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TNO_CAMS high resolution European emission inventory 2000-2014 for anthropogenic CO_2 and future years following two different pathways

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Abstract. The most important climate forcer over the period 1750-present is CO_2 from fossil fuel combustion (IPCC, 2013). European countries that are Parties to the United Nations Framework Convention on Climate Change (UNFCCC) submit national greenhouse gas (GHG) inventories to the Climate Change secretariat. However, these reported emissions are annual totals and do not provide spatial or temporal patterns within the country. Recently the interest in high resolution CO_2 emission data is growing, both from the side of the research community as well as cities that want to make tailored climate action plans. Here we present a model-ready historic emission inventory at high spatial resolution (~7x7 km) for UNECE-Europe for 15 consecutive years (2000–2014) providing CO_2 from fossil fuels (CO_2_ff) and CO_2 from biofuels (CO_2_bf) to support carbon cycle modelling and sub-national scale identification of emissions. Where available and considered fit for purpose, we have used CO_2 estimates as reported by the Parties to UNFCCC. The data have been supplemented by other estimates, most notable from the IIASA GAINS model and the JRC EDGAR database to create a complete coverage. The growing importance of biofuel over the time 2000-2014 time period is clearly visible. This changes the isotopic signature of anthropogenic emissions which is important for quantifying fossil fuel emissions. The inventory is compatible with the TNO-MACC emission inventory for air pollutants (Kuenen et al., 2014) which can provide information on co-emitted species like CO and NOx. The dataset is complemented by two projections based on the CIRCE project scenarios and using the latest historic year (2014) as the starting point for projection. 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 historical years 2000-2014 at https://doi.org/10.5281/zenodo.112889, and for the future years 2018-2050 at https://doi.org/10.5281/zenodo.1009519.

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1 Introduction

In 1992 the United Nations Framework Convention on Climate Change (UNFCCC) was ratified as a framework for international cooperation to combat climate change by limiting average global temperature increases and the resulting climate change, and coping with impacts that were, by then, inevitable (UNFCCC, 2014). The Intergovernmental Panel on Climate Change (IPCC) issued a global climate assessment in 2013 that compared the influence of three changes to the environment resulting from human activity between 1750 and 2011: the emissions of key heat-trapping gases and tiny particles known as aerosols, as well as land use change. The IPCC (2013) calculated the "radiative forcing" (RF) of each climate driver—in other words, the net increase (or decrease) in the amount of energy captured in the Earth's atmosphere attributable to that climate driver. The simple conclusion is that CO_2 has contributed more than any human-influenced climate driver to climate change between 1750 and 2011. Other gases have more potent heat-trapping ability per molecule than CO_2 (e.g. methane), but are simply far less abundant in the atmosphere (IPCC, 2013).

In accordance with Articles 4 and 12 of the UN Climate Change Convention, and the relevant decisions of the Conference of the Parties, countries that are Parties to the Convention annually submit national greenhouse gas (GHG) inventories to the Climate Change secretariat. Clearly defined methodologies have been established on how to estimate emissions of GHG from anthropogenic sources (IPCC 1996; IPCC 2006). As a result of the obligation to report to UNFCCC, the subsequent financial and political support for national inventory agencies and the clearly defined methodologies by IPCC, CO_2 emission inventories at national scales are well established in developed countries. Carbon dioxide emission inventories typically combine available (national) statistics on fuel consumption by activity, industrial production, etc. with the most appropriate emission factors. For a detailed description on how emission inventories are constructed we refer to IPCC (1996; 2006). The self-reporting of CO_2 emissions by countries to UNFCCC does not include gridded maps with spatial distribution of the emissions within the country. The main reason why this information is not required is the long life time of CO_2. Due to the long life time and the mixing of gases in the atmosphere it is irrelevant where and when within a given year a molecule of CO_2 is emitted for its contribution to global warming. This is a fundamental difference with (short-lived) air pollutants where the location and time of emission controls who is exposed to air pollution. However, for modelling and understanding the dynamics of CO_2 emissions, spatial and temporal disaggregation is necessary. One of the main suppliers of spatially disaggregated CO_2 emissions data is the Emission Database for Global Atmospheric Research (EDGAR) of EC-JRC/PBL (Olivier and Janssens-Maenhout, 2016; Janssens-Maenhout et al., 2017). EDGAR provides bottom-up estimates of the global anthropogenic emissions based on publicly available statistics and provides consistently distributed 0.1deg x 0.1deg emission maps.

Recently, Ciais et al. (2015) conclude that it is relevant and timely to develop an operational system to observe and to monitor fossil fuel CO_2 emissions. An observation system of fossil CO_2 emissions aiming to improve and/or verify national inventories will need to have a typical accuracy on the order of few percent or better, for annual emissions of each country. The fossil CO_2 emissions observation system should have capabilities to quantify emissions trends over a period of few years in a transparent way, at the scale of countries, of regions within countries, and if possible of cities and emissions hotspots (Ciais et al., 2015). This will increase the demand for spatially and temporally explicit CO_2 emissions data. While EDGAR is an important source

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of information, its rigorous choice for consistency and transparency at the global level prevents the uptake of local or national detailed information. An alternative approach is to accept and use national estimates as a starting point, cross-check them for plausibility and consistency and correct or add only where deemed unreliable. This approach is followed by the TNO-MACC European inventory for air pollutants (Pouliot et al., 2012; Kuenen et al., 2014) and has proven to be a valuable complementary source of information next to consistent bottom-up inventories like EDGAR. That this not only applies to air pollutants but also greenhouse gases was recently shown for methane by Röckmann et al. (2016) when they used their high-resolution isotope measurements in combination with models to verify and further constrain the European methane budget.

Additionally, a high resolution, spatially disaggregated inventory can be used to assess pledges for GHG reductions made by cities or regions, and to monitor progress. By disaggregating country total emissions calculated following the IPCC guidelines and approach, consistency between the national and regional/city inventories is ensured. The spatially distributed emissions cover the whole country, and describe the emissions in a consistent way, i.e. in all countries the same sources should be included, and these sources should be assessed as accurately and consistently as possible. To further develop this capacity is especially relevant since the adoption of the Paris Agreement. The Paris Agreement, adopted in Paris on 12 December 2015, marks the latest step in the evolution of the UN climate change regime and builds on the work undertaken under the Convention (UNFCCC, 2015). The Paris Agreement was enforced in Marrakech at the COP22 (November 2016) and includes an enhanced transparency framework to track progress towards the targets of the Nationally Determined Contributions (NDCs) and to make every 5 year a global stock take for setting thereafter more ambitious targets as required to prevent dangerous climate change. These developments also stress the need for projections of future CO_2 emissions including the associated spatial and temporal detail to design independent, observation-based (or so-called "top-down") verification systems as outlined by Ciais et al. (2015) and Pinty et al. (2017). The relevance here is that increasing mitigation of fossil fuel CO_2 emissions as well as the further increase of biofuel use and other renewable energy sources will substantially change the magnitude of CO_2 emissions as well as their spatial and temporal patterns. Therefore, a system suitable to monitor and verify current emissions and trends is not necessarily capable of doing just that with future emissions.

In this paper we present a high-resolution emission inventory for CO_2 for Europe, which has been constructed by disaggregating national total emissions in a consistent and transparent way following the approach previously outlined for air pollutants by Kuenen et al. (2014). CO_2 emissions from fossil fuels and from biofuels are accounted for separately. The inventory is largely based on the official reported emissions to UNFCCC by the European countries themselves, completed by other estimates for countries which are not reporting emissions to UNFCCC on an annual basis, or for countries where the reported emissions are not considered fit for use. Next we use this dataset in combination with an existing dataset from Doering et al. (2010) which provided future emissions of CO_2 following two different pathways of climate change policies. These pathways span the range of emissions from no global action on climate change and air pollution (i.e., a Business as usual (BAU) scenario) to emissions resulting from an active global climate policy (i.e., Climate Change (CC) scenario).

2 Methodology

2.1 Historic inventory 2000-2014

Current inventory techniques are retrospective since they require activity data often compiled by statistical bureaus or agencies. This implies that inventories can only be made after the statistical data become available. In practice, emission inventories are at best released 1.5 to 2 years behind the present year. The historic emissions data presented in this paper were compiled over the period November 2016-February 2017. At the time, 2014 was the latest complete reporting year. Where available, we have used CO_2 estimates as reported by the Parties to UNFCCC, which are used to monitor compliance with reduction targets, such as those specified in the Kyoto Protocol and, at European level by the European Commission. Since not all countries in the European domain are reporting to the Kyoto Protocol, the data have been supplemented by other estimates, as specified in the next section, to create a complete coverage.

2.1.1 Data sources

For an overview of the data sources used for each country (specified with respective ISO3 country code) in the country groups EU15+NOR+CHE, EU-NMS and Non-EU we refer to Table S3 (in supporting material). The different data sources are further elaborated in the sections below.

UNFCCC (http://unfccc.int/): Parties to the Convention report their CO_2 emissions each year, for all historical years back to 1990. Officially reported emissions of CO_2 are obtained from UNFCCC (2016) by CRF source category. The data are collected by source sector as defined by the Common Reporting Framework (CRF) (IPCC, 2006). Apart from the sectors, emissions are also available by main fuel type (solid, liquid, gaseous) and also separately for biofuels. A crosswalk table is made to regroup and/or aggregate the 98 CRF codes in the 9 source sector categories as used in this study (Table 1). The common sector format for this inventory (Table 1) is based on the Selected Nomenclature for Air Pollution (SNAP), similar to the typical sector format used in the modelling of air pollutant concentrations. The advantage is that emissions of co-emitted species like CO or NOx can be directly obtained from the TNO-MACC inventory (Kuenen et al., 2014) as these have the same spatial resolution and source sector grouping. Similar to Kuenen et al. (2014), industrial combustion (SNAP 3) and industrial process emissions (SNAP 4) have been aggregated to a newly defined SNAP 34. The motivation for merging these categories is that parties often use (slightly) different definitions on where to draw the line between process or combustion emissions resulting in a less comparable result between countries.

In some cases, the CRF source categories needed to be disaggregated in order to match the common sector format for this inventory. In such cases GAINS emissions were used to calculate the share of each sector in the respective CRF source category. The share by sub category was then used to disaggregate the CRF category. Moreover, the grouping does not only involve aggregation to the Table 1 sectors but can also include a further splitting of a source sector because we may use different spatial proxies to distribute the emissions. For example, emissions from urban traffic and highway traffic are distributed using different proxy maps but the emissions are reported and grouped as road transport.

GAINS (http://gains.iiasa.ac.at/models/): In cases where reported data have not been used or were not available, emissions at the country level were taken from the GAINS model (Schöpp et al., 1999, Amann et al. 2011; 2013). The GAINS model provides emission data at sector and activity level, comprising more than 200 different categories for 5-yearly intervals. For this study, the GAINS emission data are based on the TSAP_Mar13_CLE scenario for the years 2000, 2005, 2010 and 2015. This is described documented in Amann et al. (2013) and is the "Current legislation" (CLE) scenario of Thematic Strategy on Air Pollution (TSAP) Report #10. To obtain emissions for the years in between these intervals, linear interpolation was used for each of these individual categories.

EDGAR (Emission Database for Global Atmospheric Research; Olivier and Janssens-Maenhout, 2016; Janssens-Maenhout et al., 2017) (http://edgar.jrc.ec.europa.eu/): EDGAR is a global emission database used primarily as input for global atmospheric modelling studies. This database is constructed using a bottom-up approach and includes both greenhouse gases and air pollutants. In this study, version 4.2 was still used which includes emission data until and including 2008.
For the countries Armenia, Azerbaijan and Georgia, neither reported nor GAINS emission data were available., For these countries EDGAR data were used at SNAP level 1 (see also Table S3 and Kuenen et al., 2014).
For the period 2009-2014 emissions from Armenia, Azerbaijan and Georgia were assumed to remain constant and equal to 2008 which was the most recent EDGAR year at the moment of database construction. While this assumption is not correct, these three countries contribute only 47.1 Mt CO_2 in 2008 or ~0.9% of the European total. An (future) update to EDGARv4.3.2 would lead to adjustments of the emissions for Armenia, Azerbaijan and Georgia in the order of 6-20% for the years 2008 to 2012, i.e. a change from 0.9% to ~1.05% of the European total. This is foreseen in a next version but will hardly influence the European totals.

2.1.2 CO_2 emissions from fossil fuel and biofuel

In the reporting of greenhouse gas emissions, Parties report emissions by major fuel type (solid, liquid, gaseous, biomass) for the combustion sector which therefore includes CO2 emissions resulting from the combustion of biofuels. These are, however, not taken into account when total national GHG emissions are calculated since biofuel combustion results in short-cycle carbon emissions if the biofuel is grown in a sustainable way. In the emissions database compiled in this study these emissions are included by collecting emission data from the UNFCCC submissions by major fuel type (solid, liquid, gaseous, biomass) for the fuel combustion related activities. This fuel differentiation is preserved in the database for the spatial distribution. In addition, for liquid fuels a distinction is made between gasoline, diesel and medium to heavy oil (which is particularly relevant for transport). The split between these fuels is made by calculating their share per sector based on their relative share in the GAINS emission database (Amann et al., 2011).

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In both the UNFCCC inventory submissions and in EDGAR, CO_2 emissions from the biofuel combustion are separately included. In GAINS, these emissions are not included (CO_2 from biofuels is considered zero). Therefore, where needed (see countries in Table S3) we have calculated CO_2 from biofuels bottom-up using the activity statistics in GAINS for the specific sectors, combined with default IPCC emission factors (54600 kg CO_2 /TJ for biogas, 112000 kg CO_2 /TJ for wood and wood waste) (IPCC, 2006). The emission factor for biogas is currently under discussion as it may be biased low. However, until it is officially revised we use the conservative IPCC (2006) value. Furthermore, for residential wood combustion, TNO internal estimates for wood consumption per country (reported in Denier van der Gon et al. 2015) are used instead of activity statistics from GAINS.

Since CO2 emissions from the open burning of agricultural waste are considered short-cycle carbon, this source is excluded from the UNFCCC based inventories and calculated separately based on the GAINS activity data (amount of agricultural waste burned), combined with an emission factor of 1.5 kg CO_2/kg waste (Akagi et al., 2011) to ensure a consistent emission estimate across Europe for this source. The agricultural waste burning CO_2 emissions are also marked as CO_2_bf.

2.1.3 International shipping

International transport activities are not part of the emission inventories of individual countries. Therefore, emission data have to be based on or derived from other sources. For international shipping, data on emissions and trends for international sea shipping in the European domain have been developed by TNO based on reviews of existing information and expert knowledge on activity levels and emission factors (Granier et al., 2015). One of the underlying assumptions is that heavy fuel oil (HFO) is mainly used at sea, while marine diesel oil (MDO) is used in ports and around ports. In-port emissions are included based on TNO expert judgement, in turn derived from an extrapolation of available data for the port of Rotterdam. The updated TNO-MACC_III dataset used in this study takes into account different influences on ship emission trends:

- Economic growth of the sector per year;
- SECA – Sulphur emission control areas (North Sea and Baltic Sea);
- Economic crisis: slow steaming to save fuel (costs); less emission per mile;
- Trend towards bigger ships – economics of size.

The result indicated that international shipping emissions in Europe were increasing after 2000 until a trend change occurred in 2006 and a temporary dip in activity is visible around 2009 due to the economic crisis. The TNO-MACC data for international shipping are currently also used by EMEP and are, in general, below the estimates that were used by EMEP / CEIP until 2014 (see Wankmüller et al., 2015; Gauss and Jonson, 2016).

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2.2 Spatial distribution of emissions

As a next step, the inventory combining emissions from various sources is distributed across Europe at 0.125° x 0.0625° longitude-latitude resolution. The domain is between 30°W-60°E and between 30°N-72°N. For each of the 78 source categories for which emissions are available, one or more proxies were identified for distribution. These proxies provide the mapping of the emissions to the grid for a given sector and year, with a normalised factor representing the intensity. Proxies include e.g. population density, industrial area, rail and road networks, arable land cover, inland waterways. For each country, substance (CO_2_ff or CO_2_bf), sector and year the most appropriate proxy was chosen in a selection table. In specific cases, multiple proxies were chosen to distribute the emissions.

For point sources, we have made use of the E-PRTR dataset (v4.1) which represents the status of the E-PRTR dataset as on 9 June 2012 (http://www.eea.europa.eu/data-and-maps/data/E-PRTR4.1). The dataset provides information on the location (longitude, latitude) and emissions of major facilities in Europe. The processing of the E-PRTR are described in more detail by Kuenen et al. (2014). Effectively fractional maps of point source emission shares by sector by country by year are produced. The fractions are used to distribute the national total emission by (sub)sector by year to the respective point sources. This implies that the point source distribution within a country is not static over the timeseries but can vary from year to year e.g. due to temporary closure, changing of capacity or new construction. It also implies that the emission allocated to a point source is not by definition equal to the value in E-PRTR because often the total emission from a country for a (sub)sector and the total in E-PRTR do not match.

Area source emissions from e.g., . residential combustion, transport sectors and agriculture are distributed using the most applicable proxy for each particular source. These proxies include a.o. total, rural and urban population, land use, and road, rail and river networks. Most proxy maps were taken from Denier van der Gon et al. (2010) but a number of modifications and improvements have been made compared to Denier van der Gon et al. (2010). A high resolution population density map is made utilizing the LandScan (2010)™ High Resolution global Population Data Set for the year 2005. For a select number of emission types an additional distinction between urban and rural population is necessary. To this end a Grump Urban/rural mask is made using the GRUMP (Global Rural-Urban Mapping Project) dataset (CIESIN, 2008) which is applied to the LandScan (2010) derived population density grid. For land use such as arable land and industrial zones (for non-point source industrial emissions) the CORINE land cover 2000 map is used (EEA, 2007). Another import area source are road transport emissions. A road network traffic intensity map is made based on the TRANS-TOOLS network (JRC, 2005). TRANS-TOOLS (Tools for Transport forecasting and Scenario testing),is a European transport network model covering both passengers and freight, as well as intermodal transport. It combines advanced modelling techniques in transport generation and assignment. The percentage of the total road network that is covered by the Trans-tools map varies from country to country, so a varying percentage of the emissions was allocated to the Trans-tools network. The first step in estimating this percentage is estimating the amount of vehicle kilometres (vKm) driven on the Trans-tools network versus the total amount of vKm driven in a country. Estimates for the total amount of vKm per country and vehicle type are taken from the TREMOVE model (http://www.tremove.org/) and cross-checked with other sources. It also provides a split between urban, highway and rural road network. Urban transport emissions are distributed by urban population density, high-way and rural transport including provincial roads is distributed using the TRANS-TOOLS based map. It is important to realize that these tools are used to make a fractional map to allocate emissions calculated bottom-up based on fuel statistics, we do not directly use emission estimates from TREMOVE.

For the current dataset proxies for the area sources are assumed to be static in time. For example, changes in the population density due to e.g. on-going urbanization between 2000 and 2014 are not taken into account. A special proxy map is made for the distribution of residential wood combustion, taking into account the urban/rural population density with a higher "weight" for wood use for a rural person and (local) availability of wood. This results in less biogenic CO_2 emissions in city centres than when using only population density (see also Denier van der Gon et al, 2015).

In some (rare) cases emissions could not be distributed. mostly because the proxy was not available for that specific country. These "remaining" emissions are by default distributed using either total population, rural population or arable land. The gridded emissions are aggregated to the source sectors presented in Table 1 to reduce the size of the output file.

2.3 Methodology future years

Ideally future scenarios should be developed that include the most up-to-date emission reductions presented in the Nationally Determined Contributions (NDCs) and the corresponding long term goals under the Paris Agreement. This, however, is a considerable task and scenarios that link these commitments to specific sources for all countries are not yet available. In addition, an analysis by Rogelj et al. (2016) suggests that the currently submitted INDCs (Intended NDCs) may not be sufficient to achieve the long-term goal from the Paris Agreement. This may initiate further additional reduction measures in the near future, implying that future scenarios may be quickly outdated. An alternative approach, as done here, is to use existing scenarios but start from the most recent base year in the historic inventory. Moreover, to be indicative for the range that could be expected we follow both a "climate change mitigation" (CC) scenario and a "business as usual" (BAU) scenario. To this end we use two global emission scenarios developed by the EDGAR team in the CIRCE project (Doering et al., 2010). These two EDGAR-CIRCE scenarios for CO_2, CH4, N2O, CO, NOx, SO2, VOC, BC and OC from 1990-2050 span the range of emissions from no global action on climate change and air pollution (i.e., the BAU scenario) to emissions resulting from a global climate policy (i.e., the CC scenario). In the CIRCE BAU scenario the GHG emissions increase from the year 2005 onwards when no further climate and air pollution policies are implemented beyond what is in place since the year 2005. These scenarios are similar to the A1SRES and B1SRES of IPCC AR4 and were obtained applying macro-economic activity growth rates of the long term energy model POLES and the integrated assessment model IMAGE (Russ et al., 2007). This means that under the BAU scenario the energy consumption from 2005 to 2050 more than doubled by economic growth of fuel markets (POLES baseline scenario) and that agriculture and land use intensified by population growth (IMAGE-ADAMS scenario). The global climate change mitigation scenario follows the rational of limiting climate change to 2°C compared to pre-industrial

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times by assuming full implementation of a global climate policy with fuel shift and decreased fuel demand (in EU counting on renewables and energy efficiency increases). These scenarios are documented by Doering et al. (2010) and used by Pozzer et al. (2012).

The two CIRCE scenarios contain detailed information about the development of individual source sector categories. By coupling these scenarios to TNO-CAMS gridded data, the emission changes in each grid-cell and for each region can be estimated in a spatially explicit manner. The TNO-CAMS data are scaled from the year 2014 onwards using sector-detailed scaling factors derived from the relative trend in the CIRCE scenarios from 2014 onward. Therefore, the scenarios start with base year 2014 which is the same in both scenarios. The relative change compared to the most recent year in the TNO-CAMS data set (= 2014) by country for the BAU and CC scenario, with a proportional time scale, is shown in Figure 1for a selection of five large European countries (Germany, France, UK, Spain and Poland). The 5-year time steps of the global stock take and the reference years with the targets of the Nationally Determined Contributions are indicated with the blue arrows. Soon after 2020 the CC and BAU scenarios follow distinctly different trends.

For international shipping the future CO_2 projection scenarios are not taken from Doering et al. (2010) but from the International Maritime organization (IMO). Its Third IMO GHG Study (IMO, 2014) presents several future shipping scenarios. As a BAU scenario the IMO scenario 13 (based on IPCC RCP8.5 + SSP5) is selected and for the CC scenario we selected IMO scenario 2 (based on IPCC RCP6.0 + SSP1) (for details we refer to IMO (2014)). Both scenarios show a growth of shipping CO_2 emissions from the present to 2050, however, the BAU has double the emissions as the CC scenario. For more details on these scenarios we refer to IMO (2014). For intermediate years we apply linear scaling between the closest projection years. To simplify the scaling we keep 2014 and 2015 equal, this implies we project the 2014 emissions towards 2020 by using the 2015-2020 change as given in IMO (2014).

3 Results and Discussion

3.1 The historic emission inventory 2000-2014

The CO_2 emission inventories have been split between CO_2 from the combustion/use of fossil fuels and CO_2 from the combustion/use of biofuels. All process CO_2 emissions are considered "fossil" except for agricultural waste burning. The resulting emissions for all years are shown in Figure 2 per country group, separately for CO_2_ff (excluding biofuels) and CO_2_bf (biofuels only). It can be seen that the CO_2 emissions are somewhat increasing between 2000-2006, and decreasing thereafter. The dip in 2009 due to the economic downturn is clearly visible. For CO_2 from biofuels, a strong increasing trend is observed from 2000-2010, which is mostly accounted for by increasing use of biofuels in the EU15. After 2010 the trend slowed down significantly (Figure 2). In 2014 about 12% of the total European anthropogenic CO_2 emission comes from short-cycle carbon (biofuels) (Figure 2, Figure 3).

To illustrate the main sectors responsible for changes, Figure 3 shows the contribution of the different SNAP sectors to the fossil CO_2 and the CO_2_bf from biofuels, separately. It can be seen that for fossil CO_2 emissions the importance of source sectors is rather stable between 2000-2014. For CO_2 from biofuels, however, a large increase is seen in the EU15+NOR+CHE for energy production (SNAP 1) and also road transport (SNAP 7) emissions increased. For the EU-NMS residential combustion (SNAP 2) is dominant but the growth from 2000-2014 is due to increased use of biofuels in energy production and road transport. For the non-EU countries, the most important sources of CO_2 from biofuels are residential combustion (SNAP 2) and agricultural waste burning (SNAP 10).

The spatially distributed emissions of fossil CO_2 for 2014 are shown in Figure 4. Cities and urban areas are clearly visible as well as some major transport lines and international shipping activities. Visualisation of the emissions in a map like Figure 4 is partly misleading because area sources will dominate the "colouring" of the map. If we would zoom in on the North Sea, visible as a blue – green are in Figure 4, we would see yellow to brownish pixels indicating high emissions from point sources, in this case oil and gas production sites. This is not clearly visible from Figure 4. Like area source grid cells which may contain roads, housing, etc. a point source location can have emissions allocated to different source sectors. This is illustrated for the point sources on the North Sea in Table S5. Most point sources here are oil and gas fields and report flaring emissions which are grouped under SNAP5. However, the emissions for energy supply of compressors and other machinery on the platforms are in this data set grouped under SNAP1. In Table S5 this is visible by looking at a point sources for e.g. the UK that have both SNAP1 and SNAP5 emissions. The point sources are very important for CO_2 emissions and underrepresented in the visualisation by a gridded map. In 2014 about 50% of the CO_2 from fossil fuel emissions of the entire European domain excluding international shipping is emitted by point sources.

For the biofuel CO_2 emissions the emissions from the dominant source, residential combustion, are shown for the year 2014 (Figure 5). The information on biofuel CO_2 is relevant because atmospheric monitoring data will not be able to distinguish CO_2 from fossil origin or biofuels unless isotopic data are collected, which is highly expensive and therefore severely limited. To use atmospheric observations to monitor progress to objectives and reductions of fossil fuel CO_2 emissions, corrections for biofuel use in the measured data will have to be made. Although residential combustion is an area source, Figure 5 shows that in some regions it is clearly concentrated in certain regions marked by population density and wood availability (e.g Po valley in Italy, Parts of France, Germany and Portugal).

3.1.1 International shipping

International shipping is not reported by parties to the convention and therefore separately estimated based on the trend in shipping emissions developed by TNO for the TNO-MACC-III emission dataset of atmospheric pollutants (Granier et al, 2015). Estimated shipping emissions peaked around 2006 at 160 Mt CO_2/yr and stabilized since 2009 around 135 Mt CO_2/yr. Emissions for 2013 and 2014 are assumed to be equal to 2012 as no new data were available. Overall about 6% of the emissions are allocated as "in-port" emissions based on expert judgement but this fraction differs by sea, depending on the number of important ports present and the amount of transit transport: Atlantic (4%), Baltic Sea (9%), Black Sea (7%), Mediterranean Sea (3%), North Sea (12%). In the near future the quality as well as spatial allocation of CO_2 emissions from International

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shipping will improve as the emissions estimates using the Automatic Identification System (AIS) signals will become available for multiple years such as provided for 2011 by Jalkanen et al. (2016).

3.2 Downscaling of national emission inventories to sub-national or city level

There are known severe problems to reliably scale down emission distributions from the national scale to the subnational or city scale because the activity data used are often only available as national totals with no sub distributions. Comparisons between downscaled national emission inventories and city scale bottom-up inventories revealed large discrepancies (Denier van der Gon et al., 2011b; Zhu et al., 2012; Timmermans et al. 2013). While these studies mostly looked at air pollutants, a similar uncertainty exists for CO_2. For example, the most common proxy to downscale residential combustion emissions is population density. However, heating in cities profits from economy of scale – it takes less energy per person to heat an apartment block than an isolated rural country house, and the heated space per person in the city is smaller - but detailed information how to properly account for this across Europe is not yet available. More local data need to be included .to obtain more accurate sub-national and/or city level emission grids. This is achieved for the USA in the Vulcan inventory (Gurney et al., 2009) by incorporating census, traffic, and digital road data sets. Comparison of the Vulcan inventory with a global 1° × 1° fossil fuel CO_2 inventory, which relies heavily on population densities for spatial distribution, highlighted the space/time biases inherent in the population-based approach (Gurney et al., 2009). However, provided that the data exists and is available for use, the additional effort (time and costs) to process and use local data is far from trivial. Nevertheless, there is a quickly growing demand for city scale emission inventories as cities have clear (voluntary) ambitions to play a bigger role in abating climate change. Examples are the C-40 Cities Leadership Group (http://www.c40.org/) and the Covenant of Mayors (http://www.covenantofmayors.eu/). However, global or European, reliable city scale CO_2 emission inventories do not exist at present, nor do cities have the means in place to monitor their progress towards carbon reduction objectives. At city level, no binding agreements apply and most actions are voluntary. Many city inventories are not accounting all emissions that take place on the city's territory but restrict the accounting to those sectors under their governance or those with reduction measures (Ciais et al., 2015). A complicating issue in parts of Europe is the importance of biofuel (wood) use for residential heating. If we want to correct for the biofuel CO_2 emissions, either in city-scale emission inventories or in interpretation of measured city CO_2 concentrations plumes, the allocation becomes important and this is poorly know. Here we based the spatial distribution of the fuel wood consumption emissions on urbanisation degree, population density and modelled local fuel wood supply, following the approach of Denier van der Gon et al (2015) (Figure 5). The high resolution maps can be a first step towards supporting cities with complete CO_2 emissions information but significant further refinement would be needed following the example of Gurney et al. (2009) for the USA.

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3.3 Temporal and vertical emission profiles

The data set provides annual total emissions by country by grid cell by source sector. Emission sources are further broken down into point sources and area sources. In the present study no new time profiles or vertical emission profiles have been developed but the profiles available for air quality modelling can be used as a default to breakdown the emissions to hourly fluxes with a vertical distribution. For air quality modelling purposes a set of temporal factors was constructed to breakdown annual total emissions into hourly emissions. The temporal variation of specific source sectors is taken into account by applying typical time profiles and thereby distributing the emission data in time. These are weighting factors that are derived from temporal activity profiles and the sum of which is 1 and discussed in more detail by Denier van der Gon et al. (2011a) and Pouliot et al. (2012). The profiles are for aggregated source sectors according to the SNAP (Selected Nomenclature for Sources of Air Pollution) level 1 which is similar to the sectors of the current data set (Table 1). Most profiles show a sinusoidal curve and distinguish monthly, daily and hourly factors. Continuous operating facilities like power plants show a rather flat annual profile with a small summer dip because of reduced demand. For several combustion sources the temporal patterns were based on the work done in the GENEMIS project (Friedrich and Reis, 2004). The European temporal profiles are discussed and compared with US time profiles for the same sectors in Pouliot et al. (2012). Most time profiles have not recently been updated and the same profile is applied to all countries. This is a known shortcoming, for example traffic rush hours vary by country due to cultural differences and residential heating is controlled by outside temperature which for a given month or day maybe different from one yea to the next. Matthias et al. (2017) discuss the improvements that are possible when more dynamic emission timing functions are used and provide examples for a number of source sectors. Such approaches will take over from the fixed temporal profiles that are mostly used at present. Along the same lines, the vertical emission distribution profiles for air quality modelling can be used for the CO2 emission data set as an identifier for area and point sources is present in the data. Area sources are typically emitted at ground level (0-25 m), for the point sources vertical profiles have been derived by Bieser et al. (2011) taking source sector, climatic or political region, seasons and day- and night time into account.

3.4 Future CO_2 emissions following two pathways

The TNO-CAMS data are scaled from the year 2014 onwards using sector-detailed scaling factors derived from the relative trend in the CIRCE scenarios but only from 2014 onward. Therefore, both scenarios start with the same base year 2014. The projected CO_2 emissions from fossil fuels and biofuels over time are shown in Figure 7 for a few selected large countries, the EU-15 and the entire European domain. The CIRCE scenarios (Doering et al., 2010) are not thought to be up to date, nor to reflect the real or NDCs emission changes to be expected, as the projections were developed before 2010 and originally started from 2005. However, the magnitude and temporal pattern (change/yr) is assumed to be indicative for the range of future changes. The 'Climate Change (CC)' (or the 'Business As Usual)' can be indicative for the magnitude and temporal change of emissions (ton CO_2/yr) that may be seen in future years depending on more (or less) adoption of climate mitigation policies.

The changes projected for Europe are substantial (Figure 7) but, again, do not take into account the latest NDCs under the Paris Agreement (UNFCCC, 2015) and the Clean Energy winter package of EU 28 (EC, 2008; EEA, 2016).

The fossil CO_2 emissions under the CC scenario deviate substantially from the BAU scenario and by 2050 are less than half the BAU scenario emissions. Biofuel CO_2 emissions are similar under both scenarios. This is not surprising as there will be no specific measures to reduce biofuel CO_2 emissions under either scenario. This does, however, not mean that the patterns in both scenarios are exactly the same for biofuels. Under the CC scenario energy efficiency will increase demanding less energy (including biofuels) but at the same time biofuels will play a role in phasing out fossil fuels. Apparently these two opposing developments balance each other. The scaling is done for important future years like 2020 and 2030 as well (data not shown) but here we show 5-year time steps except for the final step from 2033 to 2050. These 5-year steps coincide with the global stock take planned by UNFCCC under the Paris Agreement (UNFCCC, 2015). Although EU countries follow the same patterns, developments between countries can be different. For example some countries show a slight decline of CO_2 emissions under a BAU scenario (e.g. Germany, Poland) whereas others may show a slight increase (France, Spain) (Figure 7). However in all countries the gap between the BAU and CC scenario is dominant. The future shipping emissions start from the 2014 historic emissions as a base year and are projected using information from IMO (2014). Under the climate change scenario the emissions stabilize at 200 Mt/yr. The BAU scenario starts to deviate from 2025 onwards and stabilizes at around 280 Mt/yr in 2045 (Figure 8).

As stated before the difference between the net CO_2 emissions from biofuels (CO_2_bf) for both scenarios is fairly small. Since the CIRCE scenarios were originally developed from the base year 2005 with a much smaller presence of biofuels than present, the robustness of the derived scaling factors is affected. It is recommended to update the projections for biofuels in the near future and in this respect it is interesting to see the stabilization of CO_2_bf in the 2010-2014 period (Figure 2). On the other hand, the projections for the EU15 or Europe (Figure 7) for the near future (2014 – 2023) also do not suggest a dramatic further growth. Table 2 shows the emission reductions for four large European countries by source sector as well as the national total. The source sectors are relevant here because energy industries (defined as power generation plants, refineries and oil/gas extraction and fuel transformation plants) and the manufacturing industries (large scale industrial combustion and process emissions) will mainly result in emissions from point sources (stack emissions), all other sectors will mostly consist of area sources. Table 2 shows that the total CO_2 emission reduction is smaller than the emission reduction in CO_2 from fossil fuels. This is to be expected, since biofuels will play a role in the phasing out of fossil fuels. It may, however, imply an additional challenge for future observing systems as the net changes in CO_2 concentrations will be substantially smaller than the reduction in fossil fuel CO_2 (CO_2_ff) would suggest. This is particularly detected during the 2028-2033 period for Spain, France and Poland (see Table 2). For example for France the net CO_2_ff emission reduction between 2028-2033 is about 26 Mt CO_2/yr but the emission reduction of the overall CO_2_ff + CO_2_bf is only 16 Mt/yr.

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3.4.1 Spatial patterns of the future emission changes

We anticipate negative differences under the CC scenario (see Table 2) whereas under the BAU scenario, close to zero differences correspond to a situation with no or limited changes in fossil fuel use. Zooming in on some regions, allows us to depict the concentration delta for city hot spots (e.g., over Paris and Madrid) and to see the point source changes (in particular of energy industries) over Europe. The difference between emissions in the years 2023 and 2028 for the CC scenario is presented in the form of a map, gridded with TNO spatial proxy data (Figure 9). From the overall picture for the European domain we see a dominance of emission reduction for the land-based sources (blue dominates) while emissions on seas keep growing due to no reduction in CO_2 emissions from international shipping activities. When we look more closely to the land-based emissions (zoom version of Figure 9) it can be seen that mixed with the pixels that indicate a decrease in emissions, individual grid cells exist where emissions increase, for example in Belgium and Czech Republic. Whereas the overall area sources may show a small decline in emissions, the net emission especially of smaller countries may change little. It will be highly questionable if such changes over 5 year time steps will be measurable. In Figure S10 the change of emissions in four smaller European countries (BEL, CZE, HRV, SVK) is shown by source sector. Changes between 2023-28 are marginal and sometimes, as in the case of Belgium, the decrease in one source sector compensates growth in another sector with the net emission remaining stable. It is important to be aware of these features and, as clearly stated before, there is a need for a better representation of the latest agreements in the future scenarios. This should have priority in the next years.

Moreover, in the current dataset the spatial distribution of area sources is static. However, since the historic dataset encompasses 15 years, this assumption should be revisited in a next version because urbanization patterns and road network can change substantially in 10-20 years.

4 Conclusions

The greatest contribution to the increase in atmospheric CO_2 and observed climate change over the last 50 years comes from emissions from the combustion of fossil fuels and cement production (IPCC, 2013). The purpose of this study is to present a high resolution inventory of European emissions of fossil carbon dioxide, the most important GHG and to provide a spatial explicit dataset with a range of “to be expected” changes in the CO_2 emission patterns in the near future. In this light it is important to mention the European Union's '20-20-20' climate and energy package (EC, 2008a,b). The package sets three key targets: 20% cut in greenhouse gas emissions (from 1990 levels); 20% of EU energy from renewables; 20% improvement in energy efficiency. The targets were set by EU leaders in 2007 and enacted in legislation in 2009. Recently they have been complemented by the 2030 climate and energy framework which sets three key targets for the year 2030: at least 40% cuts in greenhouse gas emissions (from 1990 levels); at least 27% share for renewable energy; at least 27% improvement in energy efficiency. (EC, 2014). The EEA (2016) concludes that the European Union is on track to meet its 2020 climate and energy targets but that the situation observed differs across individual countries and for the different targets. Moreover, achieving more ambitious longer term objectives, such as the 2030 targets, requires current efforts to be stepped up. The motivation for preparing the data presented in this paper is, amongst others, the rapidly increasing demand for independent verification of trends in national CO_2 emissions over 5-10 year time frames and longer, following the Paris agreement and subsequently the EU's 2020 and 2030 climate and energy targets. Do countries achieve what they promise? Is the "proof" acceptable to all parties?

To this end a model-ready historic emission inventory at high spatial resolution for UNECE-Europe for 15 consecutive years (2000–2014) providing CO_2 from fossil fuels and CO_2 from biofuels is constructed to support modelling and sub-national scale identification of emissions. The sectoral breakdown and spatial distribution is consistent with the air pollutant emission inventories made in support of the Copernicus Atmospheric Monitoring Service (e.g. Kuenen et al., 2014). Therefore, co-emitted species like CO or NOx can be taken into account and modelled alongside CO_2 to improve our understanding of the origin of atmospheric CO_2. The dataset is complemented by two projections based on the CIRCE scenarios and using the latest historic year (2014) as the starting point for projection. The scenarios include a BAU and a climate change scenario. While the projections are not including the latest NDCs or EC climate change packages, they provide a range of possible future emissions that can be used for sensitivity tests, for example when designing a possible future observational system.

The demand for higher resolution CO_2 emission inventories in time and space will grow in the coming years. The list of possibilities for further improvement of the current dataset is substantial and includes more dynamic spatial distribution proxies for area sources and emission time profiles. Another short coming in the current dataset is that we use the multi-year fractional point source proxy maps from Kuenen et al. (2014) but these do not go beyond 2010. Therefore, a first improvement will be to extend the point source distribution from 2010 to 2014/15. We therefore see the present dataset as a first step in a sequence of continuous improving datasets comparable to the sequential improvements for air pollutants in the TNO-MACC-I, II and III emission inventories.

Data access

Annual grid-maps for the historical years 2000-2014 are available at https://doi.org/10.5281/zenodo.112889

Annual grid-maps for the future years 2018-2050 are available at https://doi.org/10.5281/zenodo.1009519

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Tables

Table 1: Description of the aggregated source sector categories. A detailed cross-walk table is provided in the supporting material (Table S4)

Description (SNAP_name)	SNAP1 code
Energy industries	1
Small combustion	2
Industry (combustion + processes)	34
Exploration and production of fossil fuels	5
Product use	6
Road transport	7
Non-road transport	8
Waste	9
Agriculture	10

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Table 2: Changes in CO_2 emissions (kton/yr) over 5-year time steps from 2023-2028 and 2028-2033 in the CIRCE_CC scenario for fossil fuel CO_2_ff and total CO_2 (CO_2_ff+ CO_2_bf). Negative numbers indicate an emission reduction.

CO_2_ff (kton/yr)	Germany		Spain		France		Poland	
5-year period	2023-28	2028-33	2023-28	2028-33	2023-28	2028-33	2023-28	2028-33
Energy Industries	-21984	-28523	3936	868	-4832	-30	-20297	-13271
Residential combustion	-15978	-14145	-3202	-4350	-8534	-9195	-4626	-9381
Road transport	-15473	-14991	-6574	-7571	-11689	-12551	-2255	-4823
Industry	-5745	-8812	-975	-3715	-1830	-4299	-4499	-4105
Other	-393	-448	152	-138	-438	-121	-513	-466
Total CO_2_ff	-59573	-66918	-6663	-14906	-27323	-26196	-32189	-32046
CO_2_ff + CO_2_bf (kton/yr)								
Energy Industries	-18745	-24018	3971	945	-4938	2456	-11157	-4703
Residential combustion	-17024	-13197	-2682	-3315	-8351	-7572	-572	-6679
Road transport	-14657	-12984	-6284	-6654	-11353	-10975	-2457	-4560
Industry	-5745	-8812	496	712	-852	-425	-2960	-1070
Other	-393	-448	152	-138	-438	-121	-513	-466
Total CO_2_ff + CO_2_bf	-56565	-59458	-4347	-8450	-25931	-16637	-17659	-17478

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Figures

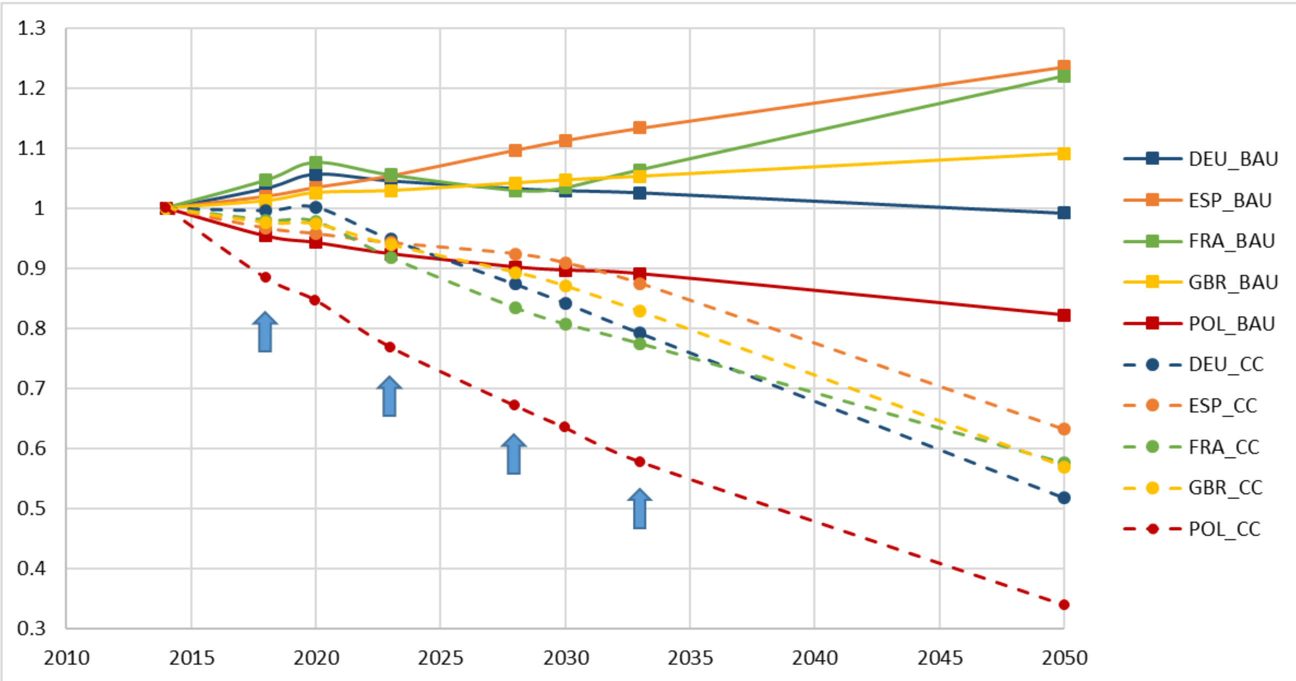

Figure 1: Relative change from the year 2014 towards 2050 by country based on CIRCE_BAU and CIRCE_CC. Blue arrows indicate 5-year time steps, coinciding with global stock takes. In the legend we present Germany by DEU, Spain by ESP, France by FRA, UK by GBR and Poland by POL.

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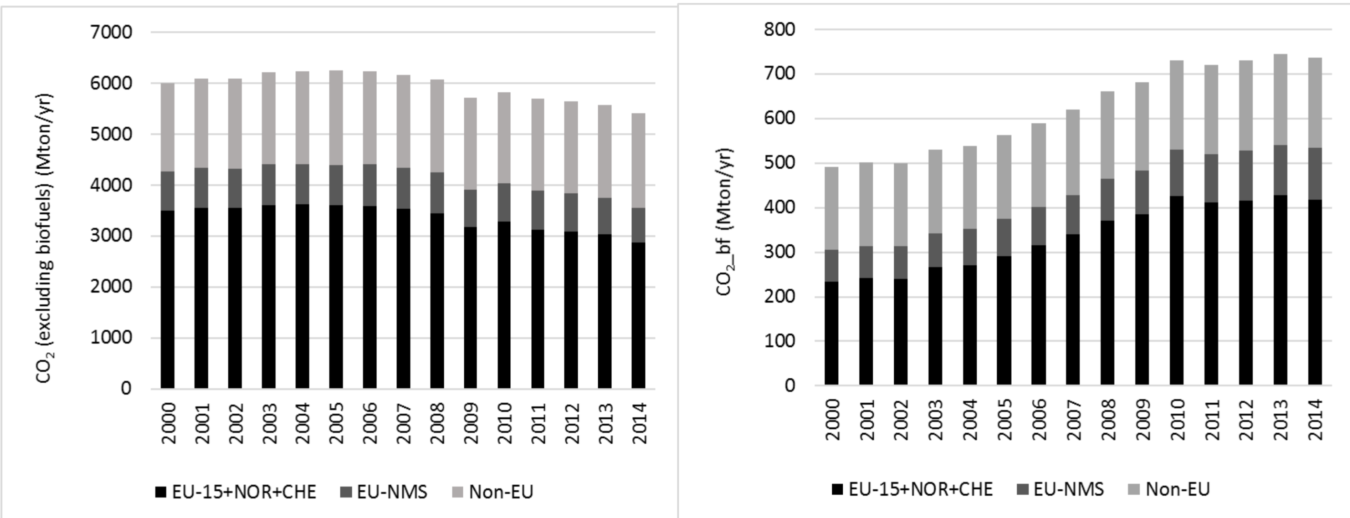

Figure 2: CO_2 emissions excluding biofuel combustion (CO_2_ff, left) and CO_2 from biofuel combustion (CO_2_bf, right) per year and per country group (EU15 = EU Member States as of 1-1-1995 plus Norway and Switzerland; EU-NMS = New EU Member States joined after 1-1-1995; Non-EU = all other countries).

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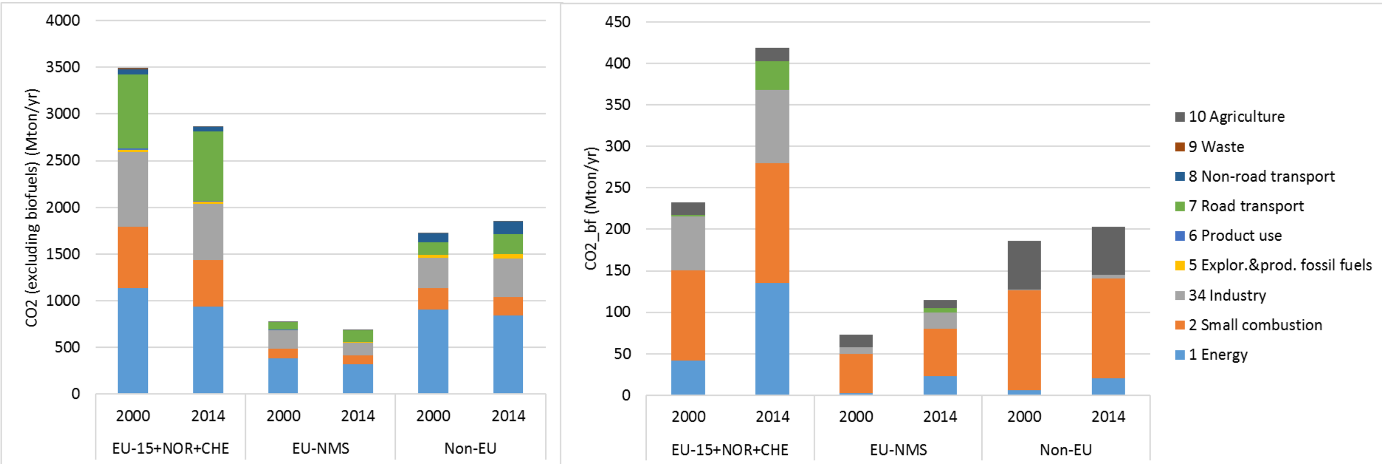

Figure 3: Sectorial contributions per country group for CO_2 emissions excluding biofuels (CO_2_ff, left) and CO_2_bf emissions (right) in 2000 and 2014.

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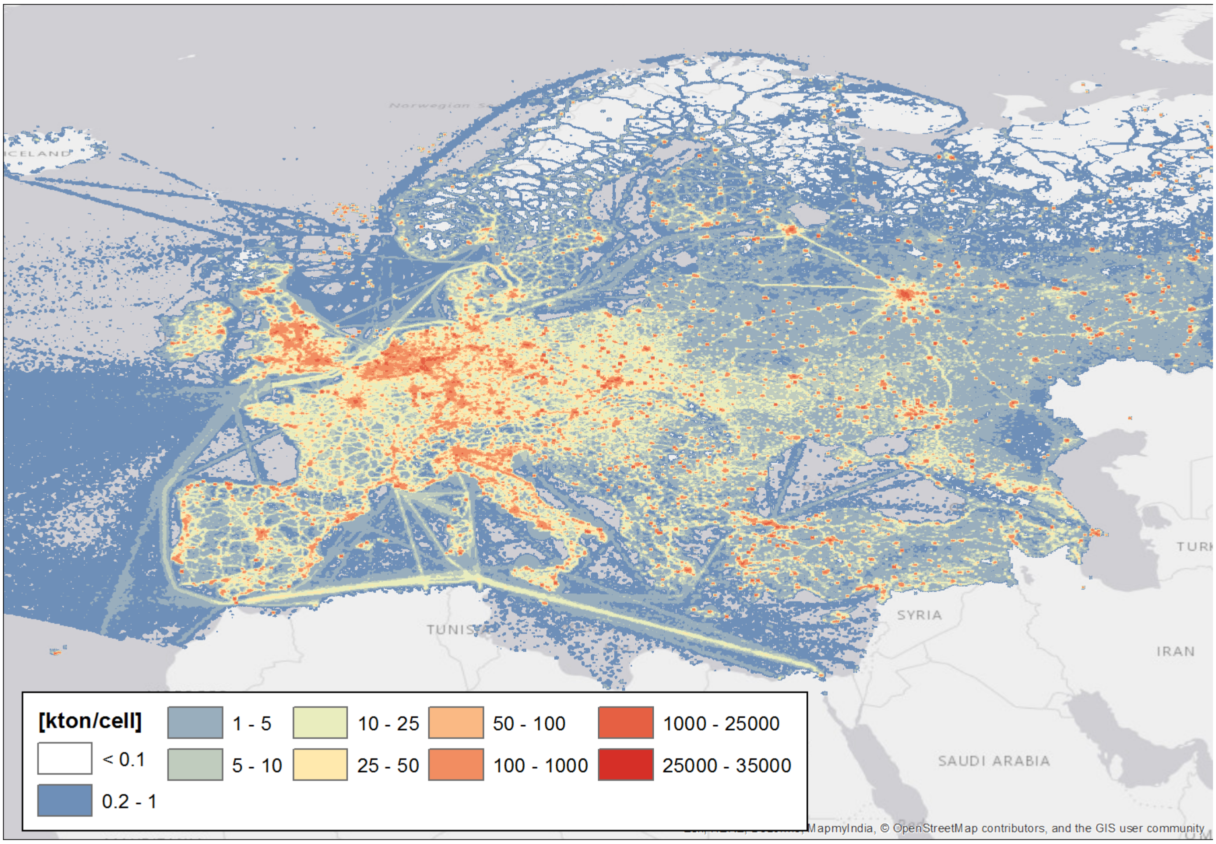

Figure 4: Gridded total CO_2 emissions of the TNO-CAMS inventory of anthropogenic sources excluding the land use, land-use change and forestry sectors (CO_2) for 2014. /[a gridcell is 0.125° x 0.0625° longitude-latitude or approximately 7x7km].

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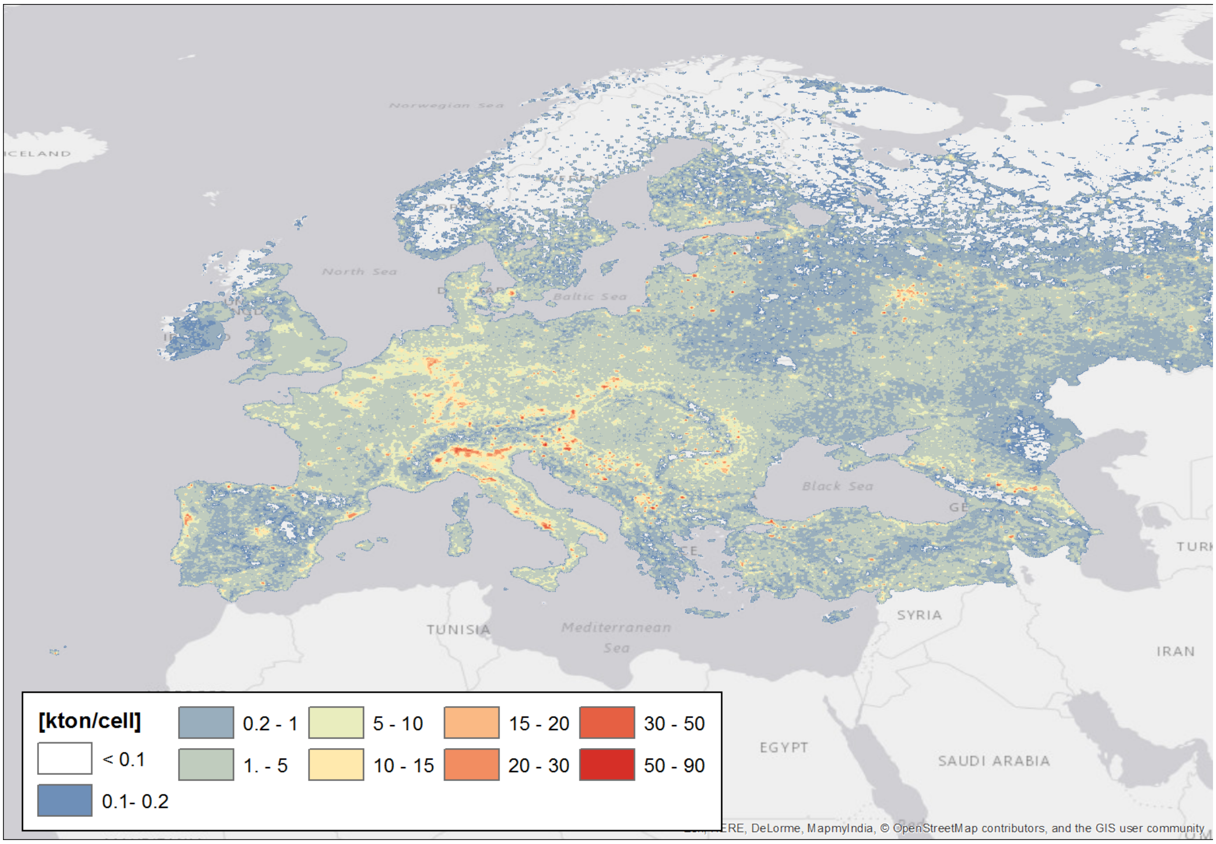

Figure 5: Gridded CO_2 emissions from residential biofuel use (SNAP2 CO_2_bf) for 2014.

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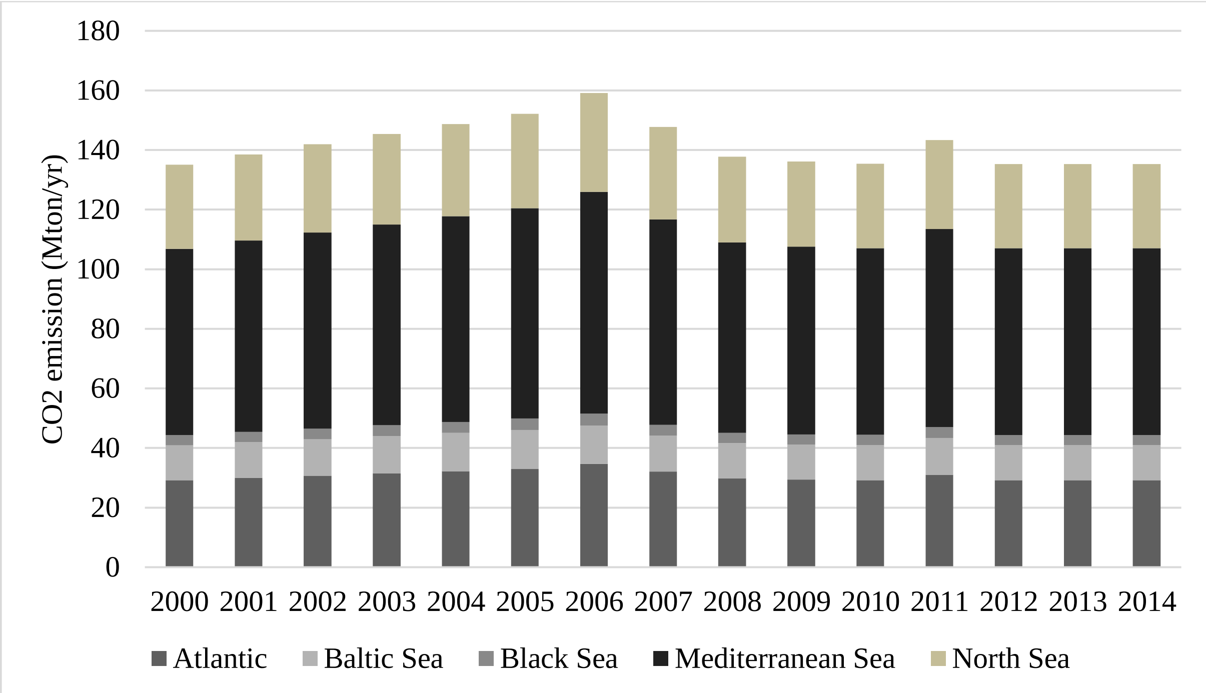

Figure 6: CO_2 emissions from international shipping 2000-2014 in the European domain (Figure 4)

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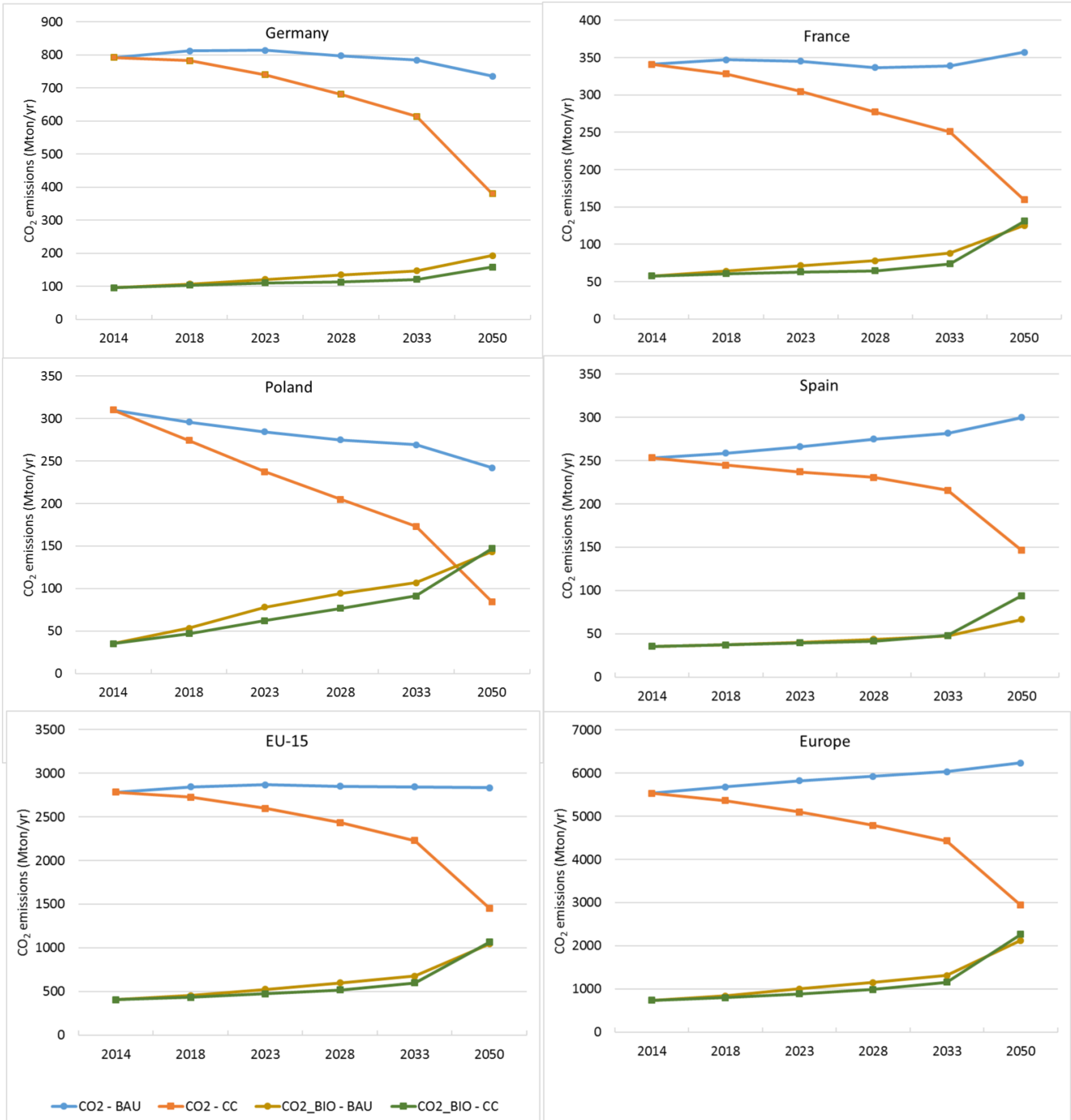

Figure 7: Overview of the projected CO_2 emissions in the TNO_CAMS data based on the CIRCE Business-As-Usual scenario (BAU) and Climate Change scenario (CC) for Germany, France, Poland, Spain, the EU-15 and the entire European domain .

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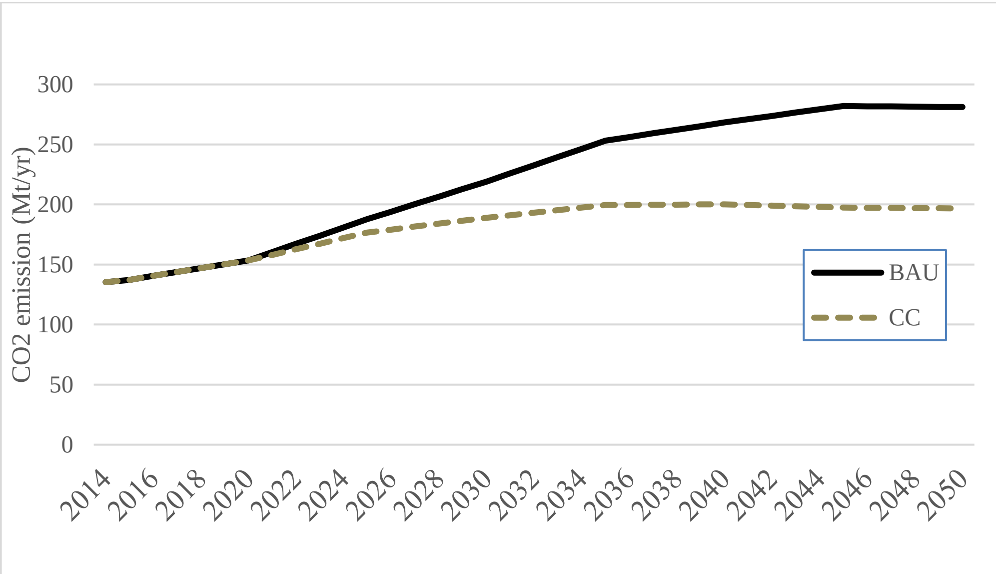

Figure 8: projected CO_2 emissions from International shipping in the European domain following a Business as Usual scenario (BAU) and Climate Change scenario (CC).

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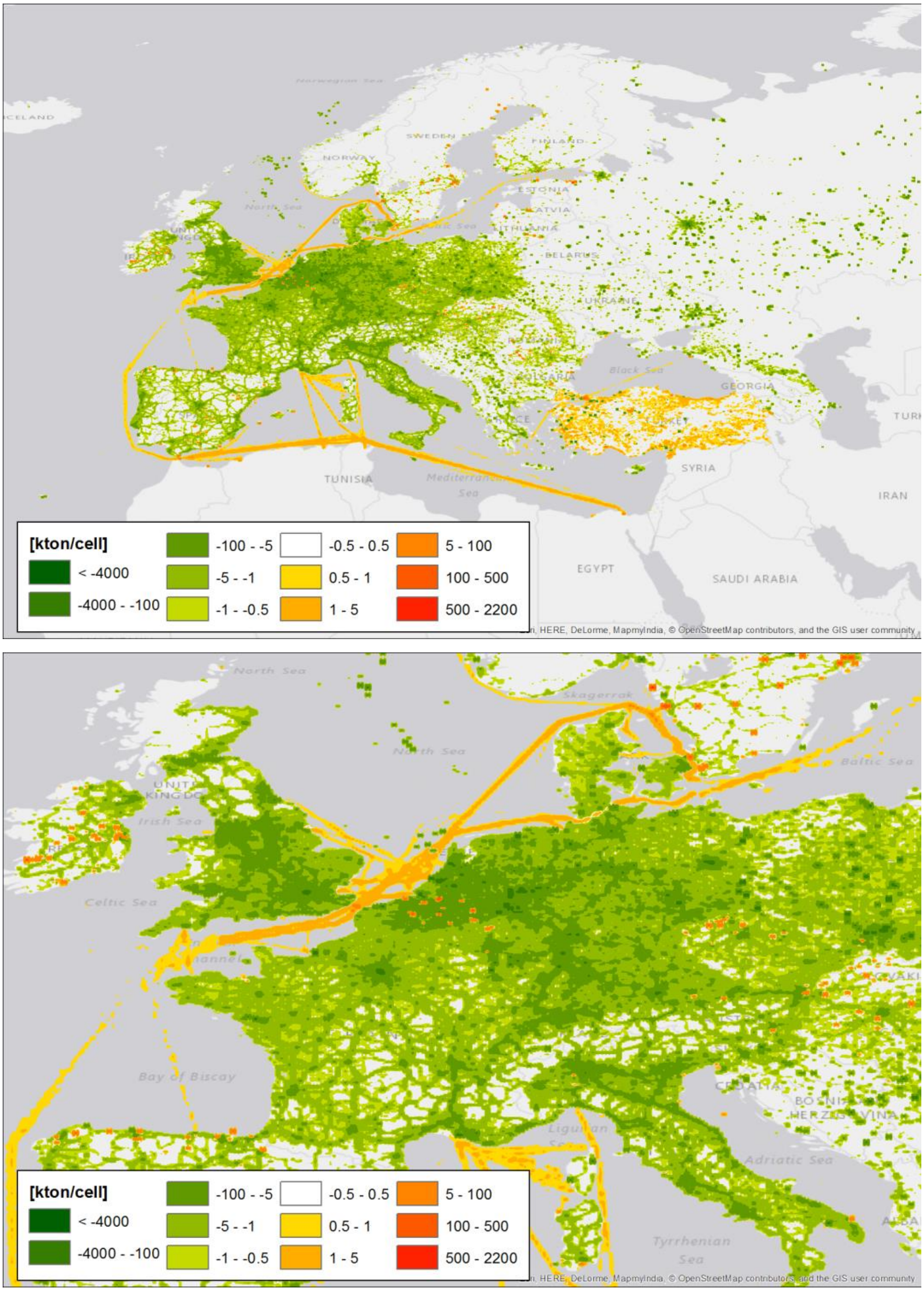

Figure 9: Difference in e*mission over a 5 year time step between 2023 and 2028 in the TNO_CAMS CO_2 dataset following the CIRCE_CC scenario for the entire domain (top) and zoomed over North-West-Central Europe (below). Negative values (green) indicate an emission reduction, unit is kton CO_2/yr/grid cell.*