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

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, $\cdot 10^{-6}$ $kg\cdot m^{-2}\cdot s^{-1}$	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

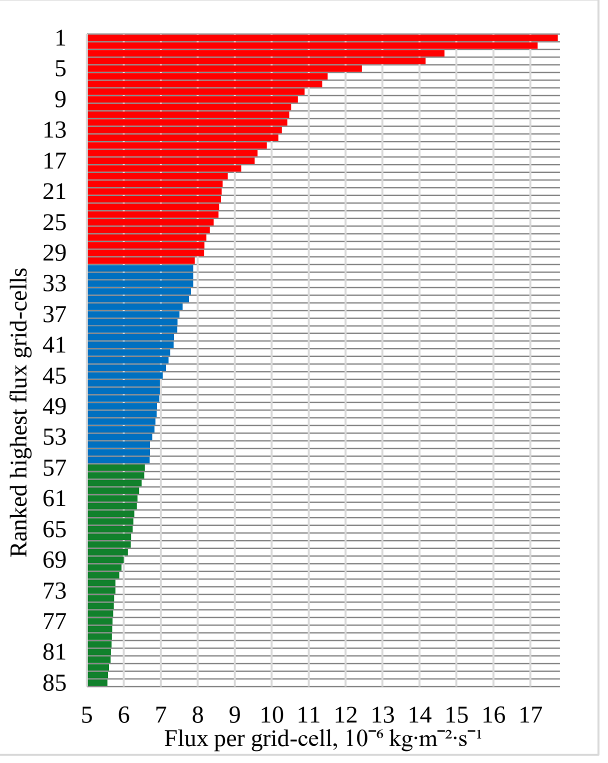

Figure S1: Ranked highest 2015 CO_2 flux values from 85 grid-cells globally (see Table S1), red colour represent grid-cells where energy is generated by super power plants, blue and green colours show possible extension of the new field based on the step change in the grid-cell values

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

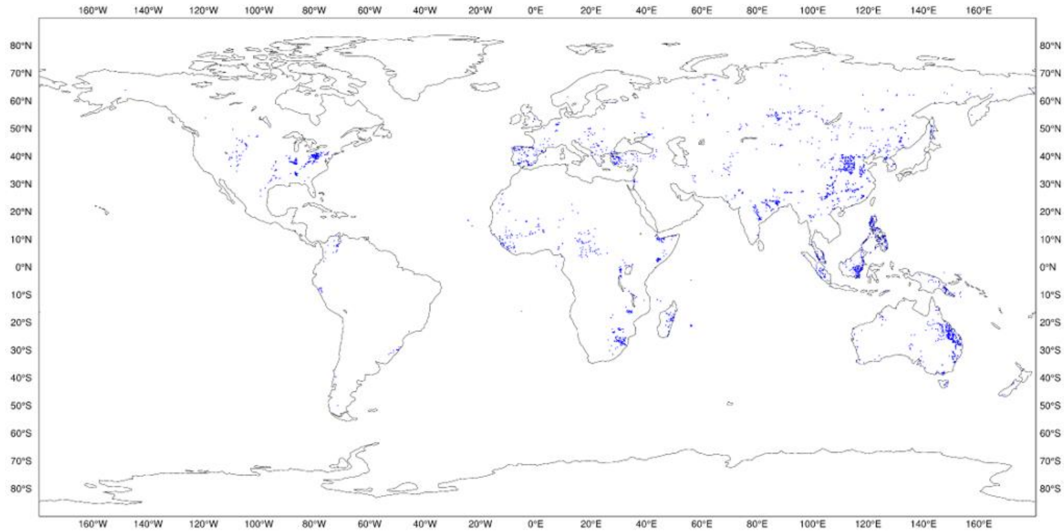

Figure S2: Global distribution of the CO_2 emission sources from coal production based on 2012 CH_4 emissions data for brown and hard coal, locations of underground mines are marked with blue dots

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 μg and geometric standard deviations σg 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 μ^{ln} and standard σ^{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 μ^{ln} and standard deviation σ^{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.

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

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”; 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”; 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”; 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”; 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; 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"
PlottingMonthlyGrou pedUncertainties	(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
PlottingMonthlyGrou pedPDF	(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.

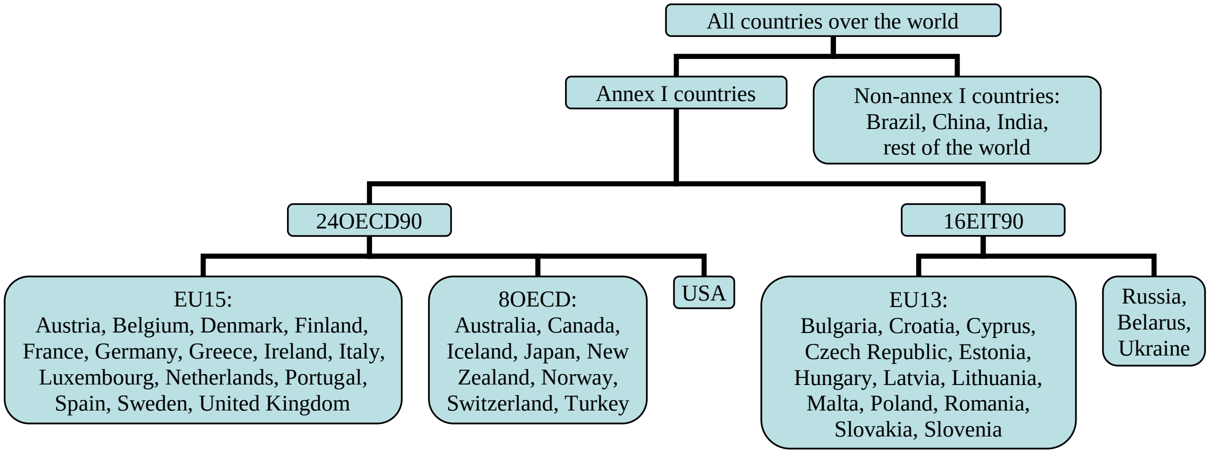

Figure S3: Schematic grouping of world countries

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.