Global Anthropogenic CO_2 Emission Budgets & Uncertainties

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D3.3 Fossil CO2 emissions per sector

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1 Executive Summary

This document reports on progress and current status within WP3 regarding the “Global Anthropogenic CO_2 Emission Budgets & Uncertainties” developed and needed in CHE. The scope of WP3 “Coordinating efforts on Uncertainty trade-off for fossil fuel emissions” is to generate a reliable uncertainty band with global and regional coverage for the yearly (and possibly monthly) emission budgets, that are the composite of biospheric fluxes and anthropogenic fluxes. Uncertainties are key when connecting in a bidirectional way the bottom-up inventories with the top down assimilations.

This report is the outcome of Task 3.3 "Providing emission uncertainties and correlations from inventories and statistics" and focusses on the anthropogenic component. Starting from 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC2006) and considering 2019 Refinements to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC2019) the global grid-maps of EDGARv4.3.2_FT2015 inventory delivering anthropogenic CO_2 emissions for 2015 were updated with improved apportionment of the energy sector and the energy used for manufacturing and with diffusive CO_2 emissions from coal mines. Uncertainties were calculated per country and sector considering the most typical fuel type using the error propagation method. According to the IPCC2006 guidance all emissions are considered to be fully uncorrelated, this assumption is further used to calculate uncertainty and covariance matrices. The uncertainties and the share to the total uncertainty are presented for the 7 ECMWF groups of sectors and two distinct country types with well and less developed statistical infrastructure. While the uncertainty of most groups remains small, the largest contribution to the total uncertainty is determined by rather small but relative uncertain group OTHER, which consists of oil refineries and transformation industry, fuel exploitation, coal production, agricultural soils and solvents and products use emissions.

2 Introduction

2.1 Background

Bottom-up emission inventory compilation needs to improve on the evaluation of uncertainties: the relative errors for sector-specific country totals and the trend uncertainties of these with the appropriate probability density functions are needed.

It should be noted that fossil fuels form a relatively small part of the natural geologic cycles in most locations, except for cities and close to power plants where fossil-fuel emissions are concentrated. This leads to a differentiation between point source emissions (i.e. energy and industry – have very strong local impact) and all the other with a wider spatial distribution of the emissions.

2.2 Scope of this deliverable

2.2.1 Objectives of this deliverable

For WP3 this deliverable aims to fulfil the following objectives:

1. determining uncertainties of the prior emission fields that are input to the atmospheric models;

2. determining the sensitivity of the emissions on relevant parameters at a variety of scales, assessing the increase in uncertainty when increasing the spatio-temporal resolution and evaluating the sensitivity of spatio-temporal profiles for the distribution of the emissions.

3. assessing emission uncertainties and preparing uncertainty grid-maps and covariance matrices for the modelling system of ECMWF.

2.2.2 Work performed in this deliverable

JRC has provided the EDGARv4.3.2_FT2015 emission budgets (in WP2). ECMWF in consultation with JRC has computed the uncertainties per country and sector (most typical fuel per sector is used) following the error propagation method and delivered grid-maps for lower and upper uncertainty band at 0.1deg x 0.1deg resolution and sectoral emission covariance matrices for the atmospheric simulations.

2.2.3 Deviations and counter measures

Although the dataset was delivered on time, intercomparison with the TNO emission dataset for European region induced some further iterations of anthropogenic CO_2 emission improvements globally which lead to the considerable improvements of the uncertainty estimates. These new insights were beneficial to ECWMF, TNO and JRC and are taken up in the final version of the uncertainty dataset. Because of these improvements the final dataset can be considered evaluated over Europe. It should be noted that the global dataset might be slightly biased towards a "European calibration".

3 Global sector-specific CO_2 emission grid-maps of EDGAR for 2015

Global gridded anthropogenic CO_2 emissions at 0.1deg x 0.1deg are input to WPs 2 and 3 for the nature run with year 2015 (EDGARv4.3.2_FT2015). These anthropogenic CO_2 emissions include all fossil CO_2 sources:

- fossil fuel combustion,
- non-metallic mineral processes (e.g. cement production),
- metal (ferrous and non-ferrous) production processes,
- urea production,
- agricultural liming,
- solvents use.

It should be noted that the large-scale biomass burning with Savannah burning, forest fires, and the sources and sinks from land-use, land-use change and forestry (LULUCF) are not considered here. Following the UNFCCC national inventory reporting guidelines, emissions of biofuel combustion are only a memo item and have to be reported under the LULUCF sector. Together with all short-cycle carbon emissions they are excluded from this study and from the bottom-up inventories underneath.

3.1 EDGARv4.3.2_FT2015 grids

The EDGARv4.3.2 emission dataset of Janssens-Maenhout et al. (2019) with annual 1970-2012 and monthly 2010 gridded emissions is used in combination with the EDGARv4.3.2_FT2015 time series update 2015 of Olivier et al. (2016) for the nature runs of WP2. The detailed EDGARv4.3.2 with the full-fledged anthropogenic emission sectors (excluding large scale biomass burning and land-use, land-use change and forestry sources and sinks) provides the basis grid-map with detailed spatial information per sector for 2012. This special distribution is used later on for mapping an updated 2015 emission values. For the update the fast track approach of Olivier et al. (2016) is used. EDGARv4.3.2_FT2015 distribution is based on 2012, statistical emission values are mainly from IEA (2016) energy statistics (missing years are filled with BP (2017) statistics). The relative changes per sector, fuel type and country from 2012 to 2015 are then applied on the EDGARv4.3.2 reference maps to obtain EDGARv4.3.2_FT2015.

After the final comparison of country/sector budgets used in this study with the ones from TNO it was revealed that energy and industry sectors need extra pre-processing of the data. EDGARv4.3.2_FT2015 energy sector emissions were divided into autoproducers and the rest. The autoproducing energy part was added to the industry sector as it is directly used for manufacturing, and not for power generation in general. The autoproducers part is reported in the energy statistics by every country separately (IEA, 2016). These reported values were shared with ECMWF by JRC, and prior implementation were limited to 30 % maximum.

In addition, the remaining energy sector was divided into one produced by super power plants, and one produced by average (non-super) power plants. As super power plants are considered grid-cells with annual flux $7.9 \cdot 10^{-6}$ $kg \cdot m^{-2} \cdot s^{-1}$ and higher. In total there are 30 super power plant grid-cells, all the remaining energy sector grid-cells are assumed to have emissions from the average power plants.

Primarily uncertainty calculation study was based on IPCC1996 and IPCC2006, but further updated and expanded with the recommendations in the 2019 Refinement of the IPCC2006 guildelines. One of the new additions in the IPCC2019 for CO_2 in is the treatment of CO_2 emissions from coal mining. IPCC2006 did not include these, whereas IPCC2019 suggests taking these into account. Even though this emission source is not that large, it was decided to generate an additional map for EDGARv4.3.2_FT2015 with coal mining emissions. For this purpose global gridded maps at 0.1deg x 0.1deg horizontal resolution of CH_4 emissions from hard coal and brown coal 2012 production provided by JRC in NetCDF format were used. According to IPCC2019 CO_2 is mainly emitted during underground mining, emissions from surface mining should be neglected. First, hard and brown coal CH_4 emission fields had to be separated into underground and surface mining emissions. Surface mines are usually represented by the large area (several touching grid-cells), underground mines – only by the mine entrance (one or maximum two touching grid-cells). For surface mining only values from grid-cells with 6 and more (up to 8) zero neighbors were used. Next, values from hard and brown coal fields are summed together and finally translated from CH_4 into CO_2 emissions by multiplying all values with (5.9/18) constant, result is in $kg \cdot m^{-2} \cdot s^{-1}$.

3.2 Access to the data

All initial EDGARv4.3.2_FT2015 grid-maps with anthropogenic CO_2 long cycle C emissions can be downloaded from ftp://edgar.jrc.ec.europa.eu/v432_FT_CHE/v432_FT_CHE.zip (anonymous) in .txt with bottom left grid coordinates of the 0.1deg x 0.1deg grid cells, expressing the emissions in ton CO_2/yr/(0.1deg x 0.1deg) for each of the 20 sectors:

- AGS (agricultural soils),
- CHE (chemical processes),
- ENE (energy generation),
- FFF (fossil fuel fires),
- IND (industrial manufacturing),
- IRO (iron & steel processes),
- NEU (non-energy use),
- NFE (non-ferrous metals production),
- NMM (non-metallic mineral processes),
- PRO (fossil fuel production),
- PRU-SOL (products use and solvents),
- RCO (energy for buildings),
- REF-TRF (refineries and transformation),
- SWD-INC (solid waste incineration),
- TNR-Aviation-LTO/CDS/CRS (aviation at 3 height levels: landing-takeoff, climbing-descent, cruise),
- TNR-Other (non-road transport over land),
- TNR-Ship (shipping),
- TRO (road transport).

3.3 Aggregation into 7 ECMWF groups

EDGARv4.3.2_FT2015 has 20 global sectors (maps) with anthropogenic CO_2 long cycle C flux values for: energy, fugitives, industrial processes, solvents and products use, agriculture and waste involved sectors. The Fossil Fuel Fires sector (FFF) is not used in this study, because the Kuwait oil fires of 1991 are of no importance to 2015 and 2030, and the coal mine fires data are considered to be very uncertain. In this study EDGAR sectors had to be additionally grouped for the use of global flux inversion and ensemble perturbation systems. Grouping was done keeping in mind possible future evolution of present systems and sector common features: activity type (point sources, 3D field, etc.); amount of knowledge for the activity (uncertainty value); geographical distribution (e.g. over urban areas only); size of sector covariance matrix (optimal size for inversion system is less than 50: 7x7); use for CO_2

co-emitting species (e.g. CH_4, CO, NO_2). Table 1 shows additional grouping of 20 EDGAR sectors (after pre-processing) into 7 ECMWF groups.

Table 1: Grouping of EDGAR anthropogenic CO_2 long cycle C emission sectors (and budgets) into ECMWF groups

№	**ECMWF group**	**EDGAR sector**	**IPCC2006 activity**	**Note**	**Emission global budget 2015, Mton CO_2**
1	ENERGY_S	ENE	1.A.1.a (subset)	Power industry: super emitting power plants	13’704
2	ENERGY_A	ENE	1.A.1.a (rest)	Power industry: average emitting power plants	
		SWD_INC	4.C	Solid waste incineration	137
3	MANUFACTURING	IND	1.A.2	Combustion for manufacturing	6’183
		IRO	2.C.1, 2.C.2	Iron and steel production	234
		NFE	2.C.3, 2.C.4, 2.C.5, 2.C.6, 2.C.7	Non-ferrous metals production	91
		NEU	2.D.1, 2.D.2, 2.D.3	Non energy use of fuels	10
		NMM	2.A.1, 2.A.2, 2.A.3, 2.A.4	Non-metallic minerals production	1’748
		CHE	2.B.1, 2.B.5, 2.B.6, 2.B.8	Chemical processes	534
4	SETTLEMENTS	RCO	1.A.4, 1.A.5.a	Energy for buildings	3’322
5	AVIATION	TNR_Aviation_CRS	1.A.3.a_CRS	Aviation cruise	412
		TNR_Aviation_CDS	1.A.3.a_CDS	Aviation climbing&descent	306
		TNR_Aviation_LTO	1.A.3.a_LTO	Aviation landing&takeoff	98
6	TRANSPORT	TRO	1.A.3.b	Road transportation	5’530
		TNR_Ship	1.A.3.d	Shipping	819
		TNR_Other	1.A.3.c, 1.A.3.e	Railways, pipelines, off-road transport	255
7	OTHER	REF_TRF	1.A.1.b, 1.A.1.c, 1.B.1.c	Oil refineries and Transformation industry	1’917
		PRO	1.B.2.a, 1.B.2.b, 1.C	Fuel exploitation	258
		COL	1.B.1.a	Coal production	7
		AGS	3.C.2, 3.C.3	Agricultural soils	99
		PRU_SOL	2.D.3	Solvents and products use	61

3.4 Geographical treatment

The whole world in this study is presented in 242 geographical entities 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).

Each entity reports its annual Greenhouse Gas (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 global country mask. Accuracy of these values strongly depend on statistical system development level of the entity. According to IPCC2006 suggestions all entities are divided into two groups – with well-developed statistical systems (WDS) and with less developed statistical systems (LDS), and can be related to Annex I and Non-Annex I countries respectively.

Annex I countries must report their GHG inventories annually and consist of the 24 OECD countries 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 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 nineties but are nowadays assumed to have been building 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 UNFCCC developing countries. Figure 1 shows schematic grouping of world countries according to IPCC (EDGARv432 report).

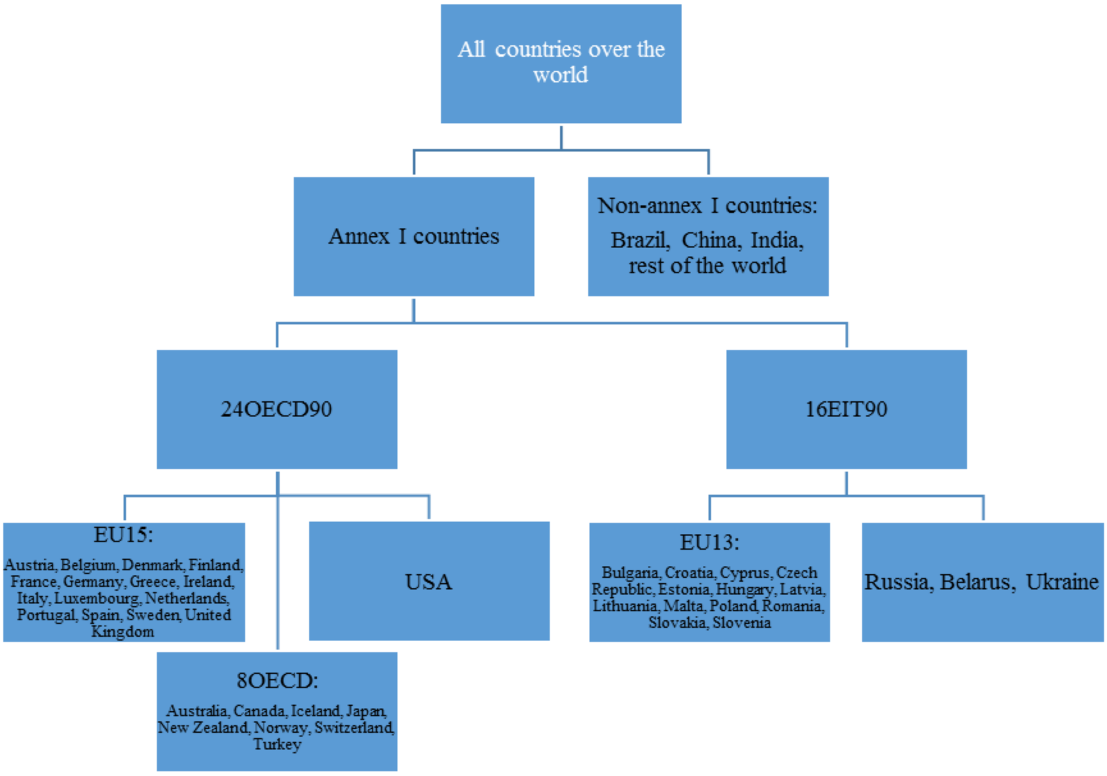


Figure 1: Schematic grouping of all world countries according to IPCC based on stability of their statistical infrastructure

We made certain exceptions to this grouping: (i) far away territories of Annex I countries are treated as LDS countries (e.g. the United Kingdom is Annex I country, Bermuda is its part yet treated as LDS country because of its far away geographical location from the main part of the United Kingdom); (ii) China is treated as WDS country, because quality of its GHG inventories has recently increased; (iii) India is treated as WDS country, because of its well-developed statistical infrastructure; (iv) Russia is treated as LDS country, because completion of its GHG inventory has recently decreased. Table 2 shows all geographical entities involved in this study with their statistical system development level and main geographical part (if necessary).

Table 2: Full list of geographical entities, their statistical infrastructure development level and their main geographical part (dependency)

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

ISO Code	Geographical name	Type	Main country (dependency)	Full information
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
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

ISO Code	Geographical name	Type	Main country (dependency)	Full information
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
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

ISO Code	Geographical name	Type	Main country (dependency)	Full information
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
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

ISO Code	Geographical name	Type	Main country (dependency)	Full information
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
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

ISO Code	Geographical name	Type	Main country (dependency)	Full information
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]

Comparison of geographical entity lists from this study and from EDGAR is shown in Table 3. EDGAR distinguish 228 geographical entities, because of some merging due to history or availability of statistics: Serbia [SRB] and Montenegro [MNE] are still treated as one State Union of Serbia and Montenegro [SCG]); Switzerland [CHE] and Liechtenstein [LIE] emission budgets are reported together under Switzerland [CHE].

Table 3: Differences in geographical entity lists from this study and from EDGAR dataset

№	EDGAR	ECMWF
1	France (including Monaco and Andorra) [FRA]	France (including Monaco) [FRA], Andorra [AND]
2	Israel (including Palestine) [ISR]	Israel [ISR], Occupied Palestinian Territory [PSE]
3	Italy (including Vatican, San Marino) [ITA]	Italy (including Vatican) [ITA], San Marino [SMR]
4	Norway [NOR]	Norway [NOR], Svalbard (including Jan Mayen) [SJM]
5	Serbia and Montenegro (including Kosovo) [SCG]	Serbia (including Kosovo) [SRB], Montenegro [MNE]
6	Spain [ESP], Gibraltar [GIB]	Spain (including Gibraltar) [ESP]
7	Switzerland (including Liechtenstein) [CHE]	Switzerland [CHE], Liechtenstein [LIE]
8	Ocean [SEA], Nauru [NRU]	Ocean (including Nauru) [SEA]
9	French Saint Martin (including Sint Maarten [SXM]) [MAF]	
10	Netherlands Antilles (including Bonaire, Sint Eustatius, Saba [BES], Curacao [CUW]) [ANT]	
11	Sudan (including South Sudan) [SDN]	

To ease further on comparison two extra geographical entities were introduced: (i) Europe (28 members) [E28], and (ii) All World Countries [GLB].

4 Results: Uncertainties per sector and per country of the Anthropogenic CO_2 budgets

4.1 Uncertainty calculation methodology and covariance matrices

4.1.1 Overview

IPCC1996, IPCC2006 and IPCC2019 provide vast information about numerous human activities that can lead to the emissions of main greenhouse gases (i.e. CO_2, CH_4, N_2O, NO_x, CO, NMVOCs and SO_2). Also, it provides guidelines how these emissions can be reported and how certain these values are. Based on different emission measurement capabilities in each country IPCC provides different approaches (Tier 1, Tier 2 and Tier 3) for emission and its uncertainty calculations. In order to use same methodology globally, it was decided to omit regionally (e.g. Europe) available more detailed information and use only information required for the most basic and simplest (Tier 1) approach. Tier 1 methodology to estimate CO_2 emissions from fuel combustion follows the concept of carbon conservation (from the fuel combusted into CO_2). Estimation of CO_2 emissions from fuel combustion for a given fuel:

$$CO_2 emissions_{fuel\ i} = Consumption_{fuel\ i} \cdot EmissionFactor_{fuel\ i},$$

where *Consumption*$_{fuel\ i}$ – amount of fuel i combusted; *EmissionFactor*$_{fuel\ i}$ – default emission factor for fuel i. Country-specific estimates of CO_2 from biomass burning are particularly difficult to ascertain, so it was decided not to account it in this study. Emissions are then summed across all fuels and all sectors of consumption to obtain national totals.

EDGAR provides gridded global CO_2 emissions based on official statistics (mainly international), and IPCC provides information on reliability of these emissions per each human activity based on expert decision. These two sources were combined at detailed sectoral level, but in order to get an overview, these were aggregated into 20 EDGAR CO_2 long cycle C emission sectors, and further into 7 ECMWF groups. Uncertainties can be derived following IPCC2006 along two different approaches:

- propagation of error (Approach 1) – gives informative results even if criteria “standard deviation divided by the mean value is less than 0.3” is not strictly met and data still have some correlation; needs only uncertainty ranges for activity data and emission factors, that are provided by IPCC; can be relatively easy to improve in case of large and asymmetric uncertainties; or
- Monte Carlo simulation or similar techniques (Approach 2) – suitable only if detailed category-by-category uncertainty information is available; complex calculations.

In order to use same methodology for all world countries (for which detailed information for each emission activity is not generally available) it was decided to use the error propagation method (Approach 1).

Final uncertainties per country (country masks were provided by JRC and adapted by ECMWF) per ECMWF’s CO_2 anthropogenic emissions group are based on: emission budgets calculated from EDGARv4.3.2_FT2015 maps, uncertainty default values from IPCC2006 Tier 1 approach (error propagation method) and the definition of a lognormal distribution , which is needed to obtain non-negative emissions. Figure 2 shows simplified scheme of uncertainty calculation roadmap. Below is a detailed description how exactly yearly and monthly uncertainties were calculated.

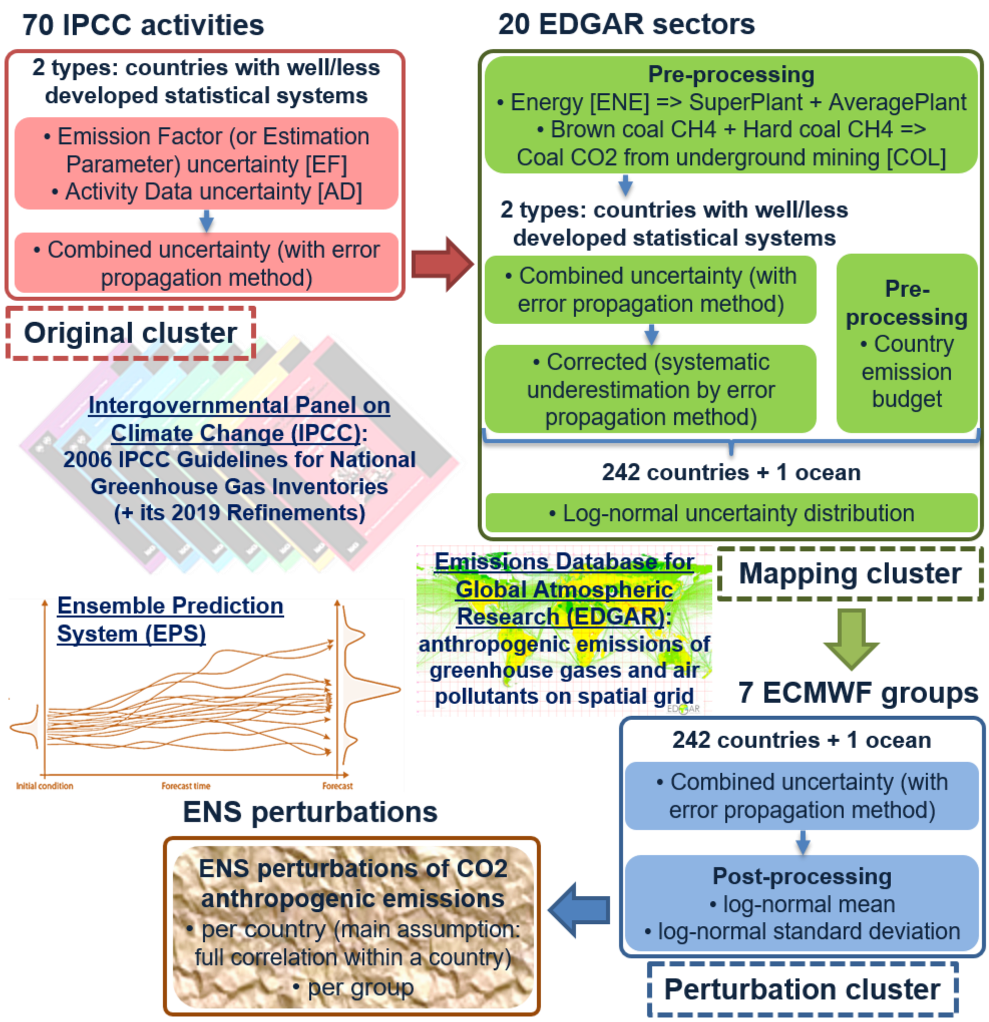


Figure 2: Simplified scheme of uncertainty calculation roadmap

4.1.2 Yearly uncertainties

Uncertainties per each IPCC activity from Table 1 – Combined Uncertainties (UC) – were calculated using uncertainties for Emission Factor or Estimation Parameter (EF) and Activity Data (AD) provided in IPCC guidelines (or calculated as prescribed, using the assumptions recommended – we used default assumptions provided in the IPCC2006 guidelines, where activity processes are not known in details):

$$UC_{IPCCi} = \sqrt{EF_{IPCCi}^2 + AD_{IPCCi}^2},$$

where $IPCCi$ means combined uncertainties per activity i; EF_{IPCCi} and AD_{IPCCi} are Emission Factor or Estimation Parameter (EF) and Activity Data (AD) uncertainties used in percentage. It should be noted that IPCC guidelines provide upper and lower limits of EF and AD, which are not always symmetrical. In order to preserve as much accuracy as possible (not to inflate artificially lower or upper limits of log-normal emission distributions) all calculations were performed for upper and lower uncertainty limits separately (although it is not required by the Approach 1 methodology!). It should be noted, that IPCC provides default EF values for different fuels in transport-related activities (e.g. railways, aviation, etc.). In this study detailed fuel consumption information per activity was not available. It was decided to use the most typical (common) fuel type (its EF value) per each activity. The following fuels were assumed as most typical ones:

- for aviation – Jet Kerosene,
- for railways – Diesel, and
- for shipping (or Water-borne Navigation) – composition of 80% Diesel and 20% Residual Fuel Oil.

Following IPCC2006 recommendations for road/off-road transport the most typical EF uncertainty was used (instead of the typical fuel type EF).

Further these uncertainties were combined according to Table 1 to calculate uncertainties per each EDGAR sector:

$$UC_{EDGARj} = \sqrt{UC_{IPCC1}^2 + UC_{IPCC2}^2 + \dots + UC_{IPCCn}^2},$$

where $EDGARj$ – combined uncertainty per sector j, and $1,2,\dots,n$ – IPCC activities that are taken into account in a particular EDGAR sector; $UC_{IPCC1}, UC_{IPCC2}, \dots, UC_{IPCCn}$ used in percentage.

The uncertainties calculated per EDGAR subsector with the error propagation method,and combined to larger sectors (the 20 EDGAR sectors). The uncertainty on the emission sector total, had to be corrected, as the error propagation method of Approach 1 systematically underestimates the uncertainty unless the model is purely additive, which was not the case. Here uncertainty calculations are estimated based on the sum of several product terms. To fix this underestimation IPCC2006 advises using a correction factor. One example of correction factor is proposed in Frey (2003), where the performance of an analytical approach for combining uncertainty in comparison to a Monte Carlo simulation with large sample sizes for many cases involving different ranges of uncertainty for additive, multiplicative, and quotient models are evaluated. Frey found that error propagation and Monte Carlo simulated estimates of the uncertainty half-range of the model output agreed well for values of less than 100 %, but with the increase of the uncertainty a systematic underestimation of uncertainty in the total inventory by the error propagation approach appeared. The relationship between the simulated and propagated error estimates was found to be well-behaved, which led to a correction factor development for the large (i.e. greater than 100 %) total inventory uncertainties. This correction factor will not necessarily be reliable for very large uncertainties (i.e. greater than 230 %) because it was calibrated over the range of 10 to 230 %. As such, the correction factor (FC) was applied if half-range uncertainty estimated from the error propagation method was ≥ 100 and ≤ 230 %:

$$FC_{EDGARj} = \left[\frac{-0.7200 + 1.0921 \cdot UC_{EDGARj} - 1.63 \cdot 10^{-3} \cdot UC_{EDGARj}^2 + 1.11 \cdot 10^{-5} \cdot UC_{EDGARj}^3}{UC_{EDGARj}}\right]^2,$$

$$\left(UC_{EDGARj}\right)_{corr} = UC_{EDGARj} \cdot FC_{EDGARj},$$

where $corr$ corresponds for corrected uncertainty; UC_{EDGARj} used in percentage. In cases where UC_{EDGARj} was < 100 and > 230 percent FC_{EDGARj} was assumed to be equal 1.

For models that are purely additive, and for which the half range of uncertainty is less than approximately 50 %, a normal distribution is often an accurate assumption for the model output form. In this case, a symmetric uncertainty range with respect to the mean can be assumed. But it's not the case for multiplicative (or mixed) models, or when the uncertainty is large for a non-negative variable (as anthropogenic CO_2 emissions!). A lognormal distribution is typically an accurate assumption for the model output form, where the uncertainty range is not symmetric with respect to the mean, even though the variance for the total inventory may be correctly estimated from Approach 1. IPCC2006 guidelines provide a practical methodology based on Frey (2003) for approximate asymmetric uncertainty range calculations based on the error propagation method. According to this methodology key characteristics of the 95 percent confidence intervals are:

- they are approximately symmetric for small ranges of uncertainty, and
- positively skewed for large ranges of uncertainty (necessary for non-negative variables, e.g. CO_2 emissions).

This methodology was applied if lower half-range uncertainty estimated from error propagation method was ≥ 50 %. IPCC suggests to define parameters of the lognormal distribution in terms of the geometric mean μg (which can be estimated based upon the arithmetic mean and the arithmetic standard deviation) and geometric standard deviation σg:

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

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

where E_{EDGARj} – anthropogenic CO_2 emissions per sector j; $\left(UC_{EDGARj}\right)_{corr}$ used in percentage.

As it was noted earlier, all calculations were performed for upper and lower uncertainty limits separately, which means that there are two values of $\left(UC_{EDGARj}\right)_{corr}$:

$\left[\left(UC_{EDGARj}\right)_{corr}\right]_{low}$ –the absolute (no sign) value of lower uncertainty limit of sector j, and
$\left[\left(UC_{EDGARj}\right)_{corr}\right]_{high}$ –the absolute (no sign) value of upper uncertainty limit of sector j.

It is preferred to preserve as much accuracy (extra knowledge) as possible in our calculations and not to inflate uncertainty upper or lower bounds limits artificially. Therefore, lower and upper uncertainty half-range from error propagation method were calculated with a logarithmic transformation using $[\mu gEDGARj]low$, $[\mu gEDGARj]high$ and $[\sigma gEDGARj]low$, $[\sigma gEDGARj]high$ respectively according to the following formulas:

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

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

where ln corresponds for logarithmic transformation of the distribution; resulting values are not absolute – they have signs! It should be also noted that according to this methodology (with these empirical constants +1.96 and -1.96) lower uncertainty half-range $\left\{\left[\left(UC_{EDGARj}\right)_{corr}\right]_{low}\right\}_{ln}$ will always be less than 100 percent. Upper uncertainty half-range is approximately symmetric relative to the 0 (Gaussian distribution) up to ~20 % , then has rather rapid growth till ~500 % (which with logarithmic transformation results in ~486.01 %), maxima at ~1350 % (which with logarithmic transformation results in ~582.64 %) and further gradual decrease. See Figure 3 for a visual representation of functions resulting upper and lower uncertainty bounds.

Figure 3: Visual representation of an empirical logarithmic transformation formula for upper and lower uncertainty bounds according IPCC2006

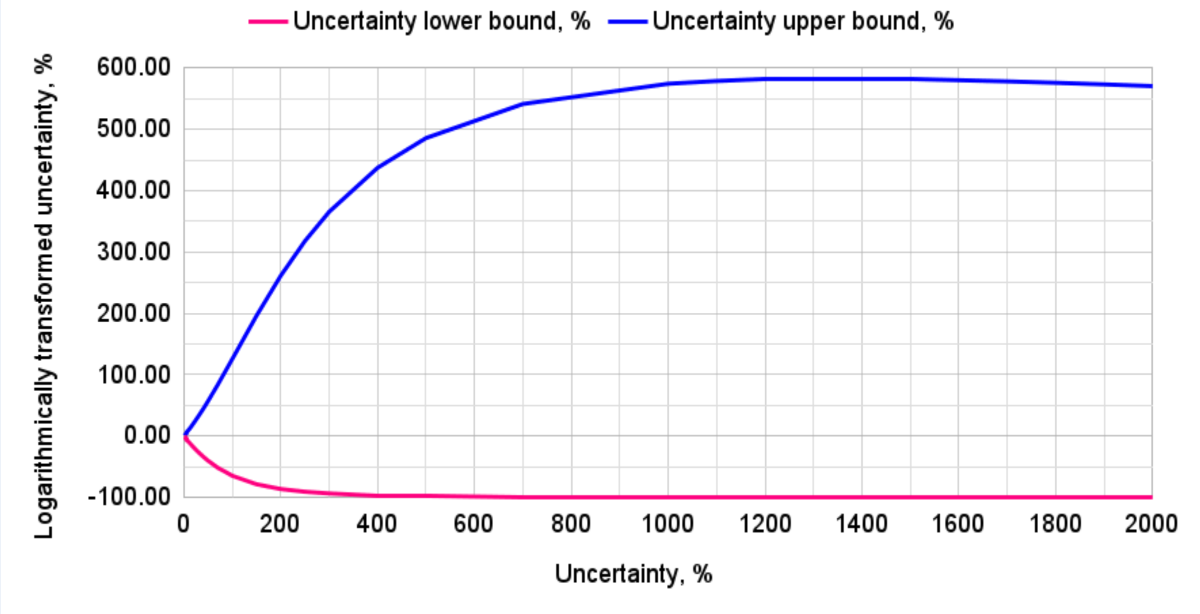


Table 4 shows the uncertainty values – prior uncertainties – for each EDGAR sector and two geographical entity types (i.e. well/less statistically developed). These values are a combination of the uncertainties calculated with the error propagation method and corrected for the underestimation at the combination. .

Table 4: Prior uncertainties per each EDGAR emission sector based on IPCC

№	ECMWF group	EDGAR sector	IPCC2006 activity	Prior uncertainties, %			
				WDS countries		LDS countries	
				Lower	Upper	Lower	Upper
1	ENERGY_S	ENE	1.A.1.a (subset)	8.6	3.0	12.2	3.0
2	ENERGY_A	ENE	1.A.1.a (rest)	8.6	8.6	12.2	12.2
		SWD_INC	4.C	40.3	40.3	41.2	41.2
3	MANUFACTURING	IND	1.A.2	8.6	8.6	12.2	12.2
		IRO	2.C.1, 2.C.2	37.1	37.1	37.1	37.1
		NFE	2.C.3, 2.C.4, 2.C.5, 2.C.6, 2.C.7	73.2	73.2	73.2	73.2
		NEU	2.D.1, 2.D.2, 2.D.3	121.7	121.7	124.0	124.0
		NMM	2.A.1, 2.A.2, 2.A.3, 2.A.4	70.9	70.9	93.0	93.0
		CHE	2.B.1, 2.B.5, 2.B.6, 2.B.8	107.8	89.9	107.8	89.9
4	SETTLEMENTS	RCO	1.A.4, 1.A.5.a	12.2	12.2	26.0	26.0
5	AVIATION	TNR_Aviation_CRS	1.A.3.a_CRS	5.5	6.4	50.1	106.8
		TNR_Aviation_CDS	1.A.3.a_CDS	5.5	6.4	50.1	106.8
		TNR_Aviation_LTO	1.A.3.a_LTO	5.5	6.4	50.1	106.8
6	TRANSPORT	TRO	1.A.3.b	5.4	5.4	7.1	7.1
		TNR_Ship	1.A.3.d	5.4	5.1	50.0	50.0
		TNR_Other	1.A.3.c, 1.A.3.e	50.3	106.9	50.5	107.0
7	OTHER	REF_TRF	1.A.1.b, 1.A.1.c, 1.B.1.c	54.4	149.3	57.7	151.4
		PRO	1.B.2.a, 1.B.2.b, 1.C	191.1	339.1	210.9	364.5
		COL	1.B.1.a	115.8	300.5	115.8	300.5
		AGS	3.C.2, 3.C.3	70.7	0.0	70.7	0.0
		PRU_SOL	2.D.3	25.0	25.0	50.0	50.0

The next step is to combine these prior uncertainties for each EDGAR sector into ECMWF groups uncertainties (see Table 4). Sector uncertainties are combined into group uncertainties by addition:

$$UC_{ECMWFk} = \frac{\sqrt{(\{(UC_{EDGAR1})_{corr}\}_{ln} \cdot E_{EDGAR1})^2 + (\{(UC_{EDGAR2})_{corr}\}_{ln} \cdot E_{EDGAR2})^2 + \ldots + (\{(UC_{EDGARn})_{corr}\}_{ln} \cdot E_{EDGARn})^2}}{|E_{EDGAR1} + E_{EDGAR2} + \ldots + E_{EDGARn}|},$$

$$E_{ECMWFk} = E_{EDGAR1} + E_{EDGAR2} + \ldots + E_{EDGARn},$$

where UC_{ECMWFk} and E_{ECMWFk} – combined uncertainty and total emissions per group k; $1,2,\ldots,n$ – EDGAR emission sectors that are combined in a particular ECMWF group k; $\{(UC_{EDGAR1})_{corr}\}_{ln}, \{(UC_{EDGAR2})_{corr}\}_{ln}, \ldots, \{(UC_{EDGARn})_{corr}\}_{ln}$ used in percentage.

Combined group uncertainties are country specific, because they take into account sector budget and adjust uncertainty values accordingly.

Finally, we needed to insure log-normal distribution of CO_2 emissions. Upper and lower uncertainty half-range values per ECMWF group k ($ECMWFk$) are descriptive, but not straight forward to use for emission perturbations in ensemble runs or flux inversions, where mean and standard deviation of the distribution are usually used. The lower and upper bounds of the 95 percent probability range, which are the 2.5th and 97.5th percentiles, respectively, calculated assuming a lognormal distribution based on an estimated uncertainty half-range from an error propagation approach, are lower and upper uncertainty values. Taking this into account and constant values from Z-table (Z, a mathematical table for the values of the cumulative distribution function of the normal distribution) for 2.5th and 97.5th percentiles (p), mean (μ^{ln}) and standard deviation (σ^{ln}) of log-normal distribution can be calculated:

$$Z_p = \frac{ln([E_{ECMWFk}]_p) - \mu^{ln}_{ECMWFk}}{\sigma^{ln}_{ECMWFk}},$$

where following variables are known

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

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

then simple system could be composed and solved accordingly

$$\mu^{ln}_{ECMWFk} = ln(E_{ECMWFk}) + \frac{1}{2} ln\left(1 + \frac{[UC_{ECMWFk}]_{low}}{100}\right) + \frac{1}{2} ln\left(1 + \frac{[UC_{ECMWFk}]_{high}}{100}\right),$$

$$\sigma^{ln}_{ECMWFk} = \frac{ln\left(1 + \frac{[UC_{ECMWFk}]_{low}}{100}\right) - ln\left(1 + \frac{[UC_{ECMWFk}]_{high}}{100}\right)}{-3.92},$$

where $[UC_{ECMWFk}]_{low}$ and $[UC_{ECMWFk}]_{high}$ used in percentage.

4.1.3 Monthly uncertainties

The monthly emission budget uncertainty can not be calculated with bottom-up emission data (which is based on annual statistics). It is evident that the monthly emission budgets are much less certain then yearly ones. The main issue is to assess the uncertainty increase by the monthly distribution profile for calculated the monthly emission budgets. The fact of a monthly time step makes it difficult to assess the representativeness of a temporal profile. Continuous measurements at a given location are rather providing hourly values. Even though these provide good input, they need to be combined into a monthly share, which might be representative for that location in that year, but not necessarily for a larger area and any other year. The monthly profiles used in EDGARv4.3.2 are standardised to 12 monthly shares per EDGAR sector and per region. They do not take the specificity of a single year and are not varying within a country. These shortcomings are recognised and therefore a full assessment of each of the monthly shares seemed not fitting the purpose of assessing the uncertainty of monthly emission budgets for a each country. Instead sensitivity analyses by evaluating the impact of using more refined temporal and spatial profiles is proposed for a followup study.

Currently monthly uncertainties are being calculated in the following way:

- the same procedure as for annual budgets is used to calculate uncertainties based on monthly emission budgets;
- then correlation (boosting parameter) between yearly uncertainties & budget with monthly uncertainties and budgets is derived based on an analysis of the variations over the different months;
- then prior uncertainties are multiplied by the boosting parameter (specific per country/sector);
- first point calculations are repeated using monthly emission budgets and boosted prior uncertainties.

This algorithm is applied in an iterative manner in order to find the best boosting parameter (to have the best fit between yearly and combined 12-month uncertainties).

4.1.4 Covariance matrices

The prior error covariance matrix of the emission inventory is required as an input to the inversion system. According to the IPCC2006 all anthropogenic CO_2 emissions are assumed to be fully uncorrelated, hence the prior error correlations between grid-cell emissions from the same sector are assumed to be uniform and equal to one. Only by assuming full absence of correlation it is possible to calculate emission uncertainties for each geographical entity and group of sectors with rather limited available information. ECMWF group of sectors covariance matrices per each geographical entity have the same representation – group of sectors is fully correlated with itself and fully uncorrelated with any other group (matrices have 1 on the diagonal and 0 everywhere else), see Table 5.

Table 5: Representation of ECMWF group of sectors covariance matrices per each geographical entity used in this study

Group of sectors	ENERGY_S	ENERGY_A	MANUFACTURING	SETTLEMENTS	AVIATION	TRANSPORT	OTHER
ENERGY_S	1	0	0	0	0	0	0
ENERGY_A	0	1	0	0	0	0	0
MANUFACTURING	0	0	1	0	0	0	0
SETTLEMENTS	0	0	0	1	0	0	0
AVIATION	0	0	0	0	1	0	0
TRANSPORT	0	0	0	0	0	1	0
OTHER	0	0	0	0	0	0	1

Due to the lack of information available to properly characterize the error correlations and error variances in the inventory, a refinement of those prior statistics will be carried out using atmospheric CO_2 observations. The methodology will consist in estimating the maximum likelihood of the prior error standard deviations and error correlation lengths following approaches described in Wu et al. (2013).

4.2 Overview of the resulting uncertainties

Main results of this study are lower and upper uncertainty bounds calculated for 242 geographical entities and one residual entity (emissions over ocean) for 7 ECMWF groups based on the yearly emissions of 2015. Table 6 shows results for main geographical entities (i.e. China [CHN], Europe (28 members) [E28], India [IND], Russian Federation [RUS] and United States of America [USA]) and All World Countries [GLB]. Table shows (values are based on year 2015!): emission budget per ECMWF groups of sectors and total per country both in kton and in percentage, upper and lower bounds of uncertainties in percentage, and contribution of each group of sectors uncertainty to the total geographical entities uncertainty in percentage.

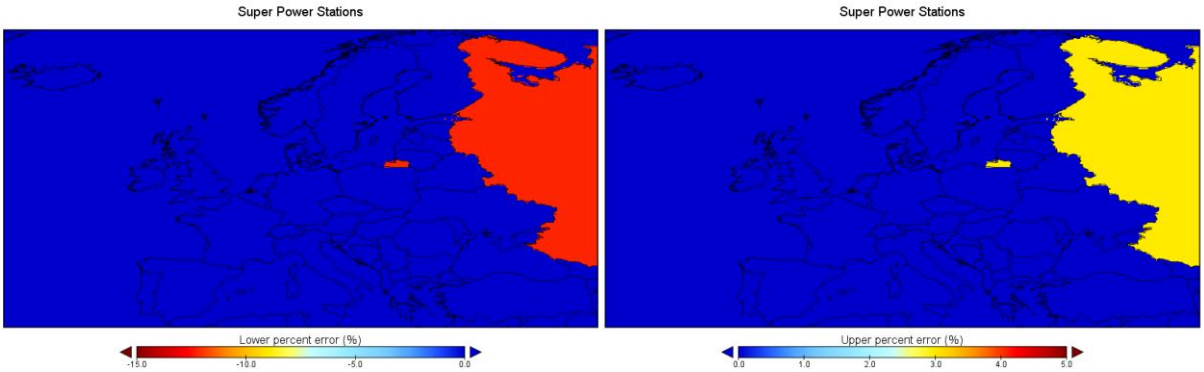
Table 6: Resulting uncertainties and emission budgets per groups of sectors for the main geographical entities (i.e. China [CHN], Europe (28 members) [E28], India [IND], Russian Federation [RUS] and United States of America [USA]) and globe in total [GLB]

ISO Code	ECMWF group	Budget 2015		Uncertainties, %		Contribution to total uncertainty, %
		kton	% of total	Lower	Upper	
CHN	ENERGY_S	169720.3	1.6	-8.6	3.0	0.0
	ENERGY_A	4041569.5	38.4	-8.6	8.6	11.5
	MANUFACTURING	4326633.0	41.1	-12.8	19.4	46.3
	SETTLEMENTS	657039.6	6.2	-12.2	12.2	0.6
	AVIATION	52865.7	0.5	-3.5	4.1	0.0
	TRANSPORT	687800.6	6.5	-5.1	8.2	0.2
	OTHER	594986.8	5.7	-39.8	181.5	41.3
	TOTAL	*10530617.0*	*100.0*	*-6.7*	*13.4*	*100.0*
E28	ENERGY_S	86957.5	2.4	-8.6	3.0	0.0
	ENERGY_A	1052417.0	29.5	-8.6	8.6	12.7
	MANUFACTURING	702598.8	19.7	-11.1	16.2	14.4
	SETTLEMENTS	580298.9	16.2	-12.2	12.2	7.9
	AVIATION	170372.7	4.8	-3.4	4.0	0.1
	TRANSPORT	792004.9	22.2	-5.3	5.6	2.9
	OTHER	186676.5	5.2	-38.4	174.9	62.0
	TOTAL	*3571326.5*	*100.0*	*-4.5*	*10.3*	*100.0*
IND	ENERGY_S	133508.4	5.5	-8.6	3.0	0.2
	ENERGY_A	939406.1	39.0	-8.6	8.6	24.0
	MANUFACTURING	793564.2	33.0	-10.7	15.1	38.5
	SETTLEMENTS	180319.6	7.5	-12.2	12.2	1.8
	AVIATION	11106.9	0.5	-3.5	4.1	0.0
	TRANSPORT	249810.3	10.4	-5.3	7.1	0.9
	OTHER	100034.1	4.2	-35.4	158.3	34.5
	TOTAL	*2407749.3*	*100.0*	*-5.2*	*9.0*	*100.0*
RUS	ENERGY_S	168420.1	9.8	-12.2	3.0	0.5
	ENERGY_A	453097.4	26.3	-12.2	12.2	8.5
	MANUFACTURING	575778.1	33.4	-12.0	15.5	17.5
	SETTLEMENTS	145938.1	8.5	-26.0	26.0	4.0
	AVIATION	39595.0	2.3	-27.1	91.5	1.5
	TRANSPORT	206879.5	12.0	-14.1	44.8	10.3

	OTHER	132116.9	7.7	-40.0	177.7	57.7
	TOTAL	*1721825.0*	*100.0*	*-6.7*	*16.2*	*100.0*
USA	ENERGY_S	0.0	0.0	0.0	0.0	0.0
	ENERGY_A	2054941.1	40.1	-8.6	8.6	23.0
	MANUFACTURING	523733.8	10.2	-10.1	13.9	2.9
	SETTLEMENTS	577605.9	11.3	-12.2	12.2	3.7
	AVIATION	159170.5	3.1	-3.5	4.0	0.0
	TRANSPORT	1522867.3	29.7	-5.5	8.7	8.6
	OTHER	281808.2	5.5	-36.9	168.3	61.8
	TOTAL	*5120127.0*	*100.0*	*-4.7*	*10.4*	*100.0*
GLB	ENERGY_S	896675.6	2.5	-7.3	2.1	0.0
	ENERGY_A	11808765.0	33.0	-7.1	7.1	12.6
	MANUFACTURING	9938720.0	27.8	-9.4	14.1	24.3
	SETTLEMENTS	3322707.3	9.3	-11.4	11.4	2.6
	AVIATION	815481.6	2.3	-12.0	39.9	0.8
	TRANSPORT	6604953.0	18.5	-5.7	8.0	3.7
	OTHER	2343249.0	6.6	-27.4	124.2	56.1
	TOTAL	*35730552.0*	*100.0*	*-4.2*	*9.6*	*100.0*

Figure 4 shows upper and lower uncertainty bounds per ECMWF groups of sectors in percentage over the whole globe and zoomed over European region. Each group uncertainty bounds are presented in separate figures, e.g. ENERGY_A group (with emissions from average emitting power plants and solid waste incineration) data is presented in Figure 4.b. Colour schemes for Global and European regions are kept the same where it was possible with respect to visual representation of the results. Countries that have no emissions in a certain group of sectors are marked with zeros on the maps, e.g. ENERGY_S group (with emissions from super emitting power plants) almost all countries have upper and lower uncertainty bounds equal zero, as only few countries over the globe have super emitting power plants (see Table 7).

Figure 4.a: Upper (right column) and lower (left column) uncertainty bounds per ENERGY_S (with emissions from super emitting power plants) ECMWF group of sectors for Global (lower row) and European (upper row) regions



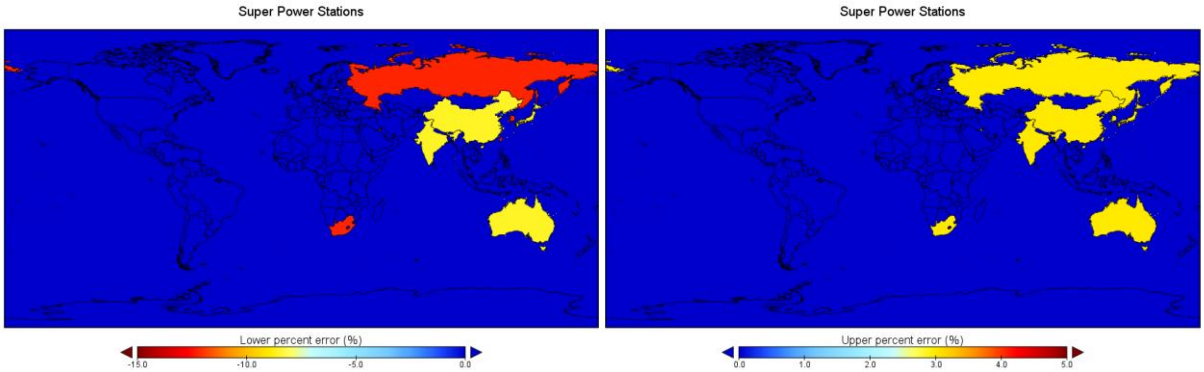


Figure 4.b: Upper (right column) and lower (left column) uncertainty bounds per ENERGY_A (with emissions from average emitting power plants and solid waste incineration) ECMWF group of sectors for Global (lower row) and European (upper row) regions

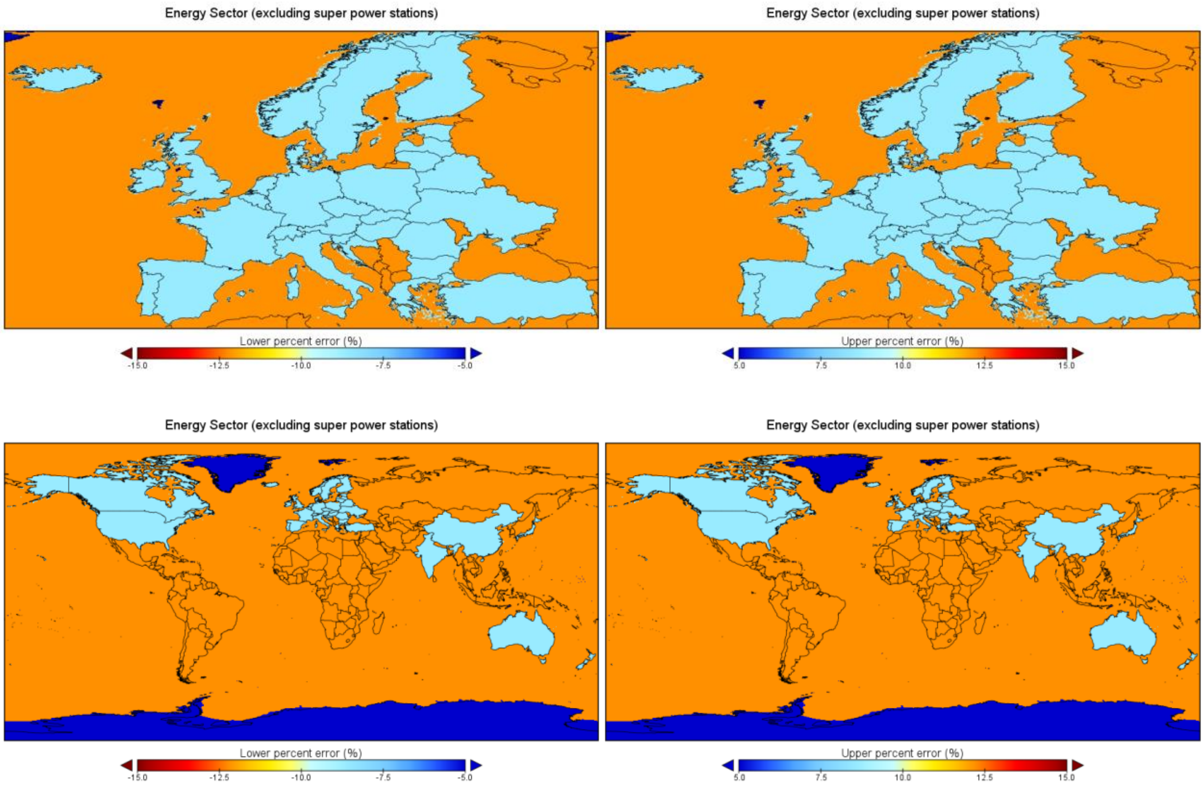


Figure 4.c: Upper (right column) and lower (left column) uncertainty bounds per MANUFACTURING (with emissions from combustion for manufacturing, iron and steel production, non-ferrous metals production, non energy use of fuel, non-metallic minerals production and chemical processes) ECMWF group of sectors for Global (lower row) and European (upper row) regions

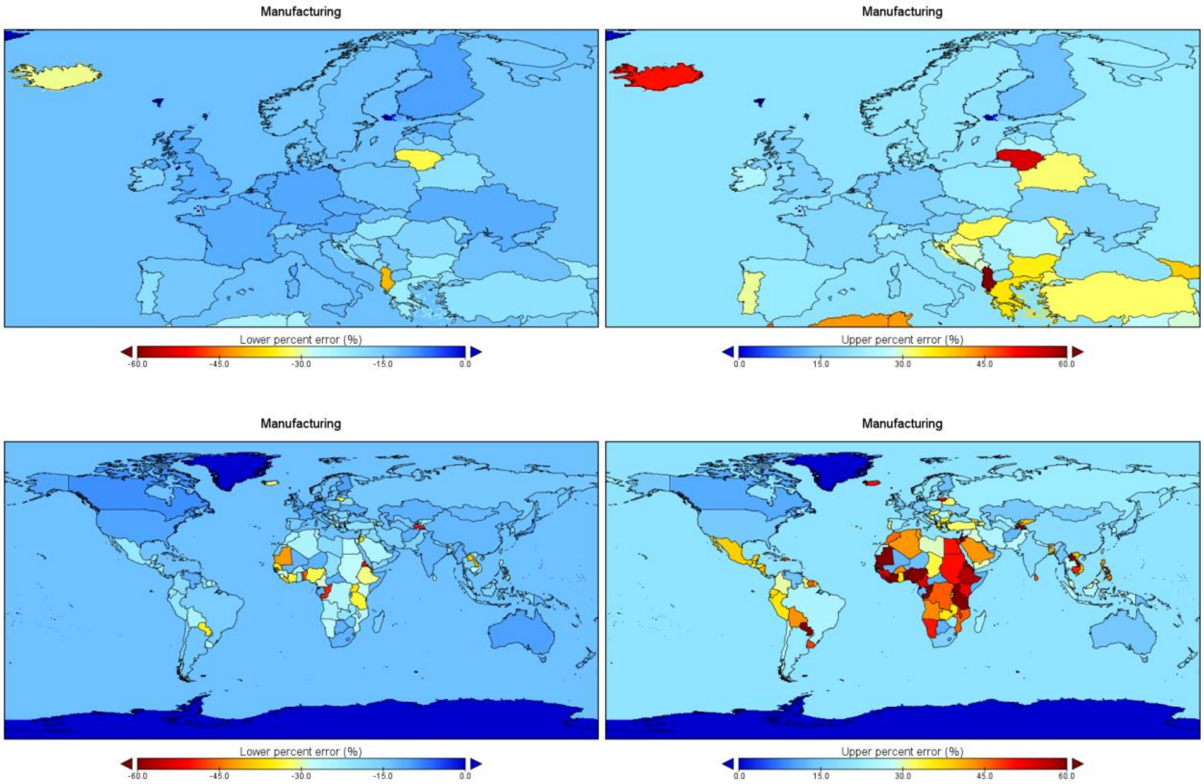


Figure 4.d: Upper (right column) and lower (left column) uncertainty bounds per SETTLEMENTS (with emissions from energy for buildings) ECMWF group of sectors for Global (lower row) and European (upper row) regions

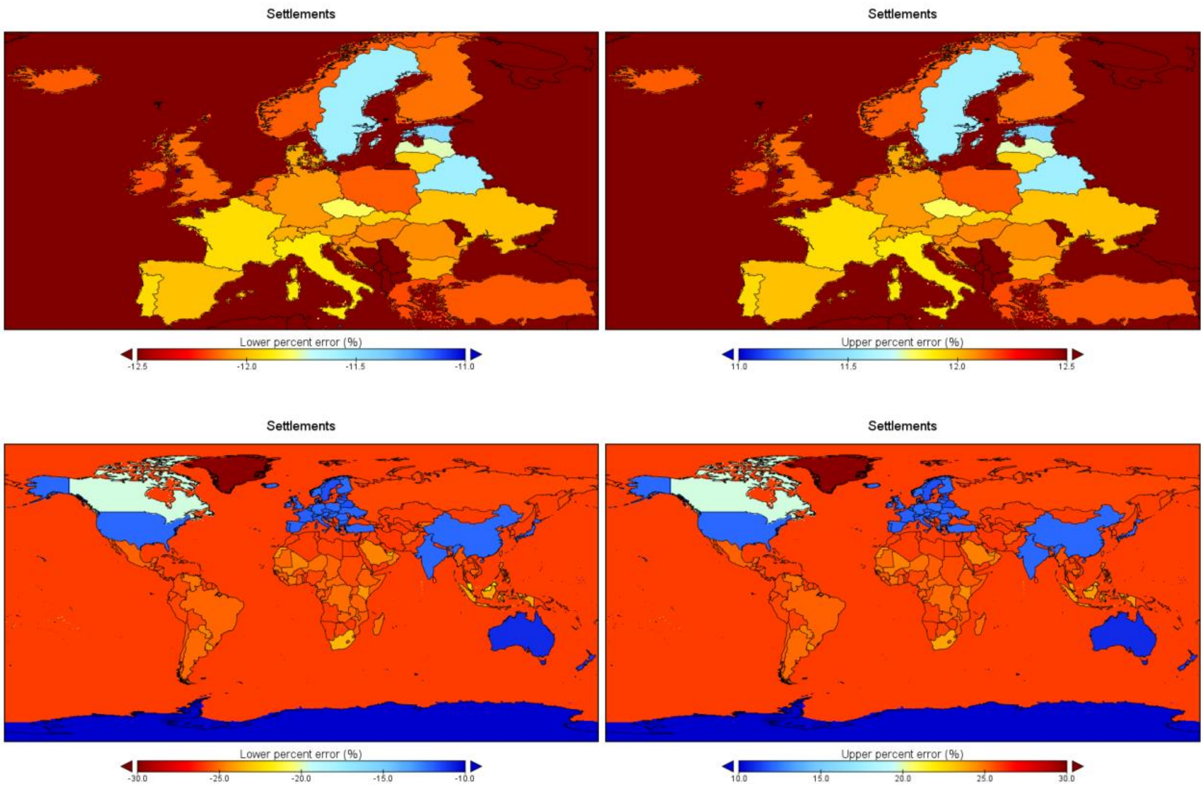


Figure 4.e: Upper (right column) and lower (left column) uncertainty bounds per AVIATION (with emissions from aviation landing & take off, climbing & descent and cruise) ECMWF group of sectors for Global (lower row) and European (upper row) regions

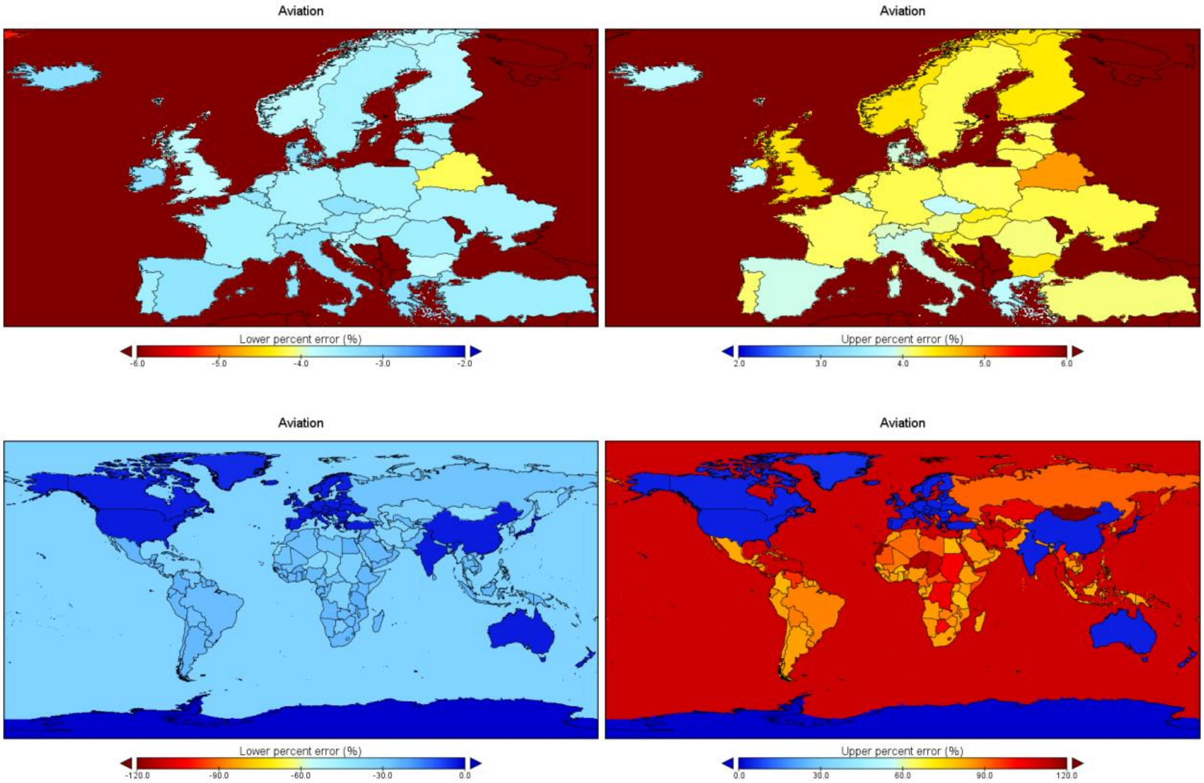
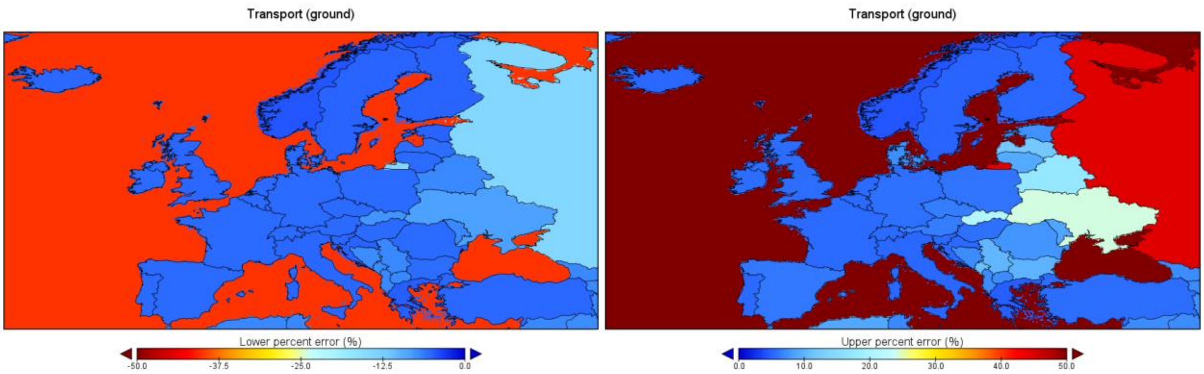


Figure 4.f: Upper (right column) and lower (left column) uncertainty bounds per TRANSPORT (with emissions from road and off-road transport, railways, pipelines and shipping) ECMWF group of sectors for Global (lower row) and European (upper row) regions



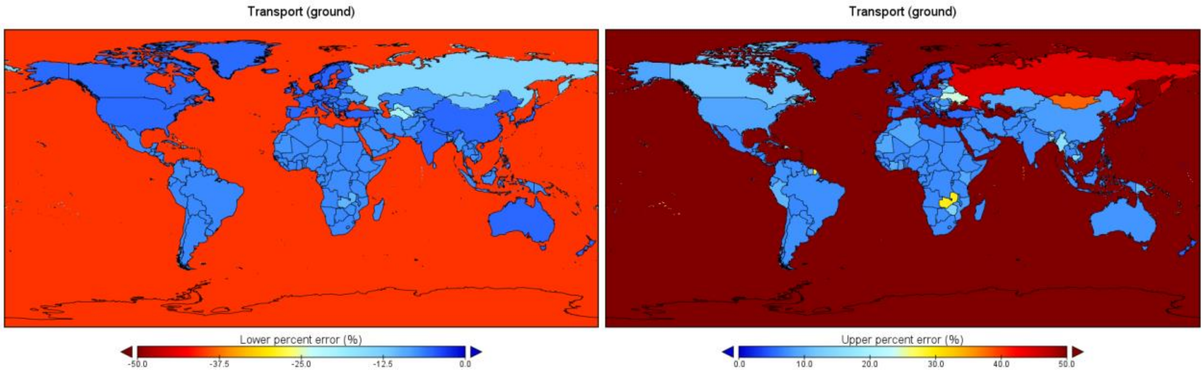
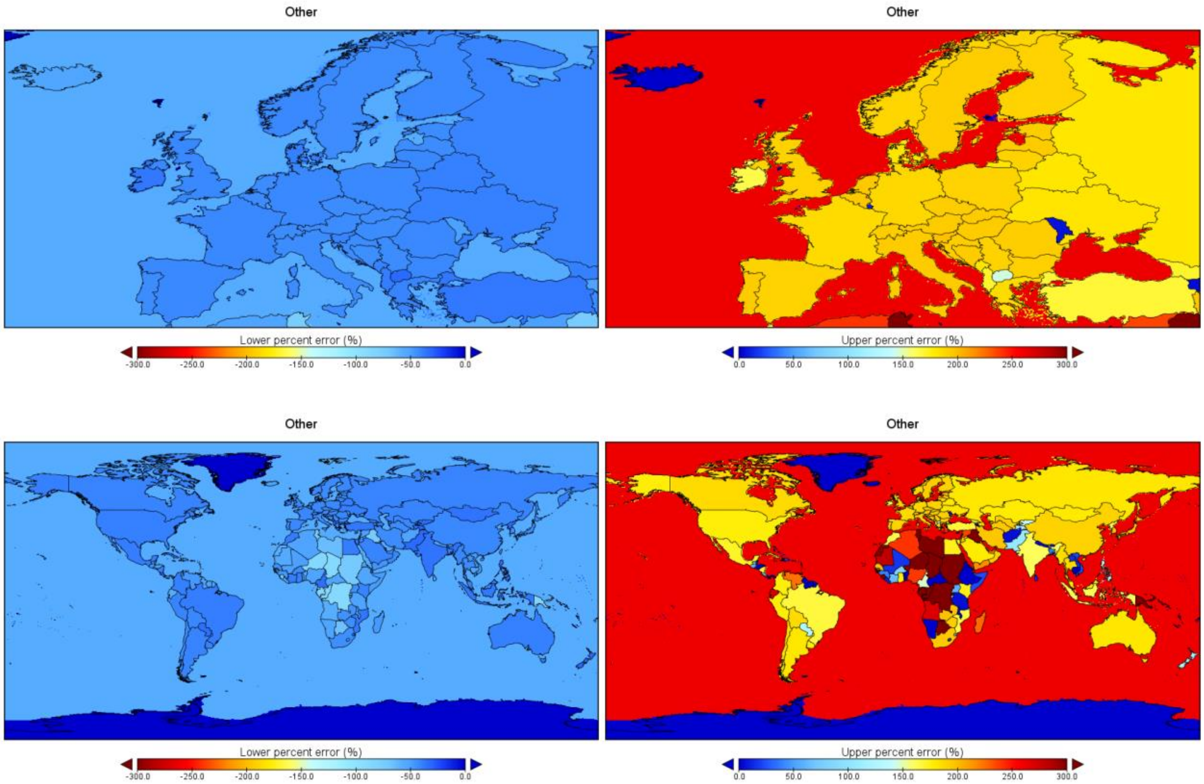


Figure 4.g: Upper (right column) and lower (left column) uncertainty bounds per OTHER (with emissions from oil refineries and transformation industry, fuel exploitation, coal production, agriculture soils and solvents & products use) ECMWF group of sectors for Global (lower row) and European (upper row) regions



4.3 Details for the power plants sector: super power plant split off

According to IPCC2006 power industry sector emission factors are quite well known, and even after taking all the assumptions and activity data uncertainty into account overall emission uncertainty grows up only till about -10 % for lower bound and +10 % for upper uncertainty bound. For small power plants such fluctuations are acceptable as they will operate more or less based on day to day needs. On the other hand huge power plants operate based on their yearly plan – their construction and maintenance are quite expensive, so usually they are operating at the full capacity and upper uncertainty bound of +10 % is unacceptable. According to the expert knowledge deviation upper limit for big power plants can't be more than +3 %, for small ones – up to +15 %. Baring this in mind it was decided to separate EDGARv4.3.2_FT2015 energy sector (ENE) into two:

- energy generated by the *super* power plants – most emitting single located plant or average emitting and close located multiple plants (fall into one grid-cell in ENE field) (in total 30 grid cells), and
- energy generated by the remaining *non-super* power plants – average emitting single or few together located plants.

First, all grid-cells of yearly ENE field were ranked according to the energy flux from the highest to the lowest flux value. Next, 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[1]. Finally, two new energy fields are generated – ENE_SUP and ENE_AVE respectively. Currently 30 grid-cells of ENE sector were moved to ENE_SUP, representing 7.1 % of the total ENE sector. Table 7 shows 30 grid-cell flux values, their ranks and geographical locations. Figure 5 shows graphical representation of ranked 30 grid-cell fluxes.

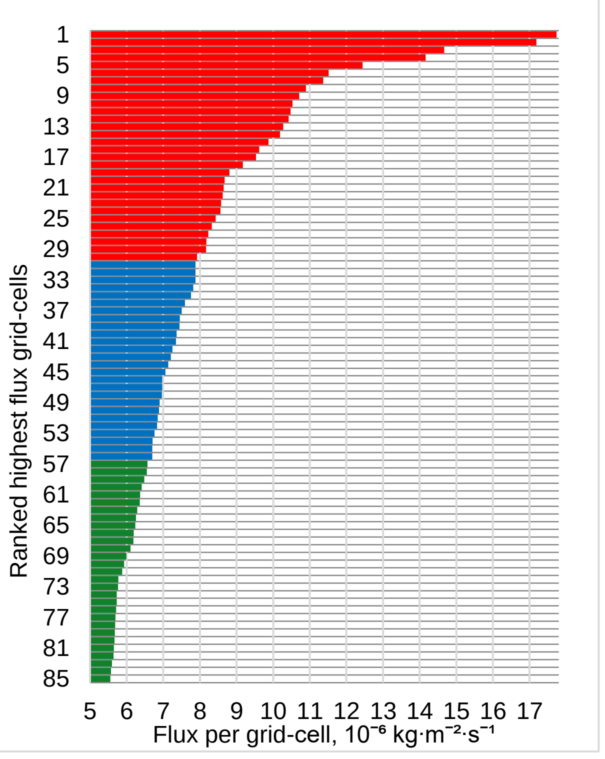
Table 7: List of 30 grid-cells with 2015 CO_2 flux values where energy is assumed to be generated by the *super* power plants, grid-cell ranks, geographical locations and budgets per country

Rank	Latitude, °	Longitude, °	CO_2 flux, $\cdot 10^{-6}$ $kg \cdot m^{-2} \cdot s^{-1}$	Country / Emission budget, Mton
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	Russia [RUS] / 168.4
2	60.35	28.65	17.19	
3	55.75	52.45	14.67	
5	54.75	20.55	12.44	

[1] Please note that this is the flux for an entire grid cell, that often includes more power plants together on one site.

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 5: Ranked 30 grid-cells with 2015 CO_2 flux values where energy is is assumed to be generated by the *super* power plants



4.4 Access to the data

Resulting global uncertainty maps with lower and upper uncertainty bounds per ECMWF group of emission sectors in a NetCDF format currently are provided on demand by email, and will become shortly available on the ftp che-project@ftp.ecmwf.int (che-project)..

4.5 Quality check and use of the results in ECMWF

Country specific uncertainty values were sanity checked by JRC emission expert of EDGAR. G. Janssens-Maenhout to avoid major discrepancies. When possible, certain geographical entity uncertainties were compared with the data available, e.g. for Finland calculated uncertainties were compared with the data from Suvi Monni (2004), no discrepancies were found either.

Uncertainties were also compared with the results from EDGAR team, which used the same methodology for anthropogenic CO_2 emission uncertainty calculations – main difference between this study and EDGAR team calculations is exact fuel knowledge. In this study for uncertainty calculations EF and AD uncertainties only for most typical fuel type (most generic values) were used, no exact fuel type or amount per IPCC activity information was available. EDGAR team has detailed knowledge of each fuel type used per sector (e.g. amount in ktons of crude oil, biofuel, gas, etc.), which allows them to use specific EF and AD uncertainties per each fuel type which sometimes lead to a complete different uncertainty values, e.g. for biofuel values are more uncertain, than for gas. This extra knowledge of which fuel type made CO_2 emissions in each country adds certain difference in the calculated uncertainties. If assumed typical fuel is the main one used by the country in reality (and part of biofuel is quite low), then values from this study and EDGAR team matched quite well.

Results of this study were used to calculate log-normal mean and log-normal standard deviation which will be further used for flux inversion scheme and ensemble run perturbations (Tier 2) planned in the CHE-project.

5 Intercomparison with TNO for E28

TNO works on the more detailed emission inventory (with higher spatio-temporal resolution) over the European area. Thereto TNO has collected more detailed emission budget information for 28 European countries with underlying activity data and proxies, than could be collected by EDGAR for all world countries. Also, TNO is running Monte Carlo simulations to derive emission uncertainties because of additional information availability and quite limited number of involved countries. Collection of more detailed information at the moment is rather expensive, and most of the time demands full renovation of the present country statistical infrastructure.

To find out if extra knowledge of the more detailed emission budgets (e.g. not per EDGAR sectors which comprises several IPCC activities, but per each IPCC activity itself) is beneficial, and if so then to what extent, in this study it was decided to compute uncertainties based on TNO sector budgets with the same error propagation Tier 1 approach from IPCC.

With EDGAR we assess the importance of the extra information for a more detailed emission grid-maps over Europe. This allows to get an opinion on the gain for other regions in pushing for more detailed information and emission calculations.

5.1 Details of the intercomparison

TNO uses emission statistical information directly from European countries or from other reliable sources (values provided for ECMWF are from actual statistics, not aggregated from emission maps!). Combination of TNO sectors into ECMWF groups shown in Table 8.

Table 8: Link between 7 ECMWF groups and 32 TNO sectors

Nr	Group Nr	ECMWF group	TNO sector	Note
1	1	ENERGY_S	ENE_SUP	Power industry (super plant)
2	2	ENERGY_A	ENE_OTH	Power industry (average plant)
3	2	ENERGY_A	SWD_INC	Solid waste incineration
4	3	MANUFACTURING	IND	Combustion for manufacturing
5	3	MANUFACTURING	IRO	Iron and steel production
6	3	MANUFACTURING	NFE_Aluminium	Non-ferrous metals production: Aluminium
7	3	MANUFACTURING	NFE_Rest	Non-ferrous metals production: Rest
8	3	MANUFACTURING	NEU_Paraffin	Non energy use of fuels: Paraffin
9	3	MANUFACTURING	NEU_Rest	Non energy use of fuels
10	3	MANUFACTURING	NMM_Cement	Non-metallic minerals production: Cement
11	3	MANUFACTURING	NMM_Lime	Non-metallic minerals production: Lime
12	3	MANUFACTURING	NMM_Glass	Non-metallic minerals production: Glass
13	3	MANUFACTURING	NMM_Rest	Non-metallic minerals production: Rest
14	3	MANUFACTURING	CHE	Chemical processes
15	4	SETTLEMENTS	RCO_OtherSectors	Energy for buildings: Rest
16	4	SETTLEMENTS	RCO_Stationary	Energy for buildings: Stationary
17	5	AVIATION	TNR_Aviation_CRS	Aviation cruise
18	5	AVIATION	TNR_Aviation_CDS	Aviation climbing&descent
19	5	AVIATION	TNR_Aviation_LTO	Aviation landing&takeoff
20	6	TRANSPORT	TRO	Road transportation
21	6	TRANSPORT	TNR_Ship	Shipping
22	6	TRANSPORT	TNR_Other_Rail	Railways, pipelines, off-road transport: Rail
23	6	TRANSPORT	TNR_Other_Rest	Railways, pipelines, off-road transport: Rest
24	7	OTHER	REF_TRF_Refining	Oil ref. and Transform. ind: Refining
25	7	OTHER	REF_TRF_Manufact	Oil ref. and Transform. ind: Manufacture

26	7	OTHER	REF_TRF_Transfrm	Oil ref. and Transform. ind: Transformation
27	7	OTHER	PRO_1B2	Fuel exploitation: Rest
28	7	OTHER	PRO_1C	Fuel exploitation: CO2 transport and Storage
29	7	OTHER	COL	Coal production
30	7	OTHER	AGS_Liming	Agricultural soils: Liming
31	7	OTHER	AGS_Urea	Agricultural soils: Urea Application
32	7	OTHER	PRU_SOL	Solvents and products use

ECMWF group uncertainties based on TNO emission budgets were calculated using the same assumptions and procedures as EDGAR budgets use. Table 9 shows prior uncertainties per each TNO emission sector. All European countries are assumed to have a well-developed statistical system.

Table 9: Prior uncertainties for the TNO and EDGAR emission sectors based on IPCC2006

№	ECMWF group	EDGAR sector	TNO sector	IPCC2006 activity	Prior uncertainties, %	
					Lower	Upper
1	ENERGY_S	ENE	ENE_SUP	1.A.1.a (subset)	8.6	3.0
2	ENERGY_A	ENE (remaining)	ENE_OTH	1.A.1.a (rest)	8.6	8.6
		SWD_INC	SWD_INC	4.C	40.3	40.3
3	MANUFACTURING	IND	IND	1.A.2	8.6	8.6
		IRO	IRO	2.C.1, 2.C.2	37.1	37.1
		NFE	NFE_Aluminium	2.C.3	10.2	10.2
		NFE	NFE_Rest	2.C.4, 2.C.5, 2.C.6, 2.C.7	72.5	72.5
		NEU	NEU_Paraffin	2.D.2	106.8	106.8
		NEU	NEU_Rest	2.D.1, 2.D.4	50.3	50.3
		NMM	NMM_Cement	2.A.1	36.7	36.7
		NMM	NMM_Lime	2.A.2	6.3	6.3
		NMM	NMM_Glass	2.A.3	60.2	60.2
		NMM	NMM_Rest	2.A.4	4.1	4.1
		CHE	CHE	2.B.1, 2.B.5, 2.B.6, 2.B.8	107.8	89.9
4	SETTLEMENTS	RCO	RCO_OtherSectors	1.A.4	12.2	12.2
		RCO	RCO_Stationary	1.A.5.a	0.0	0.0
5	AVIATION	TNR_Aviation_CRS	TNR_Aviation_CRS	1.A.3.a_CRS	5.5	6.4
		TNR_Aviation_CDS	TNR_Aviation_CDS	1.A.3.a_CDS	5.5	6.4
		TNR_Aviation_LTO	TNR_Aviation_LTO	1.A.3.a_LTO	5.5	6.4
6	TRANSPORT	TRO	TRO	1.A.3.b	5.4	5.4
		TNR_Ship	TNR_Ship	1.A.3.d	5.4	5.1
		TNR_Other	TNR_Other_Rail	1.A.3.c	5.4	5.1
		TNR_Other	TNR_Other_Rest	1.A.3.e	50.0	106.7
7	OTHER	REF_TRF	REF_TRF_Refining	1.A.1.b	8.6	8.6
		REF_TRF	REF_TRF_Manufact	1.A.1.c	12.2	12.2
		REF_TRF	REF_TRF_Transfrm	1.B.1.c	0.0	0.0
		PRO	PRO_1B2	1.B.2.a, 1.B.2.b	176.3	267.2
		PRO	PRO_1C	1.C	50.0	100.0
		COL	COL	1.B.1.a	115.8	300.5
		AGS	AGS_Liming	3.C.2	50.0	0.0
		AGS	AGS_Urea	3.C.3	50.0	0.0
		PRU_SOL	PRU_SOL	2.D.3	25.0	25.0

Due to more detailed budget partitioning per each EDGAR sector, resulting uncertainties were quite different. Figure 6 shows budgets, uncertainties lower and upper bounds and each groups contribution to countries total uncertainty for combined 28 European countries, Germany [DEU], Spain [ESP], France [FRA], United Kingdom [GBR] and Poland [POL].

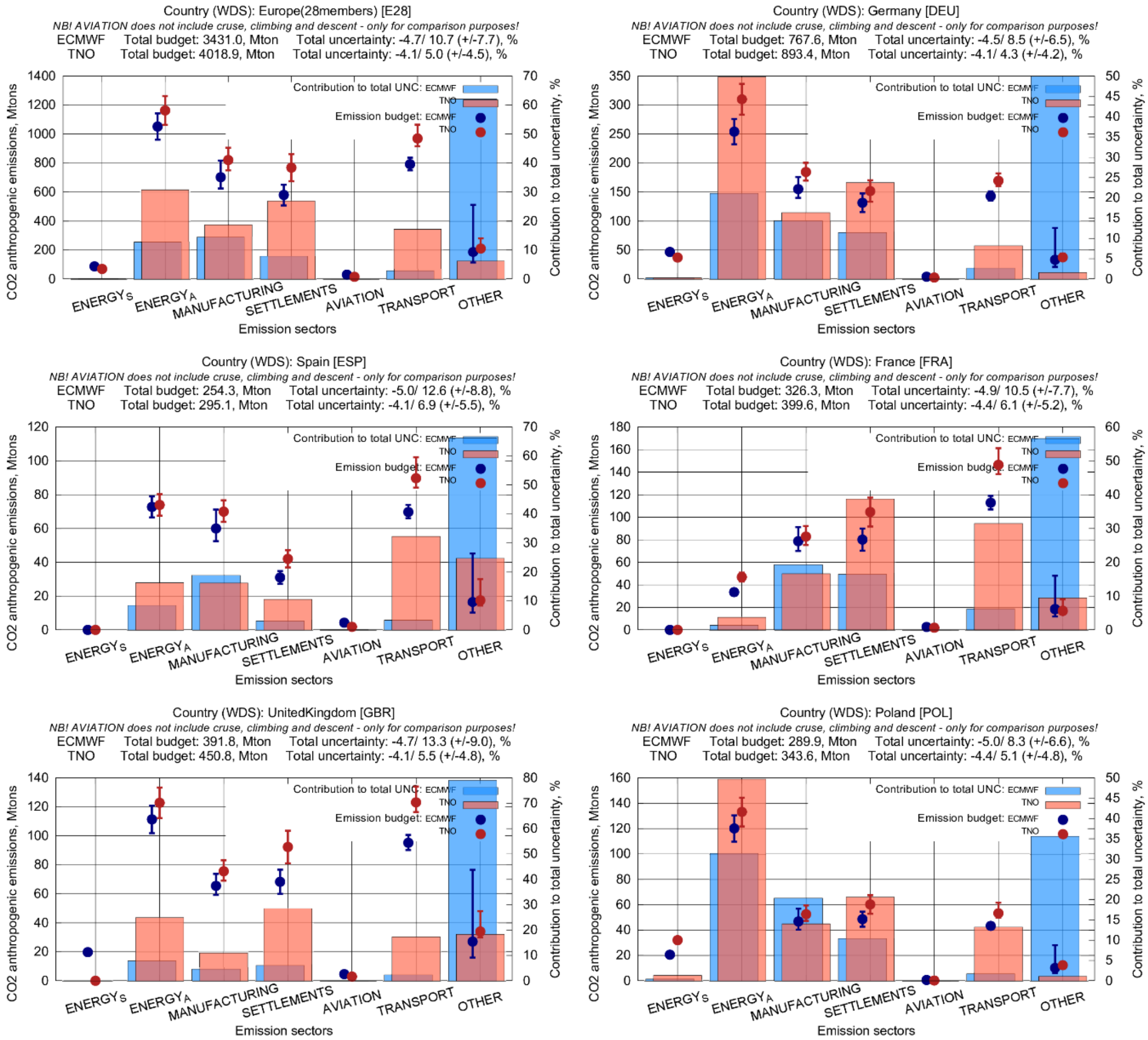


Figure 6: Budgets, uncertainties lower and upper bounds and each ECMWF groups contribution to countries total uncertainty for several European and combined 28 countries

Main difference between ECMWF and TNO budgets is that TNO is taking into account also biofuels, which shouldn't be accounted in CO_2 long C cycle according to IPCC2006. Main differences in uncertainties are found in:

- TRANSPORT group – TNO has larger uncertainty values of most uncertain off-road transport part,
- OTHER group – TNO has lower uncertainty values because of more precise knowledge about most uncertain part Oil refinery and Transformation industry: Transformation.

5.2 Corrections made based on the lessons learned from the intercomparison

First comparison results of ECMWF and TNO budgets showed some inconsistencies with energy, manufacturing and aviation data. It was noted that on average energy emissions from EDGAR are higher and manufacturing emissions are lower than the ones from TNO. Inconsistency was due to accidentally accounting autoproducers share in energy sector not in manufacturing one; this issue was successfully resolved. It was also noted that aviation emissions from TNO showed an artifact, that was corrected (with the corrected unit) by TNO.

A collaboration with WP2 resulted in a comparison at sector level and illustrated the importance of the selected sectors, as reported by Denier van der Gon (2018). This is confirmed here.

5.3 Evaluation and follow-up

This new dataset is a major step since the release of the TNO-MACC-III data and includes a number of additional recent years as well as an improved resolution and a number of methodological improvements, as explained above. At this moment, the product is being evaluated partly in combination with European modelling teams among others in the CHE and VERIFY projects. This evaluation has already led to a version v1.1 being prepared, which was released in mid-December. This updated dataset contains a number of bug fixes and correction of errors that were identified when the teams performing the simulations started working with them.

In addition, a high resolution version of the emission inventory (at 1/60° x 1/120° resolution, roughly equivalent to 1 km x 1 km) has been prepared for a specific zoom region in Europe as envisaged in the CHE project. This high resolution version is almost ready, a couple of final issues are currently being addressed and the dataset is expected to be released in early January.

5.4 Access to the data

Resulting uncertainty files currently are provided on demand by email, shortly will be available on the ftp che-project@ftp.ecmwf.int (che-project). The results have been discussed at scientific conferences with the poster in Annex 7.

5.5 Regional CO_2 emissions for 2030

A model-ready historic emission inventory at high spatial resolution (~7 km × 7 km) for UNECE-Europe for two projections based on the CIRCE project scenarios and using the latest historic year (2014) as the starting point for projection was prepared in 2018 (https://www.earth-syst-sci-data-discuss.net/essd-2017-124/). The scenarios include a business-as-usual and a climate change scenario. The projections provide a range of possible future emissions that can be used for sensitivity tests, for example when designing a possible future observational system. The annual grid-maps are available for the future years 2018–2050 at https://doi.org/10.5281/zenodo.1009519.

However, the source sector breakdown in this dataset still follows the SNAP nomenclature and TNO provided a version that is consistent with the GNFR system in January 2019 for CHE WP2.

6 Summary

This report documents deliverable 3.3.1 with the outcome of Task 3.3, fulfilling the following objectives:

1. **derivation of the uncertainties of the prior anthropogenic emission fields that are input to the atmospheric models** – uncertainties are based on IPCC2006 and IPCC2019, calculated for each of the 242 geographical entity taking into account its type (with well- or less-developed statistical systems) and for each of the 7 ECMWF groups of emission sectors. Uncertainties are calculated with the error propagation method (+ corrected for underestimation compared with the Monte Carlo approach) and presented with log-normal distribution. The uncertainties are calculated for the annual emission budgets and specified for the different emission groups and geographic entities.

2. **derivation of the sensitivity of the emissions on relevant parameters at a variety of scales at balanced, reasonable time/space resolution and uncertainty**. In addition to the annual emission budget uncertainty, also uncertainties for the monthly emission budgets were calculated, again per emission sector/group and geographic entity. The representativeness of the spatio-temporal profiles was not assessed. At this level, the validity of the 12 monthly shares that are available per sector and region and applied as default for any year, are only first estimates of the monthly budget. The approach is not refined enough to start a detailed evaluation of the validity of the spatio-temporal profiles, that would be needed for the final system, then at the resolution of 1h timestep and 0.1degx01.deg spatial grid-cell.

3. **assessment of the emission uncertainties and preparation of the uncertainty grid-maps and covariance matrices as prior input to the modelling system of ECMWF** – emission uncertainties were compared with different sources of information and no major discrepancies were found; uncertainty grid-maps are prepared (two maps per each of 7 ECMWF groups of emission sectors with upper and lower relative uncertainty bounds in percentage) in grib format; group of sectors covariance matrices per each geographical entity are calculated – group of sectors is fully correlated with itself and fully uncorrelated with any other group (matrices have 1 on the diagonal and 0 everywhere else), but they will be updated using atmospheric CO_2 observations, methodology will consist in estimating the maximum likelihood of the prior error standard deviations and error correlation lengths following approaches described in Wu et al. (2013).

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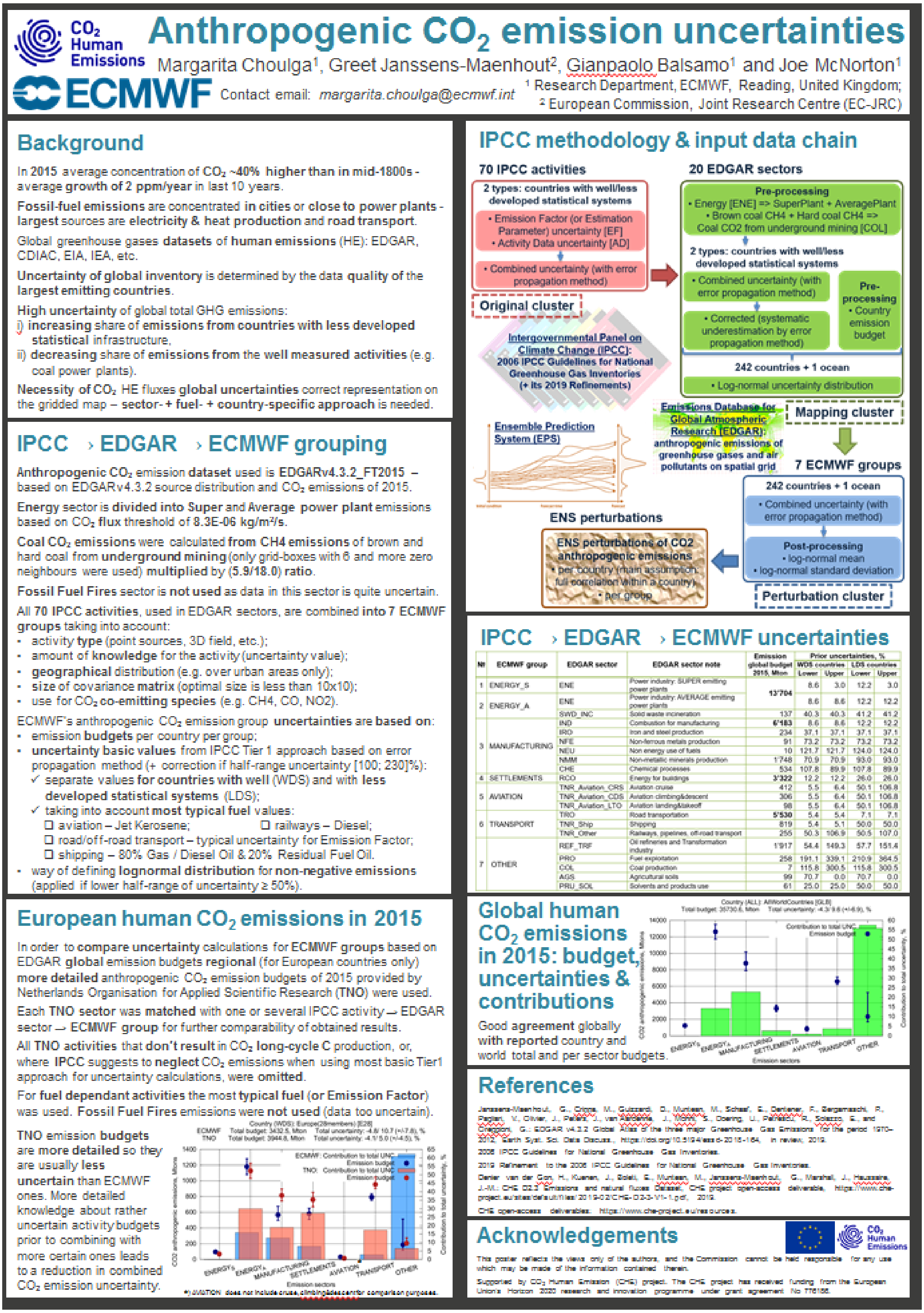
8 Annex: poster presentation



Anthropogenic CO_2 emission uncertainties

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Background

In 2015 average concentration of CO_2 ~40% higher than in mid-1800s - average growth of 2 ppm/year in last 10 years.

Fossil-fuel emissions are concentrated in cities or close to power plants - largest sources are electricity & heat production and road transport.

Global greenhouse gases datasets of human emissions (HE): EDGAR, CDIAC, EIA, IEA, etc.

Uncertainty of global inventory is determined by the data quality of the largest emitting countries.

High uncertainty of global total GHG emissions:
i) increasing share of emissions from countries with less developed statistical infrastructure,
ii) decreasing share of emissions from the well measured activities (e.g. coal power plants).

Necessity of CO_2 HE fluxes global uncertainties correct representation on the gridded map – sector- + fuel- + country-specific approach is needed.

IPCC › EDGAR › ECMWF grouping

Anthropogenic CO_2 emission dataset used is EDGARv4.3.2_FT2015 – based on EDGARv4.3.2 source distribution and CO_2 emissions of 2015.

Energy sector is divided into Super and Average power plant emissions based on CO_2 flux threshold of 8.3E-06 kg/m²/s.

Coal CO_2 emissions were calculated from CH4 emissions of brown and hard coal from underground mining (only grid-boxes with 6 and more zero neighbours were used) multiplied by (5.9/18.0) ratio.

Fossil Fuel Fires sector is not used as data in this sector is quite uncertain.

All 70 IPCC activities, used in EDGAR sectors, are combined into 7 ECMWF groups taking into account:
- activity type (point sources, 3D field, etc.);
- amount of knowledge for the activity (uncertainty value);
- geographical distribution (e.g. over urban areas only);
- size of covariance matrix (optimal size is less than 10x10);
- use for CO_2 co-emitting species (e.g. CH4, CO, NO2).

ECMWF's anthropogenic CO_2 emission group uncertainties are based on:
- emission budgets per country per group;
- uncertainty basic values from IPCC Tier 1 approach based on error propagation method (+ correction if half-range uncertainty [100; 230]%):
  - ✓ separate values for countries with well (WDS) and with less developed statistical systems (LDS);
  - ✓ taking into account most typical fuel values:
    - ☐ aviation – Jet Kerosene; ☐ railways – Diesel;
    - ☐ road/off-road transport – typical uncertainty for Emission Factor;
    - ☐ shipping – 80% Gas / Diesel Oil & 20% Residual Fuel Oil.
- way of defining lognormal distribution for non-negative emissions (applied if lower half-range of uncertainty ≥ 50%).

European human CO_2 emissions in 2015

In order to compare uncertainty calculations for ECMWF groups based on EDGAR global emission budgets regional (for European countries only) more detailed anthropogenic CO_2 emission budgets of 2015 provided by Netherlands Organisation for Applied Scientific Research (TNO) were used.

Each TNO sector was matched with one or several IPCC activity → EDGAR sector → ECMWF group for further comparability of obtained results.

All TNO activities that don't result in CO_2 long-cycle C production, or, where IPCC suggests to neglect CO_2 emissions when using most basic Tier1 approach for uncertainty calculations, were omitted.

For fuel dependant activities the most typical fuel (or Emission Factor) was used. Fossil Fuel Fires emissions were not used (data too uncertain).

TNO emission budgets are more detailed so they are usually less uncertain than ECMWF ones. More detailed knowledge about rather uncertain activity budgets prior to combining with more certain ones leads to a reduction in combined CO_2 emission uncertainty.

Country (WDS): Europe(28members) [E28]
ECMWF Total budget: 3432.5, Mton Total uncertainty: -4.8/ 10.7 (+/-7.8), %
TNO Total budget: 3944.8, Mton Total uncertainty: -4.1/ 5.0 (+/-4.5), %
ECMWF: Contribution to total UNC; Emission budget
TNO: Contribution to total UNC; Emission budget
CO2 anthropogenic emissions, Mtons; Contribution to total uncertainty, %
ENERGY_S, ENERGY_A, MANUFACTURING, SETTLEMENTS, AVIATION, TRANSPORT, OTHER
Emission sectors

*) AVIATION does not include cruise, climbing&descent for comparison purposes.

IPCC methodology & input data chain

70 IPCC activities
2 types: countries with well/less developed statistical systems
• Emission Factor (or Estimation Parameter) uncertainty [EF]
• Activity Data uncertainty [AD]
• Combined uncertainty (with error propagation method)
Original cluster
Intergovernmental Panel on Climate Change (IPCC): 2006 IPCC Guidelines for National Greenhouse Gas Inventories (+ its 2019 Refinements)

20 EDGAR sectors
Pre-processing
• Energy [ENE] => SuperPlant + AveragePlant
• Brown coal CH4 + Hard coal CH4 => Coal CO2 from underground mining [COL]
2 types: countries with well/less developed statistical systems
• Combined uncertainty (with error propagation method)
• Corrected (systematic underestimation by error propagation method)
Pre-processing
• Country emission budget
242 countries + 1 ocean
• Log-normal uncertainty distribution
Emissions Database for Global Atmospheric Research (EDGAR): anthropogenic emissions of greenhouse gases and air pollutants on spatial grid
Mapping cluster

Ensemble Prediction System (EPS)
ENS perturbations
ENS perturbations of CO2 anthropogenic emissions
• per country (main assumption: full correlation within a country)
• per group

7 ECMWF groups
242 countries + 1 ocean
• Combined uncertainty (with error propagation method)
Post-processing
• log-normal mean
• log-normal standard deviation
Perturbation cluster

IPCC › EDGAR › ECMWF uncertainties

№	ECMWF group	EDGAR sector	EDGAR sector note	Emission global budget 2015, Mton	Prior uncertainties, %: WDS countries Lower	WDS countries Upper	LDS countries Lower	LDS countries Upper
1	ENERGY_S	ENE	Power industry: SUPER emitting power plants	13'704	8.6	3.0	12.2	3.0
2	ENERGY_A	ENE	Power industry: AVERAGE emitting power plants		8.6	8.6	12.2	12.2
		SWD_INC	Solid waste incineration	137	40.3	40.3	41.2	41.2
3	MANUFACTURING	IND	Combustion for manufacturing	6'183	8.6	8.6	12.2	12.2
		IRO	Iron and steel production	234	37.1	37.1	37.1	37.1
		NFE	Non-ferrous metals production	91	73.2	73.2	73.2	73.2
		NEU	Non energy use of fuels	10	121.7	121.7	124.0	124.0
		NMM	Non-metallic minerals production	1'748	70.9	70.9	93.0	93.0
		CHE	Chemical processes	534	107.8	89.9	107.8	89.9
4	SETTLEMENTS	RCO	Energy for buildings	3'322	12.2	12.2	26.0	26.0
5	AVIATION	TNR_Aviation_CRS	Aviation cruise	412	5.5	6.4	50.1	106.8
		TNR_Aviation_CDS	Aviation climbing&descent	306	5.5	6.4	50.1	106.8
		TNR_Aviation_LTO	Aviation landing&takeoff	98	5.5	6.4	50.1	106.8
6	TRANSPORT	TRO	Road transportation	5'530	5.4	5.4	7.1	7.1
		TNR_Ship	Shipping	819	5.4	5.1	50.0	50.0
		TNR_Other	Railways, pipelines, off-road transport	255	50.3	106.9	50.5	107.0
7	OTHER	REF_TRF	Oil refineries and Transformation industry	1'917	54.4	149.3	57.7	151.4
		PRO	Fuel exploitation	258	191.1	339.1	210.9	364.5
		COL	Coal production	7	115.8	300.5	115.8	300.5
		AGS	Agricultural soils	99	70.7	0.0	70.7	0.0
		PRU_SOL	Solvents and products use	61	25.0	25.0	50.0	50.0

Global human CO_2 emissions in 2015: budget, uncertainties & contributions

Good agreement globally with reported country and world total and per sector budgets.

Country (ALL): AllWorldCountries [GLB]
Total budget: 35730.6, Mton Total uncertainty: -4.3/ 9.6 (+/-6.9), %
Contribution to total UNC; Emission budget
CO2 anthropogenic emissions, Mtons; Contribution to total uncertainty, %
ENERGY_S, ENERGY_A, MANUFACTURING, SETTLEMENTS, AVIATION, TRANSPORT, OTHER
Emission sectors

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CHE open-access deliverables: https://www.che-project.eu/resources.

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Document History

Version	Author(s)	Date	Changes
0.1	ECMWF/JRC	12/06/2019	First draft for review
0.2	ECMWF	26/06/2019	Revised draft with additions on covariance matrix, monthly budgets, sensitivity study.
1.0	JRC	29/06/2019	Language and addition on the monthly uncertainty assessment

Internal Review History

Internal Reviewers	Date	Comments
W. Peters (WUR)	19/06/2019	The structure of the document is clear. A few more graphical elements could have been added to illustrate the outcomes (map of country or sector uncertainty across Europe). After reading, it remained unclear to me where I could find the covariances (rather than the country specific numbers) that would be of interest to CHE inverse modeling. I might have simply missed it though. Finally, it would be good to come back at the end of the document to the original Objectives in Section 2.2.1 and summarize what was achieved. The report follows the description of the action and is complete. The reader could benefit from some more text about the derived covariances, including an illustration or discussion of the main outcome. A summary paragraph or table (especially for Objective 2 of identifying the main uncertain parameters) would also help. This has resulted in a very nice dataset that will find a lot of use. The effort to compare results with TNO is very nice, and as written it has also led to new insights. Further scrutiny of these differences could even result in an interesting publication in my opinion.
I Pisso (NILU)	24/06/2019	The document is well structured, but it would have benefited from further editing. Some phrases were too long and unclear which made the document difficult to read at times. A summary/conclusions section with the main take home messages would be useful for the reader.

		The uncertainty ranges and the methodology used were well described. The covariances are only marginally mentioned. Flux covariances are essential ingredients of of most used inversion methodologies but not sufficient information about them is generally available. Objective 3 “preparing covariance matrices for the modelling system of ECMWF.” Is not sufficiently described. Further details would provide a valuable contribution.

Estimated Effort Contribution per Partner

Partner	Effort
ECMWF	12
JRC	1.5
Total	**13.5**