CoCO2

Prototype system for a Copernicus CO_2 service

Documentation of new temporal and spatial profiles including a global point source database

Marc Guevara

Co-ordinated by ECMWF

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Prototype system for a Copernicus CO_2 service

D2.4 DOCUMENTATION OF NEW TEMPORAL AND SPATIAL PROFILES INCLUDING A GLOBAL POINT SOURCE DATABASE

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Table of Contents

Figures

Tables

1 Executive Summary

A correct representation of the spatial and temporal distribution of atmospheric pollutant emissions is important for modelling and data assimilation efforts, because this strongly affects the simulated concentrations at (sub)urban measurement sites and the simulation of plumes at industrial facilities detected by satellites. Current temporal profiles delivered with emission inventories are often generic and based on long-term averaged activity data collected over a limited domain without accounting for socio-demographic and/or climate dependencies. On the other hand, the spatial representation of large point sources in global state-of-the-art gridded emission inventories (e.g., EDGAR) is sometimes inadequate as they are based on old datasets (e.g., CARMA) and/or do not report their exact geographical locations (i.e., emissions from facilities are reported in the centroid of the 0.1x0.1 inventory grid cells).

The goal of this task is to improve the temporal and spatial profiles of key sectors currently considered in emissions inventories. Concerning the first topic, we built a new set of global temporal profiles for the road transport, residential combustion, aviation, shipping and energy industry sectors. Depending on the sector, the final profiles are fixed in space and time (e.g., shipping, aviation) or country- / year-dependent (e.g., road transport, public energy, residential combustion). These temporal dependencies are implemented as temporal weight factors, that are applied to total annual emissions of CO_2. Regarding the improvement of the spatial representation, we constructed a global catalogue of CO_2 emissions and co-emitted species (i.e., NOx, SOx, CO, CH_4) from power plants at high spatial and temporal resolution for the year 2018. The dataset contains emission information for individual facilities at their exact geographical location as well as associated temporal and vertical distribution profiles.

The constructed monthly temporal profiles in this task were used by CNRS to produce the global monthly PED developed in T2.1. The global point source database was used by iLab as prior information for the electricity generation sector in a 2021 CCFFDAS run for WP6. The results from the two products were also used to provide recommendations to ECMWF on the monthly and vertical distribution profiles to be considered in the global CoCO2 nature runs performed in WP3.

We recommend considering the constructed global point source database in future global and regional inverse modelling and data assimilation exercises as it provides much more detailed information on the horizontal, vertical and temporal allocation of emissions than traditional gridded inventories such as EDGAR or CAMS-GLOB-ANT, in which power plant emissions are distributed according to CARMA, a no longer maintained point source database based on plant-level information from 2009. Significant differences were found between the constructed temporal profiles and the default sector-dependent profiles provided with the regional Prior Emission Dataset (PED) developed in T2.1, which are mostly based on old datasets and do not consider the effect of different sociodemographic patterns and climatological conditions. It is therefore recommended to update the default profiles currently considered to better capture the temporal variability of emissions.

This report describes the methodologies and databases considered to construct both the temporal profiles and global point source databases. The report also discusses the main limitations of the developed datasets and future works to mitigate their effects. The global point source inventory will be released with the upcoming scientific paper describing the dataset and comparing it against existing state-of-the-art emission inventories at the country and plant-level.

2 Introduction

2.1 Background

A correct representation of the spatial and temporal distribution of atmospheric pollutant emissions is important for modelling and data assimilation efforts performed in CoCO2 WP3 and WP4. Current temporal profiles delivered with emission inventories are often generic and based on long-term averaged activity data collected over a limited domain without accounting for socio-demographic and/or climate dependencies. On the other hand, the spatial representation of large point sources in global state-of-the-art gridded emission inventories is sometimes inadequate as they are based on old datasets that are no longer maintained, such as CARMA, which is based on plant-level information from 2009. At the same time, gridded inventories do not report emissions from point sources at their exact geographical locations, but at the centroid of the inventory grid cells, which can entail deviations from the right location of at least a few kilometres.

2.2 Scope of this deliverable

2.2.1 Objectives of this deliverables

The objective of this deliverable is to improve the temporal and spatial profiles of key sectors currently considered in emissions inventories.

2.2.2 Work performed in this deliverable

The work for this deliverable has resulted in the following products:

- A dataset of updated global temporal profiles for the road transport, aviation, shipping, residential combustion and public energy sectors.
- A global catalogue of CO_2 emissions and co-emitted species (i.e., NOx, SOx, CO, CH_4) from power plants for the year 2018 with associated exact geographical location, temporal and vertical distribution profiles.

The constructed monthly temporal profiles were used by CNRS to produce the global monthly PED developed in T2.1. The global point source database was used by iLab as prior information for the electricity generation sector in a 2021 CCFFDAS run for WP6. The results from the two products were also used to provide recommendations to ECMWF on the monthly and vertical distribution profiles to be considered in the global CoCO2 nature runs performed in WP3.

2.2.3 Deviations and counter measures

No deviations from original planned task. Final version of the deliverable was submitted one month after the original deadline to incorporate comments from internal review process.

3 Global point source database

We constructed a global catalogue of CO_2 emissions and co-emitted species (i.e., NOx, SOx, CO, CH_4) from power plants at high spatial (exact geographic location) and temporal resolution (up to the hourly level) for the year 2018. The dataset includes emissions from thermal power plants that burn coal, natural gas, oil, solid biomass and municipal/industrial solid waste (hereinafter referred to as waste) to produce electricity or combined heat and electricity. The dataset includes emissions from public utilities and, for most of the countries, industrial auto-producer facilities, which generate electricity/heat wholly or partly for their own use, as an activity that supports their primary activity. Public and auto-producer plants designed to produce heat only and who sell heat to a third party (e.g., residential, commercial or industrial consumer) are excluded from the current catalogue for non-EU countries due to the limit amount of information available for this type of facilities.

For each facility, the final dataset reports information on the exact geographical coordinates (i.e., longitude and latitude), annual emissions representative for 2018, and associated temporal (i.e., monthly, weekly, hourly) and vertical distribution profiles.

This section presents the methodology considered to develop the database, as well as a general overview of the obtained results and a description of the final product.

3.1 Methodology

The approach to construct the global point source database is divided in five phases: 1) Selection of facilities and definition of associated geographical location (i.e., latitude and longitude coordinates), 2) estimation of annual emissions of CO_2 and co-emitted species (i.e., NO_x, SO_x, CO, CH_4) per facility, 3) fuel allocation per facility, 4) construction of the monthly, weekly (day-of-the-week) and hourly (hour-of-the-day) temporal profiles associated to each facility and 5) construction of the vertical distribution profiles associated to each facility.

The global point source database is a mosaic composed of a European (i.e., EU-27 plus United Kingdom, Norway, Switzerland and Serbia) and a non-European (rest of the world) dataset developed by The Netherlands Organization for Applied Scientific Research (TNO) and the Barcelona Supercomputing Center (BSC), respectively. The sources of information and approaches used to develop each dataset are described in the following sub-sections.

3.1.1 Selection of facilities and definition of geographical location

To select and assign each individual power plant to its exact geographical location, several public and commercial datasets were combined.

For the European database, the main data sources were:

- The European Pollutant and Transfer Register database (E-PRTR_v18, EEA, 2020)
- The Large Combustion Plants database (LCP_v.5.2, EEA, 2019)
- The Platts World Electric Power Plant dataset (WEPP Europe, September 2015, Platts, 2015)
- The integrated Industrial Reporting Database v.7 (EEA, 2022)

For the non-European database, the main datasets considered included:

- The Global Coal Plant Tracker (GCPTv2021_01; GEM, 2021)
- The Global Power Plant Database (GPPDv1.3.0; Global Energy Observatory et al., 2021)
- The IndustryAbout database (IndustryAbout, 2021)
- Open Infrastructure Map (OpenInfraMap, 2022)
- The Emissions and Generation Resource Integrated Database (eGRIDv2018; US EPA, 2020)
- The Chinese Ministry of Ecology and Environment's domestic waste incineration power

plant database (MIEE, 2022)

- The Tai biomass power plant database (DEDE; 2022)
- The Geocomunes Mexican power plant database (Geocomunes, 2020)
- The Taiwanese waste-to-energy plant database (Taiwan EPA, 2014)
- The electrical Japan power station database (Electrical Japan, 2022)
- The Argentinian renewable power plant database (MINEM, 2022)
- The UNFCCC Clean Development Mechanism database (UNFCCC CMD, 2022)

For both the European and non-European databases, substantial effort was put into identifying missing and incorrect facility coordinates. These were searched manually using Google Maps or other websites and added to the dataset. For Europe, the reported coordinates were consistently checked and corrected for the top-100 facilities (in terms of 2017 CO_2 emissions). Furthermore, all coordinates that did not fall within the correct country borders, or which were inconsistent between reported dataset versions, were manually checked and corrected. In addition, many other coordinates (likely about 400) were checked during the process of linking up facilities between datasets, identifying fuel types, and by looking at the resulting emission maps. In total, all checks resulted in 360 plants with corrected coordinates, including about 75 of the top-100 plants. For the non-European dataset, the review process was performed for selected countries that are among the top 30 countries in terms of installed power generation capacity and that are representative of coal (i.e., South Africa, Japan, Taiwan, Kazakhstan, Australia, Vietnam and Turkey), natural gas (i.e., Japan, Oman, Thailand, Bahrain, Algeria, Ukraine) and oil (i.e., Egypt, Iran, Iraq, Libya, Pakistan, Saudi Arabia) power plants. In both cases, some corrections improve the coordinates by only tens of meters or less, in other cases the original coordinates were further off.

An illustration of the corrections performed is shown in Figure 1. Multi-unit power plants were in most of the cases located at the same coordinates, since the distance between units is usually small (i.e., dozens of meters). However, in facilities where the distance between units was significant (i.e., few kilometres), original coordinates were edited and assigned to individual units, as shown in Figure 2. Despite these efforts, there may be some error still present in the dataset, especially in the case of small plants.

Figure 1 Difference between original (red dot) and corrected (blue dot) geographical locations for the Richards Bay Mill (South Africa) (left) and the Tabriz (Iran) (right) power stations

Figure 2 Example of two multi-unit power plants assigned with: a) the same coordinates (Matimba power plant, South Africa, left) and b) unit-specific coordinates (Callide power plant, Australia, right)

3.1.2 Estimation of annual CO_2 emissions and co-emitted species

For European power plants, annual emissions were derived as a first step from the E-PRTR_v18 database. However, for many facilities, gaps in the E-PRTR emission reporting were identified and had to be corrected following a gap filling routine (see below). The gaps are mainly due to the E-PRTR emission reporting thresholds, which obliges companies to report emissions from individual pollutants only if they are above the values summarised in Table 1. Given the pollutant-specific reporting threshold for companies, many facilities report emissions for only a small number of pollutants. NOx and CO_2 are the pollutants that are on average reported most often. CH_4 reporting is almost non-existent for power plants, while CO and SOx are reported for a limited number of facilities, and more often in the earlier years (2004 – 2010) and less in recent years, when annual emission may lie more often below the reporting threshold due to emission reduction technologies. Reporting for large combustion plants (LCP) is not dependent on an emission threshold but is mandatory for all combustion plants from 50 MW or higher thermal input capacity, excluding ovens and certain types of chemical reactors. For each LCP, annual reporting emissions of NOx, SOx, PM and fuel input by fuel type is required.

Table 1 Summary of the E-PRTR emission reporting thresholds per pollutant

Pollutant	E-PRTR threshold (ton/year)
CH_4	100
CO	500
CO_2	100000
NO_X	100
SO_X	150

To complete the reporting for all five pollutants, a 5-step gap filling routing was designed that follows several steps to estimate missing emission values:

- In **gap filling step 1**, the E-PRTR and LCP reported values are compared for those years that reporting exists in both datasets for a specific plant. If the correlation between both series is >0.5, the LCP value is used, multiplied with the average ratio between the E-PRTR and LCP reported emission values. This way, if the EPRTR facility typically encompasses several smaller units that are not in the LCP dataset (i.e. <50MWth), the gap filled emission value incorporates this relatively fixed ratio between E-PRTR and LCP emissions. The gap filled emission value is capped at the highest reported emission value in the time series for this specific facility. When the correlation is <0.5, but the aggregated ratio of the series total emissions is between 0.9 - 1.1, or if the median ratio between individual emission values for each year is between 0.9 - 1.1, the LCP value is used directly, as the two time series are considered sufficiently consistent, but no adjustment ratio can be estimated.
- In **gap filling step 2**, when no E-PRTR reporting for a specific pollutant is available for any years, or for none of the years where LCP reporting is available (which would allow a comparison), the LCP emission value is used directly when available.
- After gap filling using LCP data, many gaps in the emission reporting remained. It was decided to gap fill these if emissions for at least one pollutant had been reported for the facility in a given year (implying activity). **Gap filling step 3** was performed by calculating average ratios between reported CO_2 emissions and the reported emissions of other pollutants for the specific facility. When emissions were missing, but CO_2 emissions were available, the plant-specific ratio between CO_2 and the missing pollutant was used to estimate the missing emission. When fuel use information was not available, the use of pollutant ratios was also deemed the most appropriate method to gap fill missing CO_2 emissions. However, CO_2 was only gap filled in this step when a NOx value was reported, as this ratio is typically more constant than for the other co-emitted pollutants. Using the progression (e.g. lowering of SOx/CO_2 ratio over time due to increased implementation of abatement technologies) of country-, fuel- and year-specific emission factors from the GAINS model, the emission ratios based on co-reporting in earlier years were corrected before using in later years to simulate the effect of increasing use of abatement technologies.
- In **gap filling step 4**, missing emission values were gap filled using the ratio between the IIASA GAINS model implied emission factors (IIASA, 2018) (e.g., CO_2/CO ratio) for a specific country, year, fuel type and pollutant, applied to a CO_2 value established from E-PRTR reporting or gap filling steps 1 or 2.
- In **gap filling step 5**, all emission values that are still missing are gap filled, by applying the ratio between GAINS emission factors on values gap filled in steps 3 or 4. For CH_4, a separate fuel-specific CO_2/CH_4 ratio is used to gap fill emission values based on the Tier 1 emission factors reported by the IPCC guidelines (Eggleston et al., 2006).

As the gap filling steps progress, the gap filled emission value typically becomes more uncertain. To limit outlier values, gap filled values derived from gap filling steps 3 to 5 for all pollutants except CO_2 were capped at the E-PRTR reporting threshold value (assuming that the value has not been originally reported due to being below the reporting threshold).

Plant-specific CO_2, NO_x, SO_2 and CH_4 emissions for all US power plants were obtained from the eGRID database. Most emissions of CO_2, NO_x and SO_2 are taken from monitored data from the Clean Air Markets Division Power Sector Emission Data. For all other units and for CH_4, the reported emissions are based on measured heat input multiplied by an emission factor, as described in US EPA (2020). Emissions of CO, which are not reported by eGRID, were estimated using fuel-dependent average ratios between NO_x and CO emissions derived from the continuous emission monitoring system (CEMS) database maintained by the Environmental Protection Agency (US EPA, 2021).

For the rest of the world, emissions per power plant were estimated following the steps below:

1. Estimation of CO_2 and CH_4 emissions per country, utility type (i.e., main or auto-producer plants) and fuel type combining the national energy statistics provided by the IEA World Energy Balances (IEA, 2021a) with the Tier 1 fuel-dependent emission factors reported by the IPCC guidelines (Eggleston et al., 2006).
2. Estimation of emissions of NOx and SOx by combining the CO_2 annual emissions estimated in step 1 with calculated fuel-dependent average ratios between CO_2 emissions and emissions of other pollutants (e.g., SO_x/CO_2 ratio) reported by the eGRID database.
3. Estimation of emissions of CO by combining the NO_x annual emissions estimated in step 2 with calculated fuel-dependent average ratios between NO_x and CO emissions derived from the US EPA CEMS database.
4. Assignation of estimated country- and fuel-dependent emissions derived from step 1, 2 and 3 to each facility as a function of the installed capacity and fuel information. The information on installed capacity and fuel type per power plant is provided by the databases described in Sect. 3.1.1.

Table 2 summarises the fuel-dependent CO_2 and CH_4 emission factors and average emission ratios calculated for co-emitted species for the main IEA fuel categories.

Table 2 Fuel-dependent CO_2 and CH_4 emission factors and emission ratios (SO_x/CO_2, NO_x/CO_2, CO/NO_x) considered for the main IEA fuel categories.

IEA fuel category	CO_2 EF [kg/TJ]	CH_4 EF [kg/TJ]	SOx/CO_2	NOx/CO_2	CO/NOx
Other bituminous coal	94600	1	6.78E-04	8.40E-04	2.21E-01
Sub-bituminous coal	96100	1	1.24E-03	7.39E-04	4.02E-01
Lignite	101000	1	1.94E-03	9.39E-04	4.47E-01
Anthracite	98300	1	6.78E-04	8.40E-04	2.21E-01
Natural gas	56100	1	1.35E-05	1.20E-03	5.19E-01
Crude oil	73300	3	3.40E-03	1.31E-03	2.87E-01
Fuel oil	77400	3	3.40E-03	1.31E-03	2.87E-01
Gas/diesel oil	74100	3	1.78E-03	1.96E-02	6.78E-02
Primary solid biofuel	100000	30	1.16E-04	6.85E-04	1.25E+00
Municipal waste	95850	30	2.78E-04	1.42E-03	2.29E+00

For coal-fired power plants we assumed that main and auto-producer facilities are correctly covered in all countries, as the GCPTv2021_01 database reports both public and industrial facilities. On the other hand, emissions from auto-producer plants using oil, natural gas, biomass or waste were only considered in those countries where the difference between the total installed capacity (main plus auto-producers) reported by our database and UN (2021) was lower than 10%. For countries where this difference was larger than 10%, we assumed that our database is only covering main activity producer plants and therefore auto-producer emissions were excluded from the country-to-plant assignation process (step 4).

Figure 3 shows the relative differences between the total installed capacity reported by our database and the installed capacity reported by UN (2021) for main producers (red rectangles) and main plus auto-producers (blue circles) for the top 50 non-European CO_2 emitting countries. For each country, the marker without the transparency effect indicates whether emissions from main producers plus auto-producers (e.g., China, USA, South Korea, Saudi Arabia) or only from main producers (e.g., India, Russia, Japan, Iran) were considered.

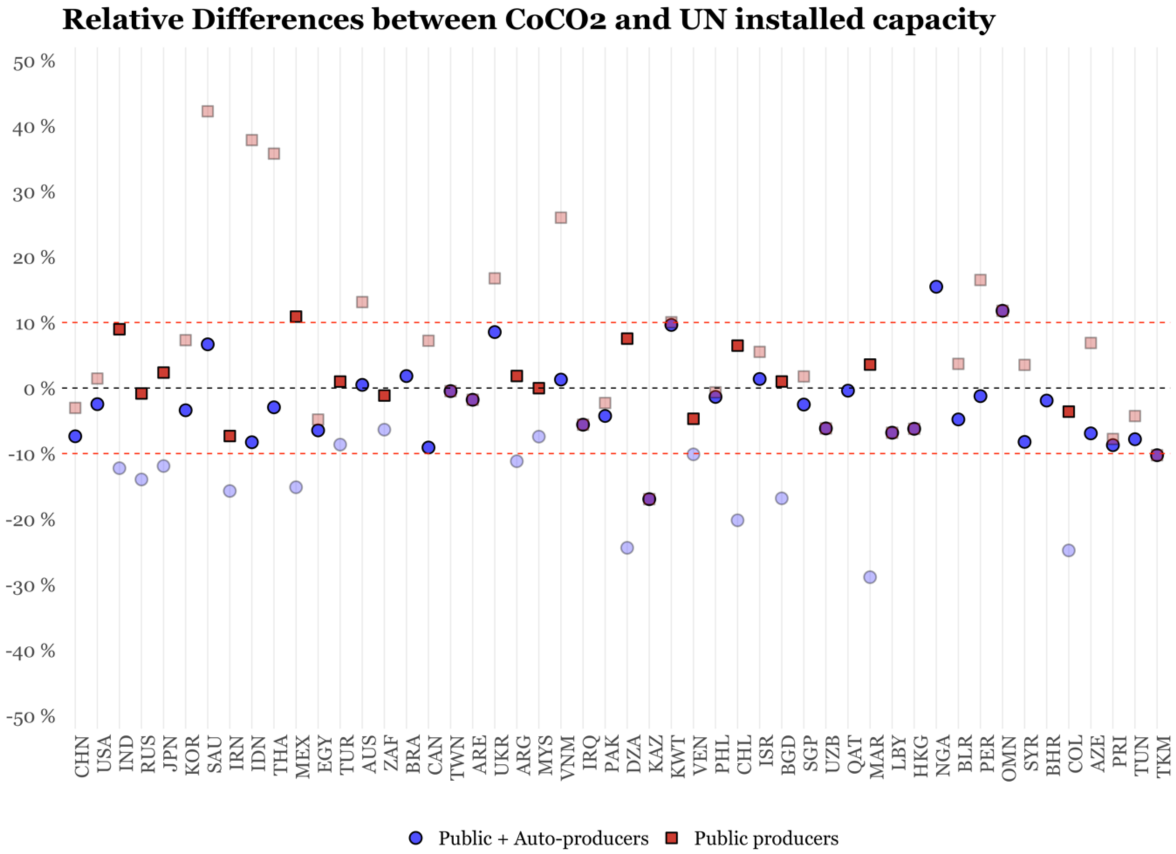


Figure 3 Relative differences [%] in the total installed capacity reported by the CoCO2 global point source database and the installed capacity reported by UN (2021) for main producers (red rectangles) and main plus auto-producers (blue circles) for the top 50 non-European CO_2 emitting countries. For each country, the marker without the transparency effect indicates whether emissions from main producers plus auto-producers or only from main producers were considered.

Overall, we could not include emissions from auto-producers in 35% of the countries considered. This translates into 4.1% of total estimated CO_2 emissions that could not be allocated to the final non-European point source database due to the lack of information from auto-producers. Figure 4 represents the share of total national CO_2 emissions that could not be allocated per country. It is observed that most of the countries where information on auto-producers could not be found are in South America and Africa. Benin, El Salvador, Mali, Ecuador, Costa Rica and Madagascar are among the countries where the largest share of total CO_2 emissions remained unallocated (between 70% and 50%). Emissions from these countries are however not significant and therefore they have a very limited impact on the overall non-allocated emissions. In large emitting countries such as Russia, India or Japan, the share of national emissions that could not be assigned to individual facilities is much lower (i.e., 14% to 21%).

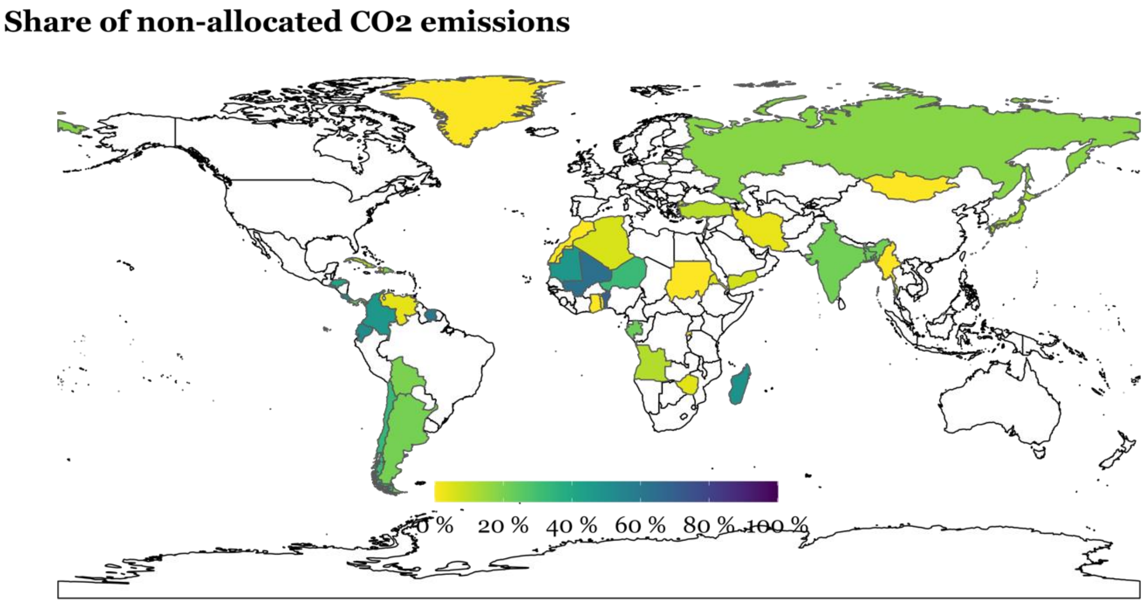


Figure 4 Share of total national CO_2 emissions [%] that could not be allocated due to the lack of information from auto-producers. Countries where emissions from main producers and auto-producers could be allocated are represented in white.

3.1.3 Fuel allocation

Each of the emission values in the European power plant dataset is allocated to one of five fuel types (i.e., biomass, coal, oil, natural gas or waste). Three methods were used to allocate the fuel type:

1. Link with LCP dataset: As LCP reporting includes the reporting of fuel input (but not for waste), this could be used to allocate emissions to different fuels when there was a link between an E-PRTR and LCP facility. Still, as only one emission value is reported, in case of a multi-fuel plant (e.g., co-combustion of biomass in a coal-fired power plant), a proxy emission value for each fuel type was estimated using country- and fuel-specific emission factors from the IIASA GAINS model. The ratio between the proxy emission values was then used to allocate the actual emission values to specific fuel types.
2. Link with Platts WEPP dataset: If no LCP fuel data was available, for some plants the fuel type could be taken from a link with the Platts WEPP dataset. The Platts WEPP dataset contains a detailed fuel type for every electricity-producing unit and also lists the electric capacity for every unit. For those facilities that could not be successfully linked to an LCP plant, a link was made to electricity producing units in the Platts WEPP database. The listed power and fuel type of the units was used together with country- and fuel specific emission factors from the GAINS model to estimate a proxy emission value for each unit and attribute the emissions to different fuel types.
3. Manual search and allocation of fuel types for the remaining plants.

For non-European power plants, we considered the plant-level fuel information provided by the databases listed in Sect. 3.1.1, which only report the main fuel even in the cases of multi-fuel plants. Therefore, for each power plant all emissions are linked to one single fuel, as we did not have information to split emissions between fuels in multi-fuel plants, as done for the European dataset. To homogenise the results reported by the European and non-European datasets, we assigned to each European power plant the fuel with the largest contribution to total CO_2 emissions.

3.1.4 Temporal distribution

Country- (state- for the US) and fuel-dependent monthly, weekly and hourly temporal profiles were constructed homogeneously for all power plants (i.e., European and non-European datasets) using the electricity production statistics summarised in Table 3. For countries where electricity generation statistics are not disaggregated by fuel type, we assumed the same temporal distribution for all types of power plants. For countries with no information on electricity generation, or information only available at e.g., monthly scale but not at hourly scale, averaged profiles from countries belonging to the same world region were used. The definition of world regions was taken from the EDGARv5 emission inventory (Crippa et al., 2018). The resulting profiles were assigned to each facility as a function of the country and fuel type information.

Table 3 Sources of electricity production statistics and corresponding characteristics

Country/Region	Source of information	Temporal resolution	Information per fuel
Uruguay	ADME (2021)	Hourly	yes
Australia	AEMO (2021)	Hourly	yes
Guatemala	AMM (2021)	Daily	yes
Indonesia	BPS (2021)	Monthly	no
Argentina	CAMMESA (2021)	Daily	yes
Mexico	CENACE (2021)	Hourly	yes
Algeria, Botswana, Lebanon, Malawi, Sri Lanka, Qatar	CEIC Data (2021)	Monthly	no
Chile	CNE (2021)	Hourly	yes
Peru	COES (2021)	Daily	thermal/renewable
United Arab Emirate	DEWA (2021)	Monthly	yes
EU27 + UK	ENTSO-E (2021)	Hourly	yes
Thailand	EPPO (2021)	Monthly	yes
South Africa	ESKOM (2021)	Hourly	yes
Malaysia	GSO (2021)	Monthly	yes
China, Canada, Colombia, South Korea, New Zealand	IEA (2021)	Monthly	yes
Kazakhstan	KOREM (2021)	Monthly	thermal/renewable
Kuwait	MEW (2021)	Monthly	no
Moldova	MOLDELECTRICA (2021)	Hourly	no
Oman	NCSI (2021)	Monthly	yes
India	NPP (2021)	Daily	yes
Japan (*)	OCCTO (2021)	Hourly	thermal/biomass/renewable
Brazil	ONS (2021)	Hourly	yes
Bangladesh	PGCB (2021)	Hourly	yes
Russia	SO-UPS (2021)	Monthly	thermal/renewable
Switzerland (*)	SWISSGRID (2021)	Hourly	no
Turkey	TEIAS (2021)	Daily	yes
Ukraine	UNEC (2021)	Hourly	yes
US	US EPA (2021)	Hourly	yes
(*) Monthly data derived from IEA as it is reported by fuel type			

Figure 5 shows results of monthly, weekly and hourly profiles for selected countries (i.e., Australia, AUS; Germany, DEU; Spain, ESP; India, IND; Poland, POL; US Pennsylvania, US-PA) and fuels (i.e., coal, natural gas).

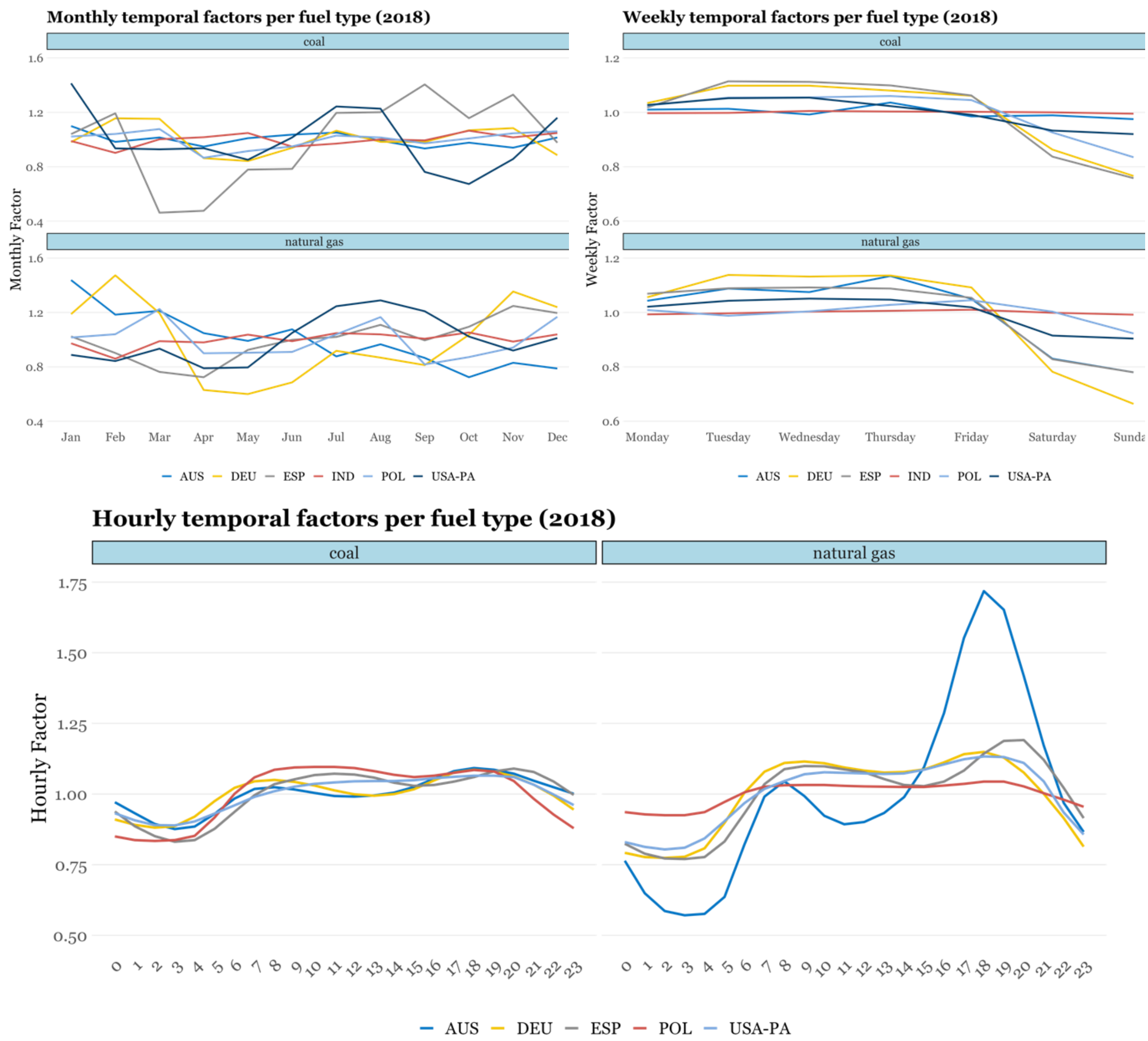


Figure 5 Monthly, weekly and hourly temporal profiles constructed for selected countries (i.e., Australia, AUS; Germany, DEU; Spain, ESP; India, IND; Poland, POL; US Pennsylvania, US-PA) and fuels (i.e., coal, natural gas).

Figure 6 illustrates, on the one hand, the countries for which specific monthly, weekly and hourly profiles were constructed based on the statistics compiled and, on the other hand, the resulting share of total CO_2 emissions for which specific monthly, weekly and hourly profiles were available. For the monthly profiles, the database constructed is covering a total of 96 countries plus 42 USA states, which translates into more than 90% of total CO_2 emissions. For weekly and hourly profiles, the coverage in terms of total CO_2 emissions is much lower (approx. 46% and 36%, respectively) partially because no information on electricity production and the daily and hourly level was available for China. For this country, we assumed that the weekly cycle of emissions follows the pattern obtained for India, which shows no significant difference between weekdays and weekends (Figure 5). This assumption is in line with the results found by Wu et al. (2022), in which weekly profiles for Chinese power plants were constructed using measured emissions derived from continuous emission monitoring systems.

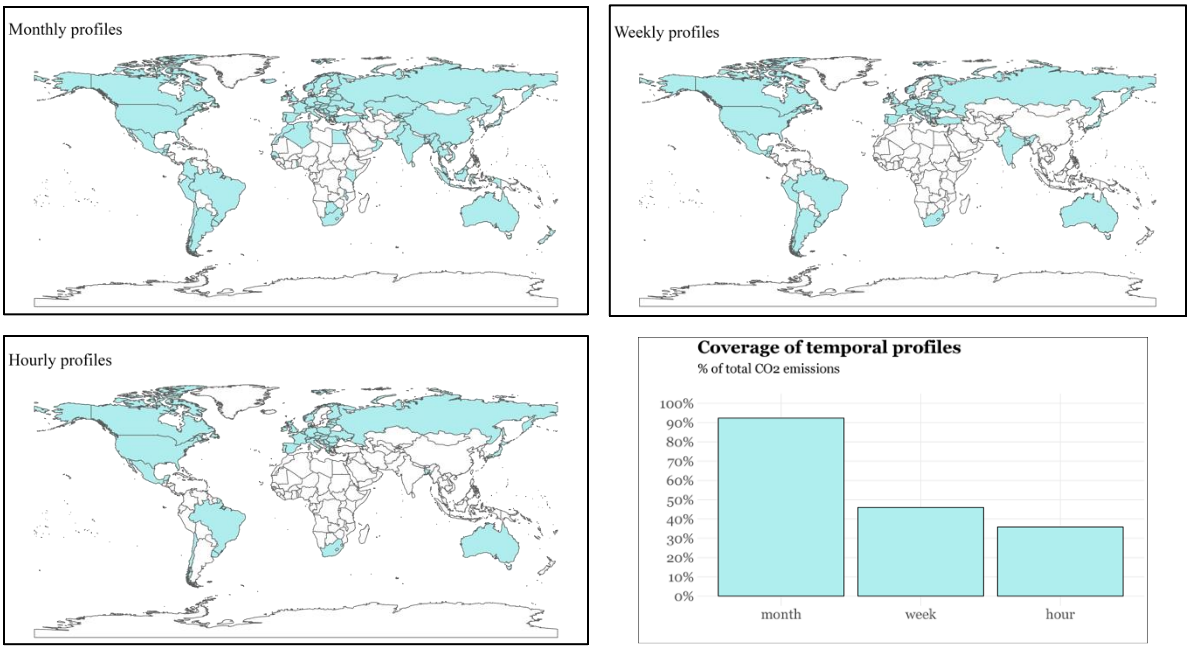


Figure 6 Spatial coverage of the constructed monthly, weekly and hourly temporal profile databases. Share of total CO_2 emissions [%] for which specific monthly, weekly and hourly profiles were developed.

3.1.5 Vertical allocation

Hourly effective emission heights at the facility level were simulated by combining 2018 global hourly gridded meteorological information (i.e., air temperature at stack height, wind speed at stack height, surface temperature, boundary-layer height, friction velocity and Obukhov length) simulated the MONARCH atmospheric chemistry model at 0.3x0.3 deg by (Badia et al., 2017) with facility-level stack parameter information (i.e., height, diameter, exit velocity and exit temperature). Information on stack parameters were obtained from the following sources:

- The point source database of electric generation units (PTEGU), obtained from the US EPA emission modelling platform (US EPA, 2021), which reports plant-level stack parameter information for US power plants.
- The HERMES Spanish power plant database (Guevara et al., 2013)
- Atmospheric emission licences of South African power plants (CER, 2022)
- The list of tallest chimneys worldwide reported by Wikipedia (2022a)
- The list of tallest chimneys in Poland reported by Wikipedia (2022b)
- The list of tallest chimneys in Czech Republic reported by Wikipedia (2022c)
- The list of tallest structures in Germany reported by Wikiwand (2022)

The Indian Ministry of Environment, Forest and Climate Change (MoEFCC, 2015) requires all coal-fired power plants with generation capacity of 500 MW and above to build a stack of minimum 275m; those between 210 MW and 500 MW to build a stack of minimum 220 m; and those with less than 210 MW to build a stack based on the estimated SO_2 emissions rate (Q in kg/hr) and a thumb rule of height = 14*(Q)0.3. Considering this information, we assumed that all coal-fired power plants in India with a generation capacity of 500 MW and above had a stack height of 275m, and those between 210 MW and 500 MW a stack height of 220m.

In some European coal -fired power plants built in recent years, which must be equipped with a flue gas cleaning system, the cooling tower also takes on the function of the chimney. Original chimneys were dismantled and now emissions are released through the cooling towers, which have different stack conditions. For Germany, we identified the list of power plants with cooling towers used as chimneys and associated stack height through Wikipedia

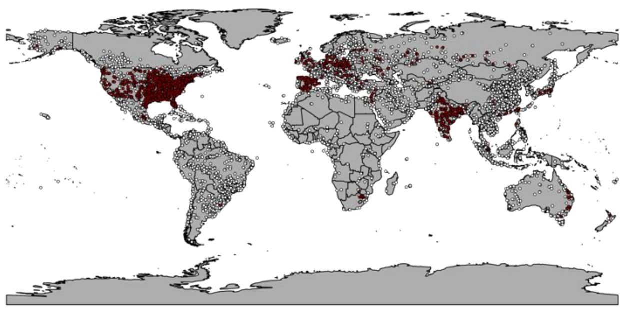
(2022d), and we completed the information with the stack diameter, exit temperature and exit velocity reported by Brunner et al., (2019). This fact is not considered in facilities from other countries due to lack of information.

Fuel-dependent and CO_2 emission-weighted average stack parameters were calculated using the PTEGU dataset and assigned to all those facilities for which no specific information was found. For waste-to-energy power plants we considered the stack parameters reported by Pregger and Friedrich (2009) as the PTEGU dataset does not include this type of facility. Table 4 summarises the stack parameters proposed per fuel type and the associated number of units considered to calculate the values.

Table 4 Fuel-dependent and CO_2 emission-weighted average stack parameters assigned to facilities with no specific information and number of sources considered to calculate them

Fuel	Stack height [m]	Stack diameter [m]	Exit temperature [ºC]	Exit velocity [m/s]	N units
Coal	182.6	7.7	91.8	21.0	675
Natural gas	53.0	5.6	143.5	20.0	1800
Oil	125.7	5.5	122.6	20.7	74
Biomass	72.6	2.8	147.6	28.5	33
Waste	103	2.5	118	8.5	230

Figure 7 illustrates, on the one hand, the facilities assigned with specific (red circles) or emission-weighted averaged (white circles) stack height information and, on the other hand, the share of total CO_2 emission assigned with specific stack parameter information. In terms of emission coverage, only 28% of total CO_2 emissions are assigned with specific stack height values. The coverage is even lower for stack diameter, exit velocity and temperature (i.e., approx. 15% in all cases). These results indicate the current lack of stack parameters information.



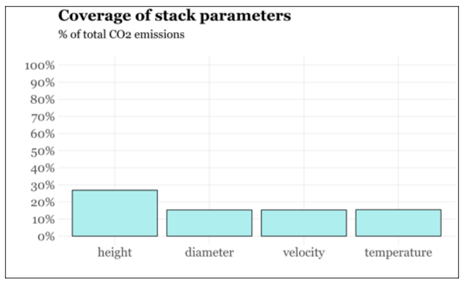


Figure 7 Facilities assigned with specific (red circles) or emission-weighted averaged (white circles) stack height information and share of total CO_2 emissions [%] for which specific stack parameters (height, diameter, exit velocity and exit temperature) were assigned.

The plume rise calculations at the hourly and facility level were performed using the HERMESv3 bottom-up emission system (Guevara et al., 2020), which includes plume rise formulas as described by Gordon et al. (2018). The HERMESv3 system was used to break down facility-level annual emissions into hourly resolution using of the temporal profiles described in Sect. 3.1.4, and to estimate hourly effective emission heights per plant considering the meteorological information provided by the nearest grid cell of MONARCH. Hourly plume top and plume bottom values per facility ($h_{top}(h,f)$, $h_{bot}(h,f)$) were derived from the estimated effective emission heights following the expressions reported by Bieser et al. (2011):

$$h_{top}(h, f) = h_s(f) + 1.5 * \Delta h(h, f) \qquad \text{Equation 1}$$

$$h_{bot}(h, f) = h_s(f) + 0.5 * \Delta h(h, f) \qquad \text{Equation 2}$$

where $h_s(f)$ is the stack height of the facility *f* and $\Delta h(h, f)$ is the modelled effective emission height for the facility *f* and hour *h*.

Figure 8 shows estimated daily bottom (blue) and top (red) plume values [m] at the Matimba (South Africa) and Bełchatów (Poland) coal-fired power plants for the year 2018. Dashed lines indicate the stack height of each facility.

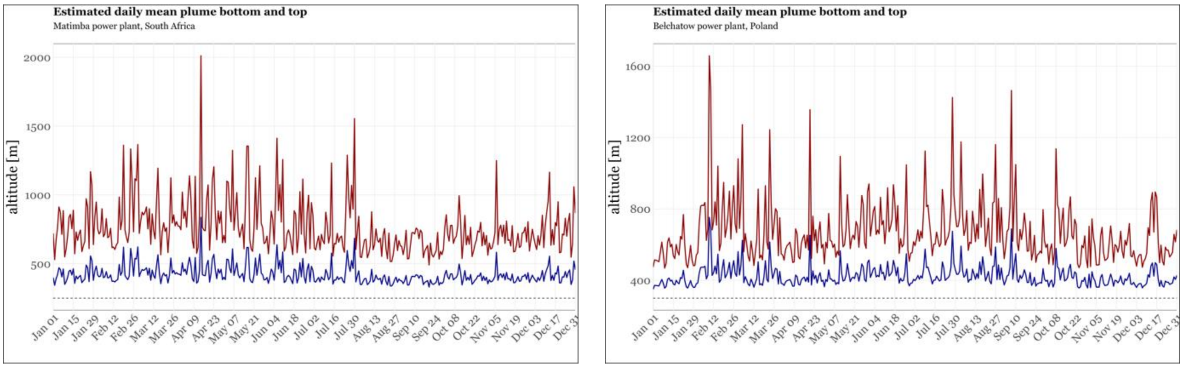


Figure 8 Estimated daily bottom (blue) and top (red) plume values [m] at the Matimba (South Africa) and Bełchatów (Poland) coal-fired power plants for the year 2018. Dashed lines indicate the stack height of each facility.

For each facility, the estimated CO_2 hourly emissions were first uniformly allocated across 16 vertical layers (from 0m up to 1500m with breaks every 100m, and above 1500m) considering the modelled hourly plume top and bottom values, then summarised to the annual level and finally normalised to 1 to derive annual and CO_2 emission-weighted vertical profiles.

3.2 Overview of the results

Figure 9 shows the plant-level CO_2 and NO_x annual emissions as reported by the resulting global point source database. Results are distinguished by fuel type. It is observed that coal-fired power plants (red circles) are the main contributors to total CO_2 emissions, the top emitters being in China, India, US, Australia, South Africa, Central Europe and Indonesia. CO_2 emissions from natural gas power plants (blue circles) are also relevant in Russia and some countries from the Middle East (e.g., Saudi Arabia and Iran). For NO_x, main contributors are oil-fired power plants (black circles), the largest emitters being in the Middle East (i.e., Iran and Saudi Arabia), Indonesia and Venezuela. In China, India, US, Australia, South Africa and Central Europe NOx emissions are mainly dominated by coal-fired power plants. For both pollutants it is observed that the number of large emitters in Africa and South America is rather scarce, expect for South Africa and some countries in North Africa as well as Venezuela. This is related to the fact that in both regions the electricity production is mainly dominated by renewable sources (e.g., hydro, solar) (IEA, 2021). Linked to this aspect, it is interesting to see the large amount of biomass power plants in Brazil (brown circles), as this fuel represents the second largest energy source, just behind hydropower. A significant number of waste-to-energy plants (green circles) are reported in Japan and China, the two countries with the largest installed incineration capacity (Lu et al., 2017).

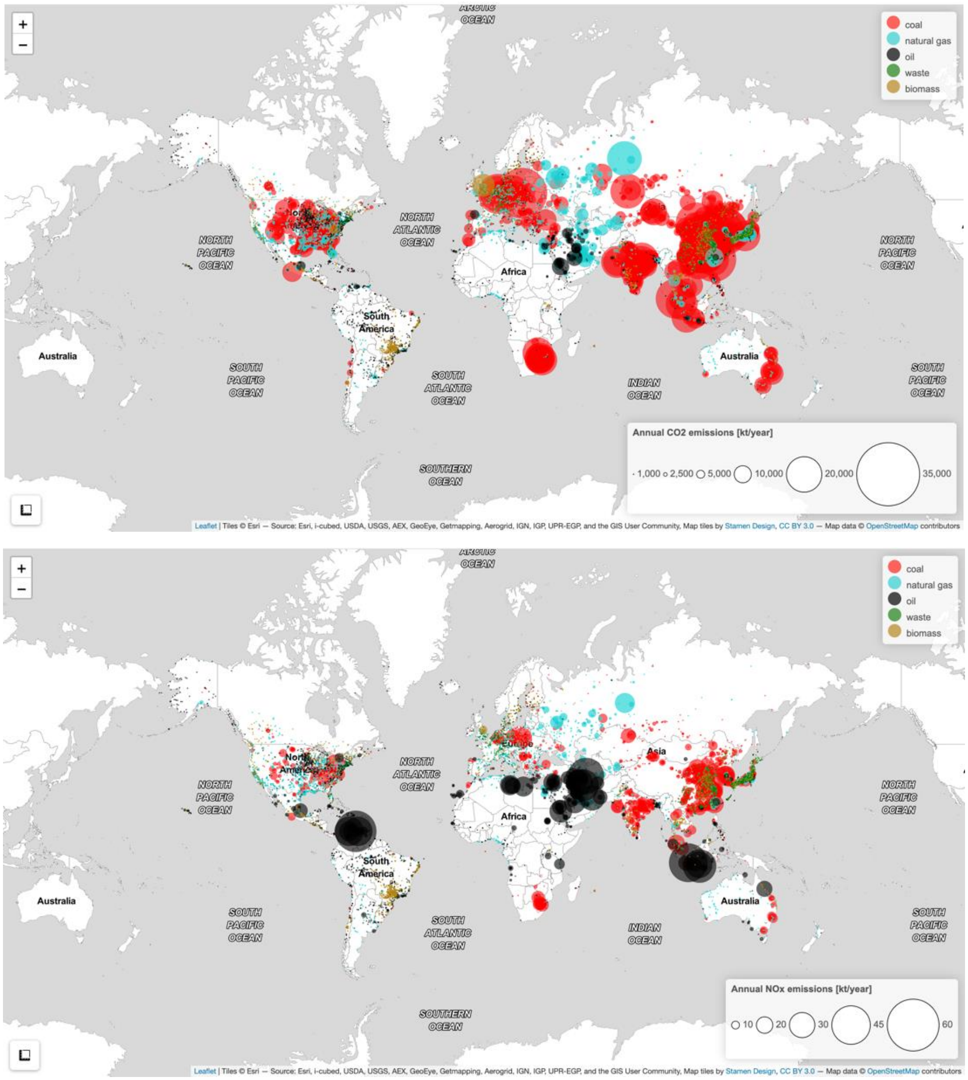


Figure 9 Plant-level CO_2 and NO_x annual emissions [kt/year] as reported by the resulting global point source database. Emissions are colour-classified according to the main fuel used: coal (red), natural gas (blue), oil (black), waste (green) and biomass (brown)

Table 5 and Table 6 list the top 15 CO2 and NOx emitters worldwide and in EU27+UK.

At the global level, the Belchatów (Poland), Taean (South Korea), Taichung (Taiwan), Dangjin (South Korea) and Datang Tuoketuo (China) power plants are the top 5 CO_2 emitters. These five facilities are also the five largest coal power stations in the world (with installed capacities between 6700MW and 5300 MW). All top 15 CO_2 emitters are coal-fired power plants, except for Surgutskaya GRES-2 (Russia), which is the largest combined-cycle natural gas-fired power station of Russia (8865MW) and supplies energy to nearly 40% of the population. Most of the top 15 CO_2 emitters are in Asian countries, including: South Korea (3), China (2), Taiwan (2), Malaysia (2), India (1) and Kazakhstan (1), while the rest are in Europe: Germany (2), Poland (1) and Russia (1). At the EU27+UK, it is observed that most of the 15 top emitters are distributed among Germany (6) and Poland (3). Similarly to what is observed at the global scale, 14 out of 15 facilities are coal-fired power plants, the remaining worst polluter being the Drax biomass power station, the largest power plant in the UK (3906MW) that is also capable of co-firing petroleum coke. The largest emitter in EU27+UK (Belchatów, Poland) reports almost 5 times more CO_2 emissions than the fifteenth facility (As Pontes, Spain).

For NOx, the list of top emitters mainly consists of oil-fired power plants (14 out of 15). Five of the emitters are in Iran, three in Venezuela, three in Indonesia and two in Saudi Arabia. The Surgutskaya GRES-2 combined-cycle natural gas-fired power plant is the only facility appearing in both the CO_2 and NO_x top 15 emitters list. At the EU27+UK level, Belchatów is again the largest emitter. Four out of the top five emitters are in Germany, all of them being coal-fired power plants. There are also four Spanish facilities, three of them being oil-fired power plants located in the Canary Islands, where no other fuels are being used to produce electricity. The other non-coal facilities that complete the European top 15 list are Drax (UK, biomass) and Atherinolakkos (Greece, oil).

Table 5 List of top 15 CO_2 and NO_x emitters worldwide. The plant name, main fuel used, country and annual emissions [kt/year for CO_2 and t/year for NO_x] is provided for each facility.

Plant	Fuel	Country	CO_2 [kt/year]
Belchatów	coal	POL	38400
Taean	coal	KOR	35877
Taichung	coal	TWN	34499
Dangjin	coal	KOR	33859
Datang Tuoketuo	coal	CHN	31435
Manjung	coal	MYS	30418
Neurath	coal	DEU	29900
Yeongheung	coal	KOR	28477
Niederaussem	coal	DEU	27200
Surgutskaya GRES-2	natural gas	RUS	25640
Ekibastuz-1	coal	KAZ	25522
Vindhyachal	coal	IND	24733
Waigaoqiao	coal	CHN	24512
Mailiao	coal	TWN	24463
Tanjung Bin	coal	MYS	24068

Plant	Fuel	Country	NO_x [t/year]
Planta Centro	oil	VEN	62817
Muara Karang	oil	IDN	58796
Shahid Salimi Neka	oil	IRN	53255
Grati	oil	IDN	49584
Shahid Montazeri	oil	IRN	48414
Ricardo Zuloaga	oil	VEN	44349
Termozulia	oil	VEN	43815
Shazand	oil	IRN	39336
Gresik	oil	IDN	39197
Bandar Abbas	oil	IRN	38731
Shuaibah Sec	oil	SAU	34455
Riyadh	oil	SAU	32343
Benghazi North	oil	LBY	30889
Surgutskaya GRES-2	natural gas	RUS	30882
Shahid mofateh	oil	IRN	30259

Table 6 List of top 15 CO_2 and NO_x emitters in EU27 + UK

Plant	Fuel	Country	CO_2 [kt/year]
Belchatów	coal	POL	38400
Neurath	coal	DEU	29900
Niederaussem	coal	DEU	27200
Jänschwalde	coal	DEU	24000
Eschweiler	coal	DEU	19100
Kraftwerk Boxberg	coal	DEU	19100
Drax	biomass	GBR	16600
Kozienice	coal	POL	14100
Lippendorf	coal	DEU	11400
Maritsa East 2	coal	BGR	9574
Agioy Dhmhtrioy	coal	GRC	9230
Enea Połaniec	coal	POL	8220
Eemshaven	coal	NLD	8210
Torrevaldaliga Nord	coal	ITA	8081
As Pontes	coal	ESP	7940

Plant	Fuel	Country	NOx [t/year]
Belchatów	coal	POL	30100
Neurath	coal	DEU	20200
Jänschwalde	coal	DEU	19000
Niederaussem	coal	DEU	18000
Kraftwerk Boxberg	coal	DEU	13500
Eschweiler	coal	DEU	13000
Drax	biomass	GBR	12200
Punta Grande	oil	ESP	11200
Atherinolakkos	oil	GRC	10700
Kozienice	coal	POL	9650
Las Salinas	oil	ESP	8220
Enea Połaniec	coal	POL	7760
Agioy Dhmhtrioy	coal	GRC	7100
Granadilla	oil	ESP	7030
As Pontes	coal	ESP	6360

Figure 10 shows the estimated hourly CO_2 emissions for the As Pontes (Spain), Belchatów (Poland), Jänschwalde (Germany) and Matimba (South Africa) coal-fired power plants. The Matimba power plant is the facility that presents the flattest distribution, the results indicating that it is a base load power source. On the other hand, emissions from Belchatów, Jänschwalde and As Pontes present a clear seasonality, with emissions peaking during February, coinciding with a European cold spell that caused below average temperatures in most European countries (C3S, 2018) and, in the case of As Pontes, also during summer, when energy demand increases due to the use of air conditioning systems. A weekend effect is also clearly observed for all facilities, with emissions significantly dropping during Saturday and Sunday when compared to the weekdays.

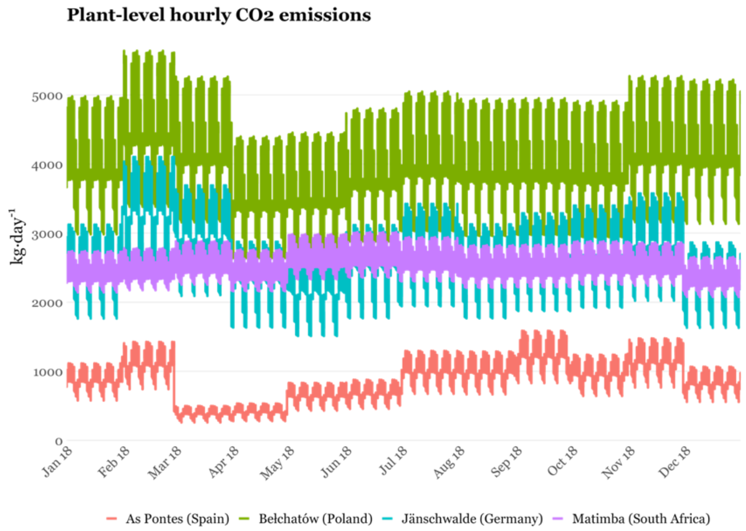


Figure 10 Estimated hourly CO_2 emissions [kg/h] for the As Pontes (Spain), Belchatów (Poland), Jänschwalde (Germany) and Matimba (South Africa) coal-fired power plants

Figure 11 shows the CO_2 emission-weighted average annual vertical profiles computed for the As Pontes (Spain), Belchatów (Poland), Jänschwalde (Germany) and Matimba (South Africa) coal-fired power plants. Jänschwalde is the power plant with the largest share of emissions occurring in lower layers (i.e., 78% of total emissions allocated between 100 and 300m). This is linked to the fact that emissions from this facility are released through the cooling towers, which have a height of only 120m. On the other hand, As Pontes is the facility with the largest share of emissions allocated between 400m and 600m (76%), as it is the power plant with the highest chimney in Europe (365.5m). Belchatów and Matimba present rather similar vertical distribution profiles, partially because both facilities have stacks of similar height (300m and 250m, respectively). Matimba is the power plant allocating the largest share of emissions across the top layers (8% of total emissions above 1000m). This is related to the larger exit velocity of the gases when compared to e.g. As Pontes (i.e., 26m/s versus 21m/s, almost 25% larger) as well as to differences in the local climatological conditions.

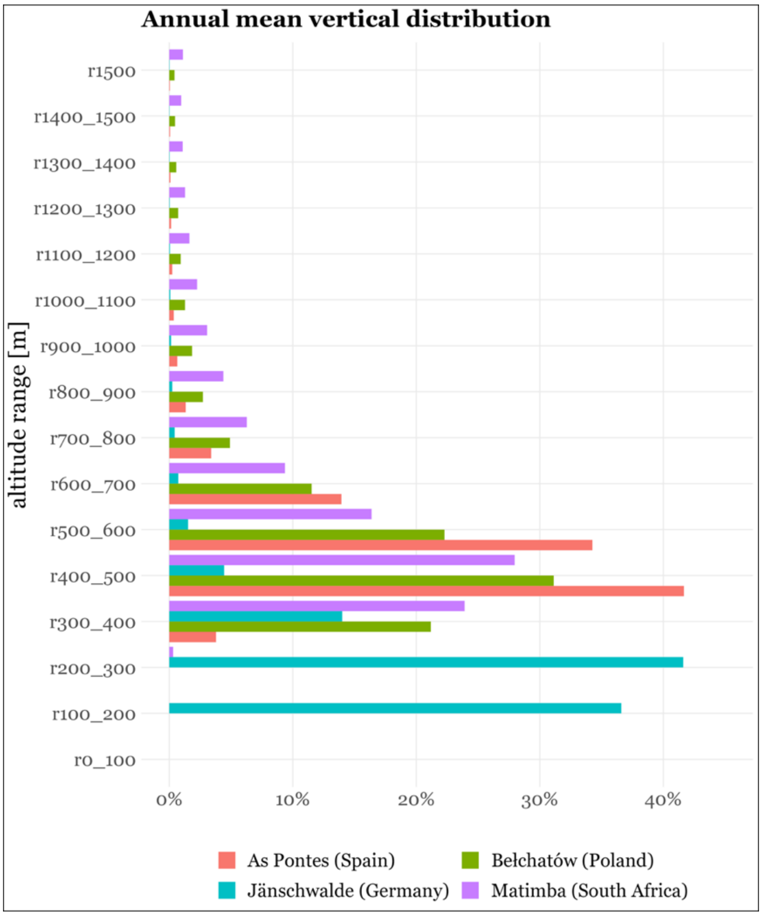


Figure 11 CO_2 emission-weighted average annual vertical profiles estimated for the As Pontes (Spain), Belchatów (Poland), Jänschwalde (Germany) and Matimba (South Africa) coal-fired power plants. For each facility we represent the associated vertical weight factors [%] across 16 vertical layers (from 0m up to 1500m with breaks every 100m, and above 1500m)

3.3 Description of the final dataset

The global point source database (coco2_ps_database_v1.zip) is composed of five CSV files:

1. Catalogue of power plants and associated profiles (coco2_ps_catalogue_v1.csv)

Field of information	Description
ID	Unique identifier assigned to each unit (CoCO2_xxxxx)
ISO3	Country where the unit is located (identified with the three-letter country code defined in ISO 3166-1)
fuel	Main fuel category associated to each unit (coal, natural gas, oil, biomass, waste)
latitude	Latitude (in degrees)
longitude	Longitude (in degrees)
co2_emis_ty	CO_2 annual emissions associated to each unit (in t/year)
nox_emis_ty	NO_x annual emissions associated to each unit (in t/year), expressed as NO_2
co_emis_ty	CO annual emissions associated to each unit (in t/year)
sox_emis_ty	SO_x annual emissions associated to each unit (in t/year)
ch4_emis_ty	CH_4 annual emissions associated to each unit (in t/year)
ID_MonthFact	Monthly temporal profile unique identifier (FM_xxx). The identifiers are cross-referenced with the monthly temporal CSV file where the numeric profiles are stored
ID_WeekFact	Weekly temporal profile unique identifier (FW_xxx). The identifiers are cross-referenced with the weekly temporal CSV file where the numeric profiles are stored
ID_HourFact	Hourly temporal profile unique identifier (FH_xxx). The identifiers are cross-referenced with the hourly temporal CSV file where the numeric profiles are stored
ID_VertProf	Vertical profile unique identifier (VP_xxxxx). The identifiers are cross-referenced with the vertical CSV file where the numeric profiles are stored

2. Monthly temporal profiles database (coco2_ps_monthly_profiles_v1.0.csv)

Field of information	Description
ID_MonthFact	Monthly temporal profile unique identifier (FM_xxx). The identifiers are cross-referenced with the catalogue of power plants.
Jan - Dec	Monthly weight factor associated to each month [0-12]
tot	Total sum of the monthly weight factors [12 for all cases]

3. Weekly temporal profiles database (coco2_ps_weekly_profiles_v1.0.csv)

Field of information	Description
ID_WeekFact	Weekly temporal profile unique identifier (FW_xxx). The identifiers are cross-referenced with the catalogue of power plants.
Monday-Sunday	Weekly weight factor associated to each day of the week [0-7]
tot	Total sum of the weekly weight factors [7 for all cases]

4. Hourly temporal profiles database (coco2_ps_hourly_profiles_v1.0.csv)

Field of information	Description
ID_HourFact	Hourly temporal profile unique identifier (FH_xxx). The identifiers are cross-referenced with the catalogue of power plants.
H0 – H23	Hourly weight factor associated to each hour of the day [0-24]. Expressed in local time.
tot	Total sum of the hourly weight factors [24 for all cases]

5. Vertical profiles database (coco2_ps_vertical_profiles_v1.0.csv)

Field of information	Description
ID_VertProf	Vertical profile unique identifier (VP_xxxxx). The identifiers are cross-referenced with the catalogue of power plants.
r0_100 – r1500	Weight factor associated to each vertical layer [0-1]. Distribution is defined across 16 vertical layers (from 0m up to 1500m with breaks every 100m, and above 1500m)
tot	Total sum of the vertical profiles [1 for all cases]

The dataset can be downloaded from the following Dropbox link:

https://www.dropbox.com/s/8jer8das5ymv2ak/coco2_ps_database_v1_0.zip?dl=0

4 Temporal profiles

The following sections describes the methods and information sources used to construct the temporal profile datasets for each targeted pollutant sector. This work is done in collaboration with and building on the CAMS_81 and CAMS2_61 projects. Note that diurnal profiles are provided in local time, and that modellers are responsible for translating them into UTC times for each corresponding time zone when using them to compute hourly emissions.

4.1 Methodology

4.1.1 Energy industry

Country and pollutant-dependent monthly, weekly and hourly profiles for the energy industry were constructed using as a basis the global point source database described in Sect. 3. We used the HERMESv3 emission system to combine the total annual emissions per facility with the corresponding country- and fuel-dependent profiles (Sect. 3.1.4) and derive hourly emissions for the year 2018. The resulting emissions were aggregated at the country level and normalised to derive the corresponding temporal profiles.

4.1.2 Road transport

A comparison between monthly variation in traffic patterns at urban and rural locations (i.e., urban streets and highways) performed by McDonald et al. (2014) and Guevara et al. (2021) highlighted that traffic regimes show differences according to the location (urban, rural) and that specific profiles should be constructed for each one of them.

The constructed monthly urban temporal profiles were derived from TomTom congestion statistics for a total of 412 cities (https://www.tomtom.com/en_gb/traffic-index/). The city level profiles were aggregated to a country level considering the annual average level of congestion and number of inhabitants of each city. As a result, 57 country-dependent monthly profiles for urban areas were constructed. Figure 12 shows the spatial coverage of the TomTom congestion statistics. As observed, the coverage is fairly homogenous across continents, except for the case of Africa, where information is only available for Egypt and South Africa.

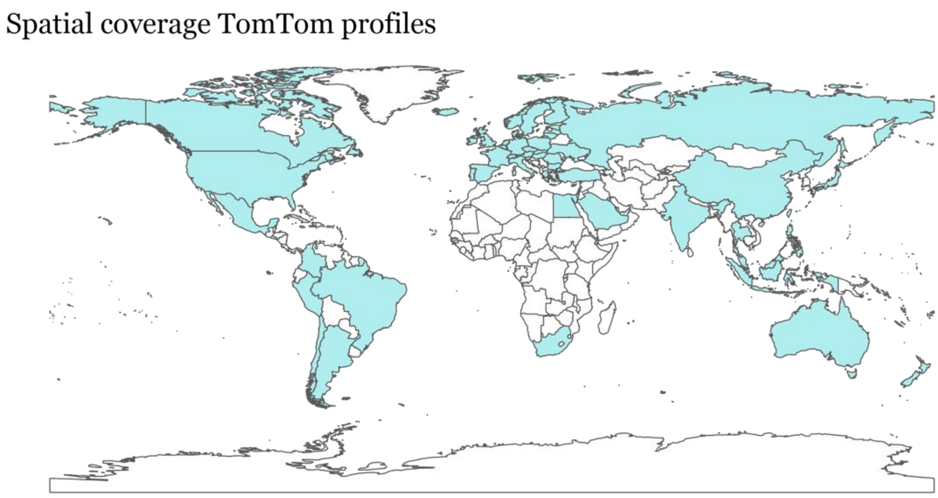


Figure 12 Spatial coverage of the temporal profiles derived from TomTom congestion statistics

On the other hand, the proposed monthly temporal profiles for rural areas are based on a wide range traffic count datasets compiled from national road administrations and that are summarized in Table 7.

Table 7 List of traffic count datasets and corresponding sources of information compiled

Country	Description	Source of Information
Austria	Monthly traffic counts registered at 275 automatic traffic stations for the year 2019	ASFiNAG (2021)
Bulgaria	Hourly traffic counts registered at 65 automatic traffic stations for the year 2017	RIA (2021)
Canada	Monthly traffic counts registered at 379 automatic traffic stations for the year 2016	AG (2017)
Colombia	Monthly traffic counts registered at 200 automatic traffic stations for the year 2019	INVIAS (2021)
Finland	Hourly traffic counts registered at 500 automatic traffic stations for the year 2019	FTIA (2021)
Ireland	Hourly traffic counts registered at 445 automatic traffic stations for the year 2019	TII (2021)
Italy	Monthly traffic counts registered at 800 automatic traffic stations for the year 2019	ANAS (2021)
Luxembourg	Monthly traffic counts registered at 25 automatic traffic stations for the year 2019	MMTP (2021)
Mexico	Monthly traffic counts registered at 120 automatic traffic stations for the year 2019	SCT (2021)
Norway	Hourly traffic counts registered at 720 automatic traffic stations for the year 2019	NPRA (2021)
Peru	Monthly traffic counts registered at 76 automatic traffic stations for the year 2019	INEI (2021)
Poland	Monthly traffic counts registered at 13 automatic traffic stations for the year 2019	GDDKiA (2021)
Portugal	Monthly traffic counts registered at 600 automatic traffic stations for the year 2019	IMT (2021)
Saudi Arabia	Monthly traffic counts registered at the King Fahad Causeway in 2019	GAS (2021)
South Africa	Monthly traffic counts registered at 18 automatic traffic stations for the years 2007 - 2015	De Jongh and Bruwer (2017)
Slovakia	Hourly traffic counts registered at the R1 motorway in 2016	MTCSR (2018)
UK	Average daily traffic flows by month, day and hour in the UK road network (2012-2016 average)	GovUK (2018)
Germany	Hourly traffic counts registered at the highways and federal highways stations for the year 2016	BASt (2018)
Spain	Monthly traffic counts registered at the national transport network for the year 2018	MITMA (2021)
USA	Monthly, diurnal profiles derived from weigh-in-motion traffic counts from 2010	McDonald et al. (2014)

For countries with no information, averaged urban and rural profiles from countries belonging to the same EDGAR world region were used, following the procedure described in Sect. 3.1.4. The resulting monthly profiles were allocated into a 0.1x0.1 deg global gridded domain that follows the same description as the global PED constructed in T2.1. Each grid cell was classified as urban or rural using as a basis the information provided by the Global Human Settlement Layer (GHSL; Pesaresi and Freire, 2016).

Weekly variations in traffic patterns were constructed using the TomTom congestion statistics. As in the case of the monthly weight factors, profiles at the city level were averaged at the country level considering the annual average level of congestion and number of inhabitants of each city. The same profiles were considered for both urban and rural areas. For countries with no information, averaged profiles from countries belonging to the same EDGAR world region were used.

Hourly temporal profiles were also constructed using the TomTom congestion statistics, which were aggregated from the city level to country level as described in the previous paragraphs. Specific profiles were constructed for weekdays, Saturdays and Sundays. For countries with no information, averaged profiles from countries belonging to the same world region were used.

4.1.3 Residential combustion

The temporal release of emissions from the residential combustion sector is assumed to be mainly caused by the stationary combustion of fossil fuels in households and commercial buildings. Gridded daily temporal profiles were derived according to the heating Degree Day (HDD) concept, which is an indicator used as a proxy variable to reflect the daily energy demand for heating a building (Quayle and Diaz, 1980). The heating degree day factor ($HDD(x,d)$) for grid cell *x* and day *d* is defined relative to a threshold temperature (T_b) above which a building needs no heating (i.e., heating appliances will be switched off), following Equation 3:

$$HDD(x,d) = \max\,(T_b - T_{2m}(x,d), 1) \qquad \text{Equation 3}$$

Where $T_{2m}(x,d)$ is the daily mean 2m outdoor temperature for grid cell *x* and day *d*. This information is obtained from the ERA5 reanalysis dataset (C3S, 2017) and interpolated to the working grid domain by applying a conservative interpolation using CDO.

As shown in the equation, the $HDD(x,d)$ value increases with increasing difference between the outdoor and base temperatures. Note that a minimum value of 1 is assumed instead of 0 to avoid numerical problems. Following the work by Spinoni et al. (2015), which developed gridded European degree-day climatologies, we assumed that T_b = 15.5°C, a value also suggested by the UK MET-Office.

A first guess of the daily temporal factor ($FD(x,d)$) for grid cell *x* and day *d* could be defined as (Equation 4):

$$FD(x,d) = \frac{HDD(x,d)}{\overline{HDD}(x)} \qquad \text{Equation 4}$$

Where $\overline{HDD}(x)$ is the yearly average of the heating degree day factor per grid cell *x* (Equation 5):

$$\overline{HDD}(x) = \frac{\sum_1^N HDD(x,d)}{N}$$ Equation 5

Where N = 365 or 366 days (leap or non-leap year)

Considering that residential combustion processes are not only related to space heating but also to other activities that remain constant throughout the year such as water heating or cooking, a second term is introduced to Equation 4 by means of a constant offset (f) (Equation 6):

$$FD(x,d) = \frac{HDD(x,d) + f * \overline{HDD}(x)}{(1+f) * \overline{HDD}(x)}$$ Equation 6

Where f = 0.2 based on the European household energy statistics reported by Eurostat (2018).

Gridded daily (day-of-the-year) temporal profiles were developed for the years 2018 and 2021. We interpolated the estimated gridded daily factors from the ERA5 working domain (0.3x0.3 deg) onto the PED global grid (0.1x0.1 deg). Monthly gridded factors were derived from the daily profiles to be combined with the annual PED emissions developed in Task 2.1.

4.1.4 Aviation

A fixed (non-gridded, no country-dependent) monthly profile for the aviation sector was constructed using as a basis the total number of daily flights tracked by Flightradar24 (2022) during 2019.

4.1.5 Shipping

A fixed (non-gridded, no country-dependent) monthly profile for the shipping sector was constructed using as a basis the monthly CO_2 emissions reported by the CAMS-GLOB-SHIPv3.1 AIS-based emission inventory (Jalkanen et al., 2016).

4.2 Overview of the results

This section presents and analyses the constructed temporal profiles for selected countries. Moreover, we compare the resulting profiles with the sector-dependent profiles that are currently provided together with the global and regional PED developed in T2.1. Note that for the monthly and weekly profiles, the comparison is limited to the profiles proposed for the European regional PED (hereinafter referred to as the TNO profiles), as: 1) the global PED already includes the monthly profiles constructed under this task and 2) when processing the global PED for modelling purposes in WP3 no weekly variations are considered (i.e., emissions are assumed to be flat during the whole week). The hourly profiles provided together with the global and regional PED are the same, based on the TNO profiles.

Figure 13 shows an example of monthly, weekly and hourly profiles constructed for the power sector for selected countries.

At the monthly level, large variations are observed between countries. Profiles for United Arab Emirates (ARE) and Kuwait (KWT) present a clear peak during summer, coinciding with the intensive use of air conditioning systems. In the case of US Pennsylvania (USA-PA), we identify two types of peaks, one related to space cooling needs during July and August, and another one linked to space heating needs during January and December. In Germany (DEU) and Poland (POL) we also distinguish the peaks during wintertime, while the increase of emissions during summer is much lower than the previous cases as these countries are in higher latitudes where the summers are not too hot. The seasonality in India (IND), China (CHN), South Africa (ZAF) and Australia (AUS) are much flatter. We can see that all the profiles differ significantly with the TNO profile, which reports a V-shape seasonality, with emissions peaking during wintertime and presenting their lowest value during summer, and therefore not capturing the peak related to space cooling needs.

Concerning weekly variability, it is observed that profiles constructed for European countries (i.e., Germany and Poland) are in line with the TNO profile, showing a strong weekend effect, with emissions being reduced more than 20% between weekdays and Sundays. On the other hand, profiles estimated for US Pennsylvania, South Africa and Australia are much flatter (between 5-10% difference between weekdays and weekends), while India shows no differences between weekdays and weekends.

Finally, constructed hourly profiles are quite consistent between countries, all of them showing a rather flat variation, with emissions being slightly larger (10-15%) during daytime (between 07:00h and 20:00h). Similarly to what we see for the monthly profiles, large inconsistencies are observed between the constructed profiles and the TNO profiles, the latter showing a much larger variation between emission levels during night- and daytime and not reproducing the afternoon peak reported by the CoCO2 profiles in most of the countries.

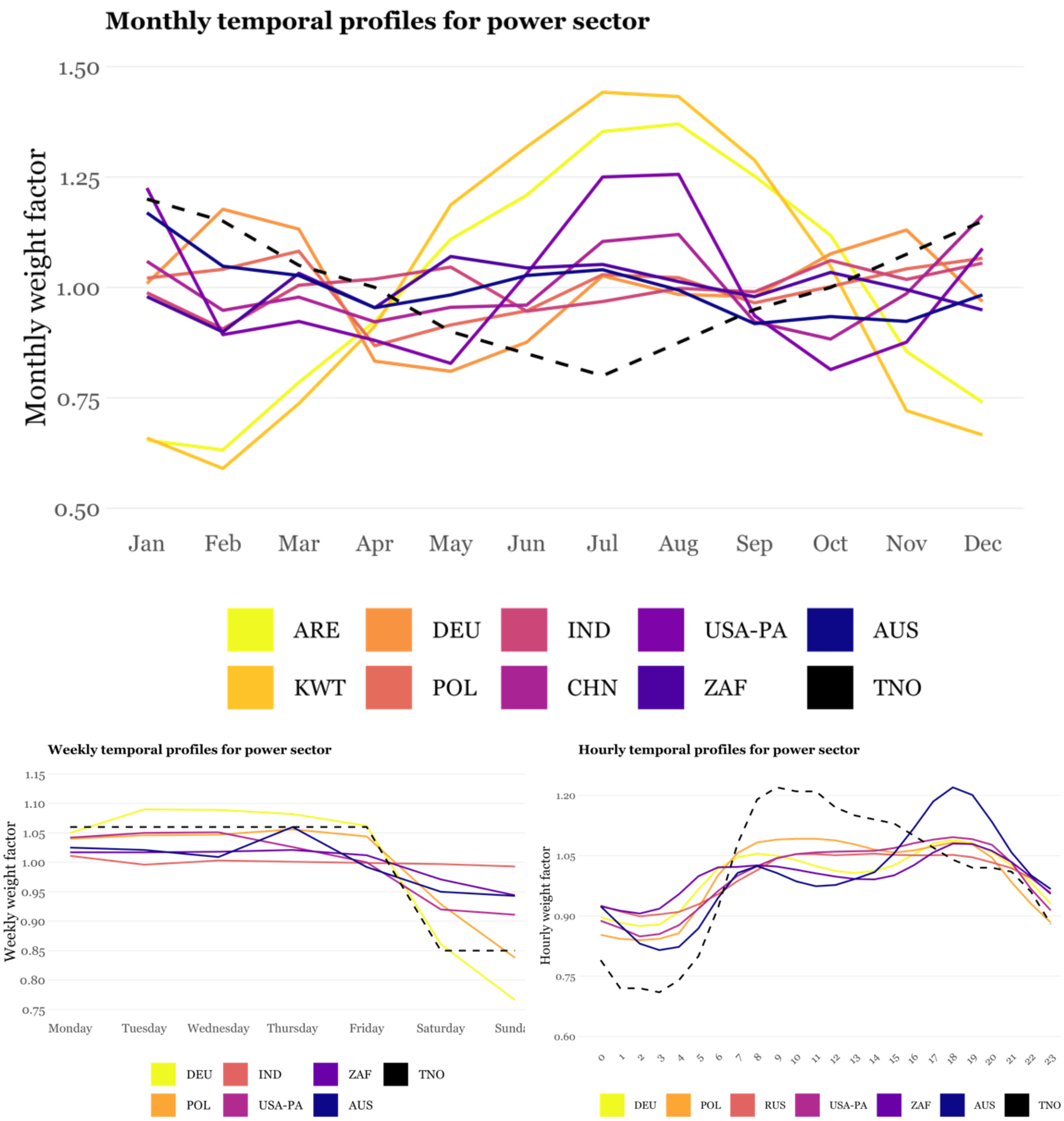


Figure 13 Power sector monthly, weekly and hourly profiles constructed for selected countries

Figure 14 shows the constructed urban and rural monthly road transport profiles for selected countries. For the urban profiles, results can be grouped into five categories: (i) Countries where urban traffic activity largely decrease during summer months due to the extreme high temperatures and subsequent decrease in mobility (i.e., KW, Kuwait, AE, United Arab Emirates), (ii) countries where traffic activity presents a large drop during August, coinciding with summer holidays (i.e., ES, Spain, IT, Italy), (iii) countries where traffic activity presents a large drop during July, coinciding with summer holidays (i.e., NO, Norway, SE, Sweden), (iv) countries from the southern hemisphere, where traffic activity presents a drop during summer holidays (December and January) (i.e., BR, Brazil, AR, Argentina) and (v) countries where traffic activity remains almost constant throughout the year (i.e., IN, India, MX, Mexico). Regarding the rural profiles, results show that, in contrast to urban areas, traffic activity tends to present an increase during summer holidays: in July and August for countries located in the northern hemisphere such as Bulgaria, Spain, Germany or the USA, and in December and January for countries located in the southern hemisphere like Peru or Colombia. However, in all cases the differences between summer and the rest of the year are not as large as the ones observed in urban areas, the monthly weight factors ranging between 0.8 and 1.2. Large discrepancies are observed between the urban and TNO profiles, especially during summer, as the latter does not reproduce the drop of emissions. The discrepancies are much lower when compared to the constructed rural profiles, but still significant during summer in European countries, where the new profiled show a larger increase of emissions.

Weekly variations for selected countries are presented in Figure 15. A clear weekend effect is identified in all cases, the drop on traffic activity between weekdays and Saturday-Sunday being more (e.g., Spain) or less (e.g., China) intense depending on the country. Interestingly, in the case of Saudi Arabia and Egypt the drop occurs during Friday-Saturday. This is in line with Muslim-majority countries, where a Friday–Saturday weekend is instituted. For other Muslim-majority countries in which no TomTom information was available, we constructed an average “Muslim” weekly profile based on the data available for other countries with same socio-cultural background. The list of countries with a Friday–Saturday weekend was derived from Wikipedia (2022e). The TNO profile also shows a weekend effect, but of less intensity when compared to other European countries such as the Netherlands or France.

Finally, Figure 16 shows some examples of hourly profiles for weekdays and Sundays constructed for selected countries. Weekday profiles exhibit a great similarity in time structure and reflect commuting patterns, which typically show morning and afternoon volume peaks and a bimodal diurnal profile. The hour and intensity of the peaks slightly varies between countries due to sociodemographic aspects. On the other hand, Sunday profiles generally show the traffic activity plateauing between later morning and early evening, Saturday exhibiting a later afternoon peak in some countries (e.g., Spain, France) coinciding with the increase of social interactions typically associated to that time of the day. While the correlation between the TNO and the constructed weekday profiles is fairly high, the inconsistency found for the Sunday profiles clearly highlights the need to separate diurnal profiles by day type.

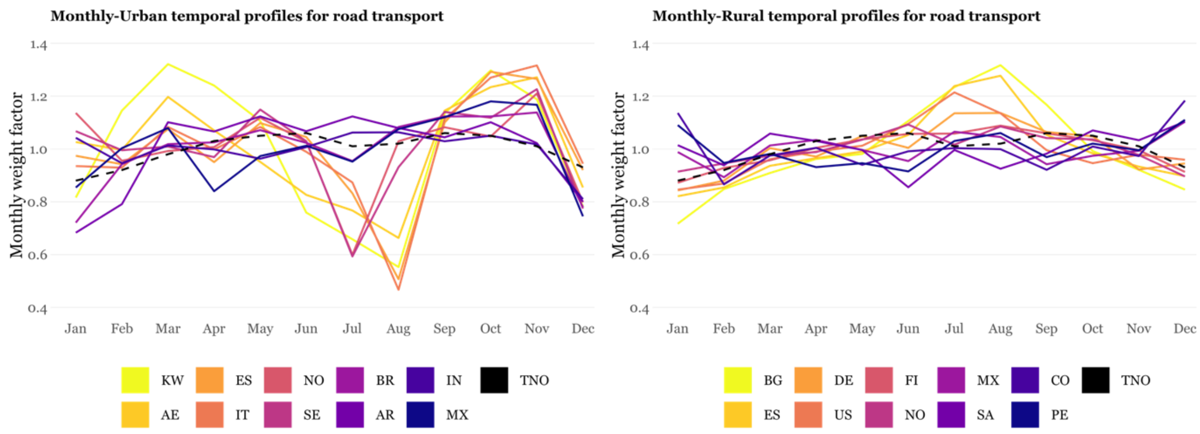


Figure 14 Road transport monthly profiles constructed for urban and rural areas for selected countries

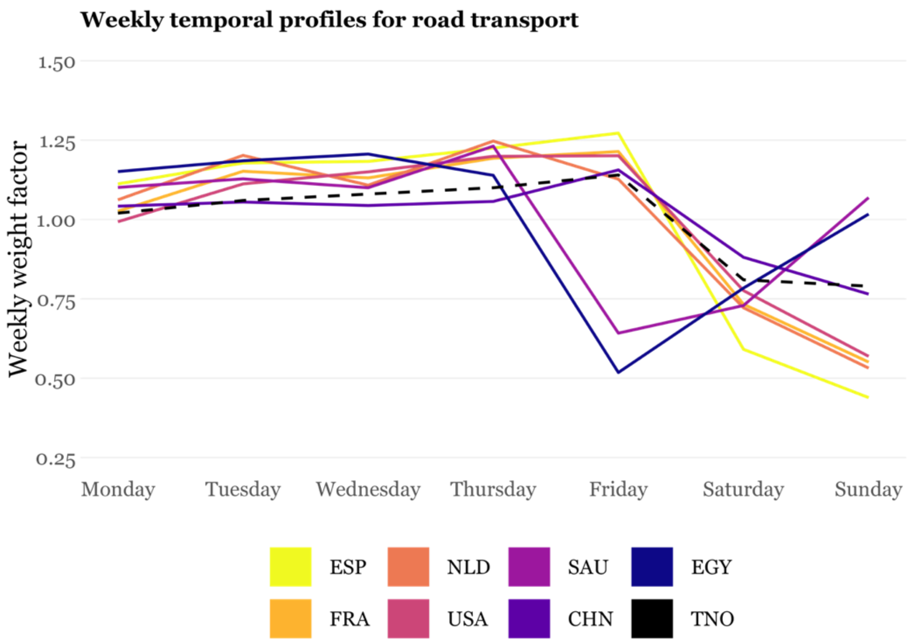


Figure 15 Road transport weekly profiles constructed for selected countries

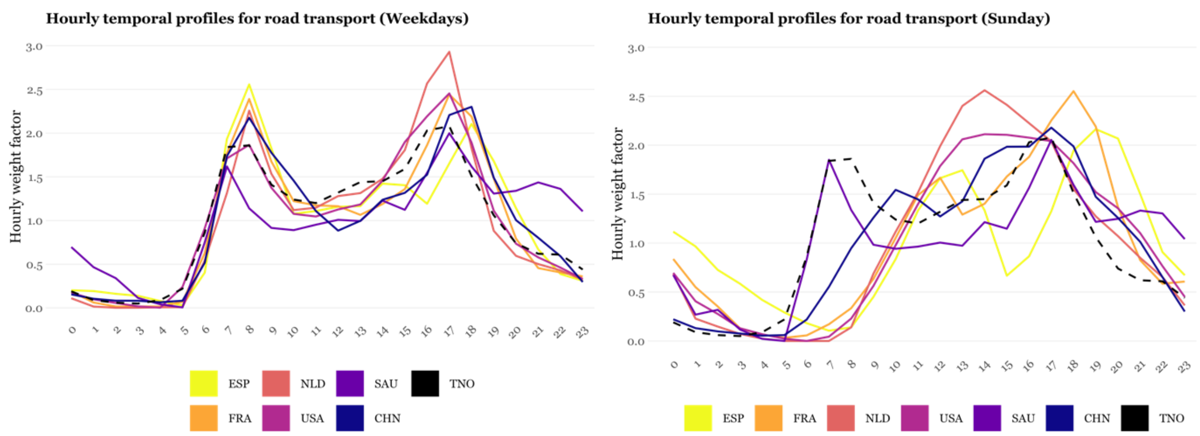


Figure 16 Road transport hourly profiles constructed for weekdays and Sundays for selected countries

Figure 17 shows the resulting monthly profiles for the residential combustion sector for years 2018 and 2021 at four countries that are geographically and/or climatically different (i.e., Spain, Germany, Argentina, South Africa). The highest factors for the five locations occur during winter and the lowest one during the summer. Emissions in Spain, Germany, Argentina or South Africa can be 3 to 5 higher during the cold periods (i.e., January/February in Spain, Germany, June/July in Argentina and South Africa) than during warm periods (i.e., August in Spain, Germany, January in Argentina and South Africa). Large inter-annual variability observed at the different locations. Extreme weather events can in fact strongly affect the resulting temporal profiles. For instance, the large peaks observed in Spain and Germany February 2018 are related to an exceptionally cold and snowy weather occurred in Europe during that month. On the contrary, in 2021 the maximum peak in Spain occurs in January, coinciding with the storm Filomena, an extratropical cyclone that brought unusually heavy snowfall to several parts of the country. The constructed profiles for European countries tend to present a U-shape, with a large and rapid drop occurring between cold and warm months, and rather constant emissions during end of Spring and beginning of Autumn. On the other hand, the TNO profile presents a V-shape, with emissions decreasing (increasing) in a more continuous way, and the minimum value occurring in July. While the differences between profiles during warm month are minimum, significant discrepancies are observed during winter, the temporal weight factors presenting differences of up to 1.5 times.

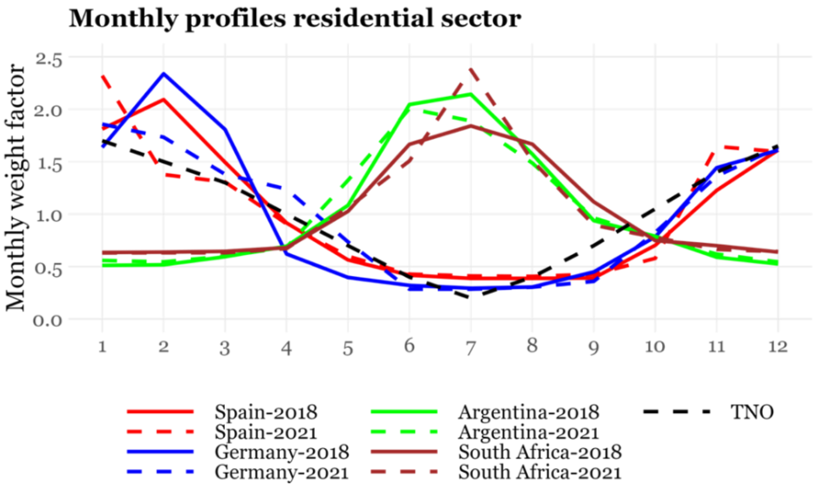


Figure 17 Monthly temporal factors for residential combustion sector obtained over Spain, Germany, Argentina and South Africa for the years 2018 and 2021.

Figure 18 shows the monthly profiles constructed for the aviation and shipping sectors. A similar seasonality are observed in both sectors, with emissions increasing during summer, especially in the case of aviation.

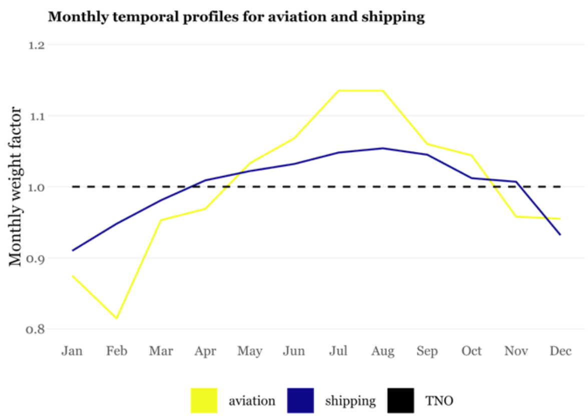


Figure 18 Monthly temporal profiles constructed for the shipping and the aviation sector

4.3 Description of the final dataset

The constructed temporal profiles (coco2_temporal_profiles_database_v1_0.zip) are provided in the form of CSV or NetCDF files depending on if the weight factors are either fixed (i.e., road transport weekly and hourly profiles, power industry, aviation, shipping) or vary spatially by region (i.e., residential combustion and road transport monthly profiles).

1. Monthly temporal profiles database (coco2_monthly_profiles_v1.0.csv)

Field of information	Description
Sector	Indicates the sector for which the profile is constructed: power, shipping, aviation
ISO3	Country associated to the profile (identified with the three-letter country code defined in ISO 3166-1). "ALL" indicates that a unique profile is proposed for all countries/sea-regions (aviation and shipping sectors)
Jan - Dec	Monthly weight factor associated to each month [0-12]
tot	Total sum of the monthly weight factors [12 for all cases]

2. Weekly temporal profiles database (coco2_weekly_profiles_v1.0.csv)

Field of information	Description
Sector	Indicates the sector for which the profile is constructed: power, road transport
ISO3	Country associated to the profile (identified with the three-letter country code defined in ISO 3166-1)
Monday-Sunday	Weekly weight factor associated to each day of the week [0-7]
tot	Total sum of the weekly weight factors [7 for all cases]

3. Hourly temporal profiles database (coco2_hourly_profiles_v1.0.csv)

Field of information	Description
Sector	Indicates the sector for which the profile is constructed: power, road transport
DayType	Only for road transport profiles: Weekday (profile for Monday to Friday), Saturday (profile for Saturdays), Sunday (profile for Sundays)
ISO3	Country associated to the profile (identified with the three-letter country code defined in ISO 3166-1)
H0 – H23	Hourly weight factor associated to each hour of the day [0-24]. Expressed in local time.
tot	Total sum of the hourly weight factors [24 for all cases]

The spatial resolution of the NetCDF files is 0.1x0.1 degrees, following the same domain descriptions defined in the global PED. NetCDF gridded maps with the temporal factors per sector and year are constructed using the following naming convention:

CoCO2_temporal_profiles_v1.0_month_<sector>_<year>.nc

where:

- <sector> indicates the pollutant sector: “res” (residential combustion), “tro (road transport)
- <year>: indicates the year of references: “2018” or “2021”. Only applicable to those temporal profiles that are year-dependent.

For each file, the monthly gridded weight factors are reported as FM and the total sum is 12.

As an example, output of the ncdump command-line tool from one of the NetCDF files us given. This dump shows the number of latitudes and longitudes in the files, the format of each field and the global attributes included.

```
netcdf CoCO2_temporal_profiles_v1.0_month_res_2021 {

dimensions:
	longitude = 3600 ;
	latitude = 1800 ;
	time = 12 ;
variables:
	double longitude(longitude) ;
		longitude:units = "degrees_east" ;
		longitude:long_name = "longitude" ;
		longitude:axis = "X" ;
		longitude:standard_name = "longitude" ;
	double latitude(latitude) ;
		latitude:units = "degrees_north" ;
		latitude:long_name = "latitude" ;
		latitude:axis = "Y" ;
		latitude:standard_name = "latitude" ;
	int time(time) ;
		time:units = "months since 2021-01-15" ;
		time:long_name = "time" ;
		time:axis = "T" ;
		time:standard_name = "time" ;
	double FM(time, latitude, longitude) ;
		FM:units = "unitless" ;
		FM:_FillValue = -1. ;
		FM:long_name = "Gridded monthly weights for residential emissions. Year 2021 .Total sum equals to 12" ;
		FM:standard_name = "Gridded_monthly_weights" ;

// global attributes:
		:_NCProperties = "version=2,netcdf=4.7.0,hdf5=1.10.5," ;
		:description = "CoCO2 global monthly temporal profiles" ;
		:projection = "latlon" ;
		:dataset_version_number = "v1.0" ;
		:title = "CoCO2 global monthly temporal profiles" ;
		:authors = "M. Guevara, O. Jorba and C. Perez" ;
		:institution = "Barcelona Supercomputing Center" ;
```

:references = "Guevara, M., et al., 2021, Earth Syst. Sci. Data, 13, 367–404, https://doi.org/10.5194/essd-13-367-2021" ;
}

The temporal profiles can be downloaded from the following Dropbox link:

https://www.dropbox.com/s/vkpehubokc3few9/coco2_temporal_profiles_database_v1_0.zip?dl=0

5 Conclusion

Under this task we improved the temporal and spatial profiles of key sectors currently considered in emissions inventories. Concerning the first topic, we built a new set of global temporal profiles for the road transport, residential combustion, aviation, shipping and power industry sectors. Depending on the sector, the final profiles are fixed in space and time (e.g., shipping, aviation) or country/region- / year-dependent (e.g., road transport, public energy, residential combustion). Regarding the improvement of the spatial representation, we constructed a global catalogue of CO_2 emissions and co-emitted species (i.e., NO_x, SO_x, CO, CH_4) from power plants at high spatial and temporal resolution for the year 2018. The dataset contains emissions information from individual facilities at their exact geographical location as well as associated temporal and vertical distribution profiles.

The constructed monthly temporal profiles in this task were integrated in the global PED developed in T2.1. The global point source database was used by iLab as prior information for the electricity generation sector in a 2021 CCFFDAS run for WP6. The results from the two products were also used to provide recommendations to ECMWF on the monthly and vertical distribution profiles to be considered in the global CoCO2 nature runs performed in WP3.

5.1 Limitations of the datasets

Regarding the global power plant database, the following limitations are identified:

- Despite putting substantial efforts in correcting the location of facilities that are originally reported with wrong coordinates, there may be some error still present in the dataset, especially in the case of small and medium sized plants.
- Emissions from non-European auto-producer facilities are not consistently considered across countries due to the lack of information. Overall, we could not include emissions from auto-producers in 35% of the non-EU countries considered, which translates into 4.1% of total estimated CO_2 emissions that could not be allocated to the final point source database The most relevant countries affected by this limitation are Russia, India and Japan, the share of national emissions that could not be assigned to individual facilities in them being between 14% and 21%.
- For the non-European dataset, heat only facilities are not included due to the lack of information. This gap may be relevant in countries in high latitudes where the share of fossil fuels used to produce heat only is significant, including Ukraine (25%), Russia (20%), Belarus (20%), Kyrgyzstan (18%) and Uzbekistan (10%).
- We identified a list of countries for which we found the location of their power plants but that we could not include in the final catalogue since their energy balances are not reported by the IEA World Energy Balances database, and subsequently corresponding emissions could not be estimated. Most of them are small island countries (e.g., Aruba, Anguilla, Samoa Nord-americana, Antigua and Barbuda, Bahamas, Bermudas, Barbados, Fiji, the Cook Islands, Cabo Verde, Cayman Islands) and subsequently we do not expect that their absence significantly affects the total estimated CO_2 emissions.
- For the European dataset, a substantial number of emission values was gap filled using a tiered routine, using facility-specific-, or more generic pollutant ratios to estimate emissions. This could lead to significant under- or overestimations of emissions for individual plants.
- For the non-European dataset, plant-level emissions were estimated by distributing fuel-dependent national emissions among facilities as a function of their installed capacity, which in some cases may not be representative of their actual activity (i.e., capacity factor) and may lead to over- or underestimations.
- The final catalogue of power plants covers the main fuels used to produce energy and heat, including coal, natural gas, oil, solid biomass and solid waste. However, we are

still missing some fuels that are relevant in specific countries such as biogas (e.g., Thailand, India, Turkey, Australia) and liquid biofuel (e.g., South Korea).

- The temporal profiles assigned to the power plants are country and fuel-dependent, but not facility-dependent. Large differences between the emission temporal distribution of plants belonging to the same country may occur, e.g., if they are used for electricity only or electricity and heat. However, information to develop such detailed level of temporal profiles is very scarce and limited only to certain regions (e.g., EU27).
- The final database provides plant-level annual mean vertical profiles that take into account meteorology and stack parameters information. However, large variations in the vertical distribution of emissions may occur between seasons, days of the year and hours of the day due to changes in the meteorological parameters that influence the atmospheric stability and the corresponding vertical dispersion of the emissions.
- Despite identifying several power plants in which emissions are released through the cooling towers instead of the traditional chimneys (mainly in Germany), there may still be multiple facilities in the catalogue that are not correctly flagged. Moreover, for power plants using the cooling towers to release the emissions, we considered the same plume rise formulas as the ones used for traditional stack chimneys. According to Brunner et al. (2019), this assumption may entail an underestimation of the resulting effective emissions height of between 20% and 100% due to the combination of several factors, including the additional release of latent heat from cooling towers or the interaction of plumes from cooling towers located next to each other, among others.
- The stack parameters information used to perform the plume rise calculations has a limited coverage (e.g., only 28% of total CO_2 emissions have specific stack height information, and only 15% specific exit velocity data), which may bring an additional uncertainty to the estimated vertical profiles. According to the sensitivity runs performed by Bieser et al. (2011), changes in estimated emission heights are almost linear with changes in stack height and exit velocity, indicating a large influence of these parameters on the result.
- Caution should be taken when combining the global point source dataset with other existing gridded emission inventories (e.g., EDGAR, CAMS-GLOB-ANT) to avoid issues of double counting or incompleteness. Avoiding these problems can be challenging if, for instance, the sector classification of the gridded inventory is broad (e.g., emissions from power plants are included together with emissions from refineries and other energy industries under the same sector). A reclassification of the gridded emissions may be needed in these cases to ensure an appropriate combination of datasets.

Concerning the dataset of temporal profiles constructed, the following limitations were identified:

- The sources of information considered to construct the temporal profiles for the road transport sector present a very limited coverage in Africa (i.e., only covers South Africa and Egypt), the profiles for most of the countries being based on an average continent-level profile that may not correctly capture specific national features.
- The global monthly temporal profiles constructed for the aviation and shipping sector are based on global information but may not correctly represent the observed seasonality in specific/singular regions such as e.g., the Greenland and Kara seas, where shipping activity mainly occurs during summertime due to the decrease of sea ice during this season and a correspondent increase of passenger-related ship traffic.
- The computation of residential combustion temporal factors was done using a heating degree-day approach that considers a threshold temperature and a fraction of non-space-heating activities homogenous for all the world (i.e., 15.5ºC and 0.2, respectively). These two values can vary across regions due to changes in local climate, building characteristics and sociodemographic aspects (e.g., Grythe et al.,

2019; Daioglou et al., 2012) Region-dependent HDD parameters should be considered to overcome this limitation.

5.2 Future perspectives

- The new global point source database should be considered in future global and regional inverse modelling and data assimilation exercises as it provides much more detailed information on the horizontal, vertical and temporal allocation of emissions than traditional gridded inventories such as EDGAR or CAMS-GLOB-ANT, in which power plant emissions are distributed according to CARMAv3.0 (2012), a no longer maintained point source database based on plant-level information from 2009.
- For that, current modelling systems may need to be adapted to be able to ingest point source emissions, and a guidance on how to combine the new point source inventory with traditional gridded data will have to be done to avoid double counting or incompleteness issues.
- Future works should focus on overcoming the limitations currently identified with the first version of the global point source database (e.g. missing of auto-producer and heat only facilities in some countries) and extending the temporal coverage to more recent years in order to capture, on the one hand, the impact of the decarbonisation efforts that are occurring in several countries and regions such as EU27, UK or USA and, on the other hand, the large uptick in commissioning of new coal power plants that is happening in China (https://www.carbonbrief.org/mapped-worlds-coal-power-plants/).
- In parallel, other large CO_2 emitting industries that are detected by satellite instruments, including cement and steel and iron plants, should be added in future versions of the global point source database.
- In its current version, the IFS system can only ingest hourly emission temporal profiles that vary per sector and pollutant, and it is assumed that the weekly distribution of emissions is flat. The profiles constructed within this CoCO2 task clearly highlight that emissions from certain sectors present clear weekend effects (e.g., road transport, energy) and that the temporal distribution of emissions can largely vary between countries and regions due to different sociodemographic patterns and climatological conditions. It is therefore recommended that day-of-the-week variations and the spatial component is considered when disaggregating total emissions into finer temporal resolutions in future versions of the IFS system.
- Following with what has been done with the heating degree day approach for temporal distribution of residential emissions in CoCO2 WP3, it is recommended that future versions of the IFS system implement an online parametrisation to perform plume rise calculations, to better capture the spatial and temporal variation of the vertical distribution of point source emissions, instead of just considering a global and fixed vertical distribution profile.
- Significant differences were found between the constructed temporal profiles and the default sector-dependent profiles provided with the regional PED developed in T2.1, which are mostly based on old datasets and do not consider the effect of different sociodemographic patterns and climatological conditions. It is recommended to update the default profiles to better capture the temporal variability of emissions. This task could be done in coordination with the work performed under CAMS2_61.
- Information on stack parameters is currently limited not only in developing countries but also in developed regions such as EU27. Efforts should be put to compile this information from individual national environmental permits and centralised it in a European database, at least for the large point sources considered under the European Industrial Emissions Directive (2010/75/EU). Flagging the power plants that channel emissions through cooling towers should be also assessed in order to better represents the vertical distribution of their emissions.

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Document History

Version	Author(s)	Date	Changes
0.1	Marc Guevara (BSC)	09/12/2022	
0.2	Marc Guevara (BSC)	15/12/2022	Added minor comments and contributions from co-authors. Added links to download the datasets
1.0	Marc Guevara (BSC)	23/12/2022	Introduced minor comments from internal reviewers (DWD). Completed table of estimated effort contribution per partner
1.1	Marc Guevara (BSC)	27/01/2023	Introduced minor comments from internal reviewers (AGH).

Internal Review History

Internal Reviewers	Date	Comments
Andrea Kaiser-Weiss (DWD)	21/12/2022	Minor suggestions for improvements
Michał Gałkowski (AGH)	23/12/2022	Minor suggestions for improvements

Estimated Effort Contribution per Partner

Partner	Effort
BSC	26
TNO	3
Total	**29**