainty calculation from IPCC (2006) is hereinafter referred to as EDGAR-JRC. Table S7 shows $CO_2$ emission factor uncertainties by process or fuel type (based on Table 3.2.1 of IPCC (2006)) as used in EDGAR-JRC. Uncertainties are specified for countries with well- and less well-developed statistical infrastructures. Upper and lower ranges refer to the 95 % confidence interval of the mean. No specification means that process or fuel type uncertainty was applied to all sectors.

**Table S7: Prior uncertainties (lower and upper bounds) per each process or fuel type from EDGAR-JRC dataset and two geographical entity types (countries with well- (WDS) and less well-developed (LDS) statistical infrastructures)**

| Fuel type | Specification | Prior uncertainty bounds, % | | | |
|---|---|---|---|---|---|
| | | WDS countries | | LDS countries | |
| | | Low | Up | Low | Up |
| Motor Gasoline | | 2.6 | 5.3 | 5.3 | 5.3 |
| Aviation Gasoline | | 3.6 | 4.3 | 4.3 | 4.3 |
| Gas/Diesel Oil | | 2.0 | 1.0 | 2.0 | 2.0 |
| Liquefied Petroleum Gases (LPG) | | 2.3 | 4.0 | 4.0 | 4.0 |
| Kerosene | | 2.0 | 3.0 | 3.0 | 3.0 |
| Naphta, Lubricants, Refinery Feedstocks' Soda, Paraffin Waxes, White Spirit, Non-specified Petroleum Products, Other Hydrocarbon | in road transport sector | 1.9 | 2.6 | 2.6 | 2.6 |
| | in Lubricant and Naphta in commercial and residential sectors | 1.5 | 1.5 | 1.5 | 1.5 |
| | in energy, industry, transformation and residential sectors | 3.0 | 3.0 | 3.0 | 3.0 |
| Natural Gas | | 3.2 | 3.9 | 3.9 | 3.9 |
| Natural Gas Liquids | | 9.2 | 9.6 | 9.6 | 9.6 |
| Anthracite | | 3.8 | 2.7 | 3.8 | 3.8 |
| Biogasoline, Biodiesel | | 15.5 | 19.1 | 19.1 | 19.1 |
| Blast Furnace Gas | | 15.8 | 18.5 | 18.5 | 18.5 |
| Additives/Blending Components | in residential sector | 1.5 | 1.5 | 1.5 | 1.5 |
| | in all other sectors | 3.0 | 3.0 | 3.0 | 3.0 |
| Crude Oil | | 1.5 | 1.5 | 1.5 | 1.5 |
| Bitumen | | 15.5 | 18.1 | 18.1 | 18.1 |
| Sub-Bituminous Coal | | 3.4 | 4.0 | 4.0 | 4.0 |
| BKB/Peat Briquettes | | 14.5 | 18.0 | 18.0 | 18.0 |
| Brown Coal | | 10.0 | 14.0 | 14.0 | 14.0 |
| Other Bituminous Coal | | 7.7 | 6.8 | 7.7 | 7.7 |
| Charcoal | | 25.0 | 25.0 | 25.0 | 25.0 |
| Ethane | | 8.3 | 11.3 | 11.3 | 11.3 |
| Biogas | | 50.0 | 50.0 | 50.0 | 50.0 |
| Gas Coke | | 16.0 | 17.0 | 17.0 | 17.0 |
| Gas Works Gas | | 16.0 | 22.0 | 22.0 | 22.0 |
| Residual Fuel Oil | | 2.4 | 1.8 | 2.4 | 2.4 |
| Municipal Waste (Renew) in Fuel Combustion Petrole | | 7.0 | 7.0 | 7.0 | 7.0 |
| Bagasse in Pumped Storage of Electricity | | 7.0 | 7.0 | 7.0 | 7.0 |
| Heat Output from Non-specified Manufacture Gases | | 7.0 | 7.0 | 7.0 | 7.0 |
| Primary Solid Biomass in Fuel Combustion Petroleum | | 16.0 | 17.0 | 17.0 | 17.0 |
| Shale Oil | | 16.0 | 17.0 | 17.0 | 17.0 |
| Petroleum Coke | | 15.0 | 18.0 | 18.0 | 18.0 |
| Coke Oven Coke | | 10.5 | 11.2 | 11.2 | 11.2 |

| | | | | | |
|---|---|---|---|---|---|
| Coke Oven Gas | | 16.0 | 22.0 | 22.0 | 22.0 |
| Coking and Hard Coal | | 7.7 | 7.0 | 7.7 | 7.7 |
| Coal Tar | | 0.1 | 11.4 | 11.4 | 11.4 |
| Crude/NGL/Feedstock | | 3.0 | 3.0 | 3.0 | 3.0 |
| Gasoline Jet Fuel | | 2.6 | 4.3 | 4.3 | 4.3 |
| Kerosene Jet Fuel | | 2.5 | 4.0 | 4.0 | 4.0 |
| Industrial Waste | | 23.0 | 28.0 | 28.0 | 28.0 |
| Municipal Waste | | 20.0 | 32.0 | 32.0 | 32.0 |
| Oxygen Steel Furnace Gas | | 20.0 | 11.0 | 20.0 | 20.0 |
| Patent Fuel | | 15.0 | 18.0 | 18.0 | 18.0 |
| Peat | | 5.7 | 1.9 | 5.7 | 5.7 |
| Refinery Gas | | 16.3 | 20.0 | 20.0 | 20.0 |
| Venting and Flaring during Oil and Gas Production, Oil Transmission, Transport by Oil Trucks | | 50.0 | 50.0 | 75.0 | 75.0 |
| Crude Oil, Natural Gas, Gasoline, Diesel, Residual Fuel Oil, LPG, Ethane, Naphta, Bitumen, White Spirit, Anthracite, Other Bituminous Coal, Gas Coke, Gas Works Gas, Blast Furnace Gas, Biodiesel, BKB/Peat Briquettes, Renewables Wastes (1B1c only, Coke Ovens input: Non-specified Combust) | in fuel transformation coke ovens | 50.0 | 50.0 | 50.0 | 50.0 |
| | in fuel transformation of gaseous fuels (non-specified transformation) | 100.0 | 100.0 | 100.0 | 250.0 |
| | in other non-energy use of fuels in industry | 100.0 | 100.0 | 100.0 | 100.0 |
| | in blast furnaces | 25.0 | 25.0 | 25.0 | 25.0 |
| Production | cement | 11.0 | 11.0 | 61.0 | 61.0 |
| | lime | 2.0 | 2.0 | 2.0 | 2.0 |
| | limestone | 3.0 | 3.0 | 3.0 | 3.0 |
| | ammonia | 7.0 | 7.0 | 7.0 | 7.0 |
| | titanium | 7.0 | 7.0 | 7.0 | 7.0 |
| | silicon, calcium | 10.0 | 10.0 | 10.0 | 10.0 |
| | ethylene, methanol | 30.0 | 30.0 | 30.0 | 30.0 |
| | vinyl | 50.0 | 20.0 | 50.0 | 50.0 |
| | carbon black, urea | 15.0 | 15.0 | 15.0 | 15.0 |
| | steel, ferroalloys | 25.0 | 25.0 | 25.0 | 25.0 |
| | aluminium | 10.0 | 10.0 | 10.0 | 10.0 |
| | magnesium | 5.0 | 5.0 | 5.0 | 5.0 |
| | lead, zinc | 50.0 | 50.0 | 50.0 | 50.0 |
| | glass | 60.0 | 60.0 | 60.0 | 60.0 |
| Solvents | | 25.0 | 25.0 | 25.0 | 25.0 |
| $CO_2$ from Urea, Dolomite, and Limestone Application | C in urea fertilizer applied | 50.0 | 50.0 | 100.0 | 100.0 |
| Oil/Coal Fires | | 100.0 | 100.0 | 100.0 | 100.0 |
| Waste Incineration without Energy Recovery | | 40.0 | 40.0 | 40.0 | 40.0 |

Uncertainties from the EDGAR-JRC dataset aggregated to "groups" were compared with the ones from CHE_EDGAR-ECMWF_2015 (Choulga et al., 2020), see Table S8 for selected countries. Comparison showed that uncertainties derived in this study are an upper bound of the uncertainty estimation with more detailed information. Even though sometimes differences might be quite high in percent, they are usually quite small in Megatonne.

**Table S8: Aggregated to "group" uncertainties (lower and upper bounds) in percent and contributions in percent to the total uncertainty (CV) for selected geographical entities from EDGAR-JRC (with extra fuel type knowledge) and CHE_EDGAR-ECMWF_2015 (with typical fuel knowledge only)**

| Country | "Group" name | EDGAR-JRC | | | CHE_EDGAR-ECMWF_2015 | | |
|---|---|---|---|---|---|---|---|
| | | Low, % | Up, % | CV, % | Low, % | Up, % | CV, % |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| DEU | ENERGY_S | 0.0 | 0.0 | 0.0 | -8.6 | 3.0 | 0.3 |
| | ENERGY_A | -5.6 | 7.1 | 67.5 | -8.6 | 8.6 | 19.1 |
| | MANUFACTURING | -6.1 | 6.3 | 9.8 | -11.5 | 17.0 | 22.5 |
| | SETTLEMENTS | -6.8 | 6.9 | 12.2 | -12.2 | 12.2 | 10.3 |
| | AVIATION | -5.5 | 6.3 | 0.0 | -3.5 | 4.1 | 0.0 |
| | TRANSPORT | -3.9 | 4.0 | 4.8 | -5.3 | 5.7 | 2.5 |
| | OTHER | -15.5 | 15.5 | 5.8 | -31.2 | 139.3 | 45.3 |
| | *TOTAL* | *-3.0* | *3.6* | *100.0* | *-4.7* | *8.7* | *100.0* |
| ESP | ENERGY_S | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | ENERGY_A | -4.5 | 4.2 | 26.3 | -8.6 | 8.6 | 8.2 |
| | MANUFACTURING | -8.6 | 8.7 | 37.5 | -12.5 | 18.9 | 20.4 |
| | SETTLEMENTS | -5.8 | 5.9 | 6.1 | -12.2 | 12.2 | 3.0 |
| | AVIATION | -5.6 | 6.4 | 0.2 | -3.3 | 3.9 | 0.0 |
| | TRANSPORT | -4.2 | 4.1 | 16.1 | -5.3 | 6.1 | 3.3 |
| | OTHER | -13.7 | 14.0 | 13.7 | -32.5 | 146.3 | 65.0 |
| | *TOTAL* | *-2.7* | *2.7* | *100.0* | *-5.0* | *12.4* | *100.0* |
| FRA | ENERGY_S | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | ENERGY_A | -4.8 | 5.2 | 5.8 | -8.4 | 8.4 | 1.2 |
| | MANUFACTURING | -6.3 | 6.4 | 23.7 | -12.4 | 18.9 | 26.8 |
| | SETTLEMENTS | -6.0 | 6.1 | 27.0 | -12.2 | 12.2 | 14.9 |
| | AVIATION | -5.4 | 6.2 | 0.0 | -3.5 | 4.0 | 0.0 |
| | TRANSPORT | -4.5 | 4.3 | 28.1 | -5.3 | 5.3 | 5.6 |
| | OTHER | -17.0 | 17.0 | 15.4 | -31.0 | 138.6 | 51.5 |
| | *TOTAL* | *-2.8* | *2.8* | *100.0* | *-5.1* | *10.7* | *100.0* |
| GBR | ENERGY_S | 0.0 | 0.0 | 0.0 | -8.6 | 3.0 | 0.1 |
| | ENERGY_A | -6.6 | 6.1 | 52.4 | -8.6 | 8.6 | 7.7 |
| | MANUFACTURING | -6.0 | 6.1 | 4.6 | -10.7 | 15.4 | 7.1 |
| | SETTLEMENTS | -8.7 | 8.9 | 20.2 | -12.2 | 12.2 | 5.8 |
| | AVIATION | -5.4 | 6.3 | 0.0 | -3.5 | 4.1 | 0.0 |
| | TRANSPORT | -3.7 | 3.9 | 7.8 | -5.2 | 5.7 | 2.3 |
| | OTHER | -15.1 | 15.1 | 15.0 | -34.2 | 154.6 | 77.0 |
| | *TOTAL* | *-3.4* | *3.3* | *100.0* | *-4.8* | *13.2* | *100.0* |
| POL | ENERGY_S | 0.0 | 0.0 | 0.0 | -8.6 | 3.0 | 0.4 |
| | ENERGY_A | -6.7 | 7.2 | 72.1 | -8.6 | 8.6 | 31.1 |
| | MANUFACTURING | -8.7 | 8.8 | 10.1 | -14.1 | 21.9 | 21.2 |
| | SETTLEMENTS | -7.7 | 7.5 | 9.8 | -12.2 | 12.2 | 10.3 |
| | AVIATION | 0.0 | 0.0 | 0.0 | -5.2 | 6.1 | 0.0 |
| | TRANSPORT | -3.7 | 3.8 | 1.9 | -5.3 | 5.9 | 1.7 |
| | OTHER | -26.5 | 26.5 | 6.1 | -35.3 | 160.2 | 35.3 |
| | *TOTAL* | *-4.0* | *4.2* | *100.0* | *-5.0* | *8.3* | *100.0* |
| BRA | ENERGY_S | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | ENERGY_A | -5.6 | 5.6 | 0.8 | -12.1 | 12.1 | 0.4 |
| | MANUFACTURING | -8.2 | 8.3 | 26.6 | -14.3 | 22.5 | 32.7 |
| | SETTLEMENTS | -13.9 | 13.9 | 5.5 | -26.0 | 26.0 | 4.1 |
| | AVIATION | -67.3 | 136.8 | 24.4 | -25.6 | 86.3 | 1.4 |
| | TRANSPORT | -7.1 | 7.1 | 35.8 | -6.9 | 7.3 | 7.6 |
| | OTHER | -12.8 | 17.2 | 6.8 | -35.5 | 153.7 | 53.7 |
| | *TOTAL* | *-5.2* | *5.2* | *100.0* | *-6.7* | *15.4* | *100.0* |
| CHN | ENERGY_S | 0.0 | 0.0 | 0.0 | -8.6 | 3.0 | 0.0 |
| | ENERGY_A | -8.6 | 7.9 | 44.2 | -8.6 | 8.6 | 11.5 |
| | MANUFACTURING | -8.8 | 8.8 | 48.5 | -12.8 | 19.4 | 46.4 |
| | SETTLEMENTS | -8.5 | 8.2 | 1.0 | -12.2 | 12.2 | 0.6 |
| | AVIATION | -5.6 | 6.4 | 0.0 | -3.5 | 4.1 | 0.0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | TRANSPORT | -3.2 | 3.6 | 0.2 | -5.1 | 8.2 | 0.2 |
| | OTHER | -22.1 | 22.1 | 6.0 | -39.7 | 180.9 | 41.3 |
| | *TOTAL* | *-5.2* | *5.0* | *100.0* | *-6.7* | *13.4* | *100.0* |
| IDN | ENERGY_S | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | ENERGY_A | -7.2 | 7.2 | 29.0 | -12.2 | 12.2 | 7.8 |
| | MANUFACTURING | -8.5 | 8.5 | 22.9 | -14.2 | 21.5 | 33.5 |
| | SETTLEMENTS | -11.5 | 11.5 | 3.0 | -26.0 | 26.0 | 2.9 |
| | AVIATION | -67.8 | 139.0 | 14.3 | -24.4 | 82.2 | 0.3 |
| | TRANSPORT | -7.6 | 7.6 | 24.4 | -7.0 | 7.4 | 4.3 |
| | OTHER | -11.1 | 16.1 | 6.4 | -33.5 | 147.6 | 51.1 |
| | *TOTAL* | *-4.4* | *4.4* | *100.0* | *-6.6* | *14.2* | *100.0* |
| IND | ENERGY_S | 0.0 | 0.0 | 0.0 | -8.6 | 3.0 | 0.2 |
| | ENERGY_A | -6.3 | 5.8 | 63.4 | -8.6 | 8.6 | 23.7 |
| | MANUFACTURING | -8.5 | 8.4 | 31.0 | -10.7 | 15.2 | 39.4 |
| | SETTLEMENTS | -5.3 | 5.3 | 1.0 | -12.2 | 12.2 | 1.8 |
| | AVIATION | -5.6 | 6.4 | 0.0 | -3.5 | 4.1 | 0.0 |
| | TRANSPORT | -4.0 | 3.9 | 1.1 | -5.3 | 7.1 | 0.9 |
| | OTHER | -17.3 | 17.4 | 3.4 | -35.0 | 156.7 | 34.0 |
| | *TOTAL* | *-4.0* | *3.8* | *100.0* | *-5.2* | *9.0* | *100.0* |
| JPN | ENERGY_S | 0.0 | 0.0 | 0.0 | -8.6 | 3.0 | 0.2 |
| | ENERGY_A | -4.3 | 4.2 | 53.9 | -8.5 | 8.5 | 22.7 |
| | MANUFACTURING | -6.2 | 6.4 | 28.5 | -9.8 | 13.2 | 25.3 |
| | SETTLEMENTS | -5.4 | 5.5 | 6.7 | -12.2 | 12.2 | 5.9 |
| | AVIATION | -5.6 | 6.4 | 0.0 | -3.4 | 4.0 | 0.0 |
| | TRANSPORT | -3.9 | 4.8 | 7.0 | -5.3 | 5.3 | 1.7 |
| | OTHER | -13.2 | 13.3 | 3.9 | -39.5 | 180.1 | 44.1 |
| | *TOTAL* | *-2.6* | *2.6* | *100.0* | *-4.7* | *8.5* | *100.0* |
| RUS | ENERGY_S | 0.0 | 0.0 | 0.0 | -12.2 | 3.0 | 0.5 |
| | ENERGY_A | -7.2 | 7.2 | 61.4 | -12.2 | 12.2 | 8.6 |
| | MANUFACTURING | -7.4 | 7.4 | 8.1 | -12.1 | 15.7 | 18.2 |
| | SETTLEMENTS | -13.6 | 13.6 | 6.0 | -26.0 | 26.0 | 4.0 |
| | AVIATION | -67.6 | 138.0 | 5.3 | -25.4 | 85.8 | 0.3 |
| | TRANSPORT | -6.6 | 6.6 | 2.7 | -14.1 | 44.8 | 10.4 |
| | OTHER | -22.0 | 26.9 | 16.6 | -39.2 | 174.3 | 58.1 |
| | *TOTAL* | *-4.7* | *4.9* | *100.0* | *-6.8* | *16.2* | *100.0* |
| USA | ENERGY_S | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | ENERGY_A | -4.0 | 4.0 | 44.9 | -8.6 | 8.6 | 22.3 |
| | MANUFACTURING | -6.2 | 6.3 | 6.2 | -12.5 | 18.9 | 5.9 |
| | SETTLEMENTS | -7.9 | 8.1 | 13.2 | -12.2 | 12.2 | 3.6 |
| | AVIATION | -5.5 | 6.4 | 0.5 | -3.5 | 4.1 | 0.0 |
| | TRANSPORT | -4.0 | 5.1 | 30.2 | -5.5 | 8.7 | 8.3 |
| | OTHER | -8.6 | 8.8 | 5.0 | -32.1 | 145.2 | 59.9 |
| | *TOTAL* | *-2.3* | *2.5* | *100.0* | *-4.7* | *10.4* | *100.0* |

*Data availability.* EDGARv4.3.2 data are open access and available at http://edgar.jrc.ec.europa.eu/overview.php?v=432&SECURE=123, last access: 29 June 2021, doi:https://data.europa.eu/doi/10.2904/JRC_DATASET_EDGAR, documented in Janssens-Maenhout et al. (2019). CHE_EDGAR-ECMWF_2015 data (Choulga et al., 2020) are freely available https://doi.org/10.5281/zenodo.3967439, and documented in the main part of this paper. CHE_UNC_APP anthropogenic $CO_2$ emission uncertainty calculation tool (Choulga et al., 2021) is freely available https://doi.org/10.5281/zenodo.5196190, and documented in this paper.

*Author contribution.* All the authors participated in the uncertainty calculation tool CHE_UNC_APP design and CHE_EDGAR-ECMWF_2015 maps generation (methodology, data generation), model experiment set-up, and analysis of the result. Margarita Choulga and Greet Janssens-Maenhout wrote the manuscript with contributions from all the other authors.

*Competing interests.* The authors declare that they have no conflict of interest.

*Acknowledgements.* The authors thank Glenn Carver (ECMWF) for editorial help and assistance; Vladimir Tupoguz for invaluable support during the preparation of the paper and numerous discussions. Margarita Choulga was funded by the $CO_2$ Human Emissions (CHE) project which received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 776186, and by the Prototype system for a Copernicus $CO_2$ service ($CoCO_2$) project which received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 958927.

*Financial support.* This research has been supported by CHE (grant no. 776186) and CoCO2 (grant no. 958927).

**References**

CHE: $CO_2$ Human Emissions (CHE) project official website, available at: https://www.che-project.eu, last access: 29 June 2021.

Choulga, M., McNorton, J., Janssens-Maenhout, G.: CHE_EDGAR-ECMWF_2015 [Data set], Zenodo, doi:10.5281/zenodo.3712339, 2020.

Choulga, M., Janssens-Maenhout, G., McNorton, J.: Anthropogenic $CO_2$ emission uncertainty calculation tool CHE_UNC_APP [Software], Zenodo, https://doi.org/10.5281/zenodo.5196190, 2021.

Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., Bergamaschi, P., Pagliari, V., Olivier, J. G. J., Peters, J. A. H. W., van Aardenne, J. A., Monni, S., Doering, U., Petrescu, A. M. R., Solazzo, E., and Oreggioni, G. D.: EDGAR v4.3.2 Global Atlas of the three major greenhouse gas emissions for the period 1970–2012, Earth Syst. Sci. Data, 11, 959-1002, https://doi.org/10.5194/essd-11-959-2019, 2019.

Janssens-Maenhout, G., Pinty, B., Dowell, M., Zunker, H., Andersson, E., Balsamo, G., Bézy, J.-L., Brunhes, T., Bösch, H., Bojkov, B., Brunner, D., Buchwitz, M., Crisp, D., Ciais, P., Counet, P., Dee, D., Denier van der Gon, H., Dolman, H., Drinkwater, M., Dubovik, O., Engelen, R., Fehr, T., Fernandez, V., Heimann, M., Holmlund, K., Houseling, S., Husband, R., Juvyns, O., Kentarchos, A.,. Landgraf, J., Lang, R., Löscher, A., Marshall, J., Meijer, Y., Nakajima, M., Palmer, P., Peylin,

P., Rayner, P., Scholze, M., Sierk, B., and Veefkind, P.: Towards an operational anthropogenic $CO_2$ emissions monitoring and verification support capacity, Bull. Amer. Meteor. Soc., 0, doi:10.1175/BAMS-D-19-0017.1, 2020.

IEA: Energy Balances of OECD and non-OECD countries, International Energy Agency, Paris, Beyond 2020 Online Database, available at: http://data.iea.org, last access: 29 June 2021.

IPCC: 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Eggleston, S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K. (eds.). IPCC-TSU NGGIP, IGES, Hayama, Japan. www.ipcc-nggip.iges.or.jp/public/2006gl/index.html, 2006.

IPCC: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Calvo Buendia, E., Guendehou, S., Limmeechokchai, B., Pipatti, R., Rojas, Y., Sturgiss, R., Tanabe, K., Wirth, T., Romano, D., Witi, J., Garg, A., Weitz, M.M., Bofeng, C., Ottinger, D.A., Dong, H., MacDonald, J.D., Ogle, S.M., Theoto Rocha, M., Sanz Sanchez, M.J., Bartram, D.M., and Towprayoon, S. (aut.); Gomez, D. and Irving, W. (eds.), Vol1. Ch.8, May 2019.

McNorton, J., Bousserez, N., Agusti-Panareda, A., Balsamo, G., Choulga, M., Dawson, A., Engelen, R., Kiping, Z., and Lang, S.: Representing Model Uncertainty for Global Atmospheric $CO_2$ Flux Inversions Using ECMWF-IFS-46R1, Geoscientific Model Development Discussions, 2020, 1-30, https://doi.org/10.5194/gmd-2019-314, 2020.

Olivier, J.G.J., Janssens-Maenhout, G., Muntean, M., and Peters, J.A.H.W: Trends in global $CO_2$ emissions: 2016 report, JRC 103425, https://edgar.jrc.ec.europa.eu/news_docs/jrc-2016-trends-in-global-co2-emissions-2016-report-103425.pdf, 2016b.