Variation in trends of consumption based carbon accounts

Richard Wood, Daniel Moran, Konstantin Stadler

**Abstract**

The United Nations Framework Convention on Climate Change requires the annual reporting of greenhouse gas emissions. These reports focus on emissions within a territory, and do not capture the effect of de-carbonization in developed countries that has resulted simply by the relocation of emissions-intensive production to other countries. Consumption based carbon accounting has been proposed as a complementary method to capture the emissions occurring globally due to final consumption in a country. A number of global models have been developed in the last decade in order to operationalise consumption based accounting. However, the direct comparison of results from the models is hampered by differences in model construction. Here, we processed results of all the major global models in order to produce a unified and consistent global dataset over a long-time series. Indexing the annual changes to a base year, we also include an analyses of the variability across the models, both in absolute terms and in indexed terms in order to give an insight into robustness at both national and regional level.

**Keywords:**

Consumption based carbon accounting, uncertainty, robustness, variability, carbon footprints

# Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) requires the annual reporting of greenhouse gas emissions by Annex 1 countries[[1]](#footnote-1). There has been discussion about the holistic nature of such reporting, as it became evident that the de-carbonisation of some developed countries was mostly due to a displacement of energy intensive industries to Annex II countries1.

Consumption based carbon accounting has been proposed as a complementary method to capture the emissions occurring globally for consumption in a country2. Hence, increasing focus is being placed on consumption-based accounting of greenhouse gas emissions, or carbon footprints. In order to set policy targets using carbon footprint values there is a clear need for understanding the robustness in the footprint accounts and calculations.

Recent advances in global multi-regional input-output (MRIO) modelling has led to the development of a number of large databases suitable for calculating consumption based carbon accounts for the last decades3. Due to construction challenges in MRIO, incomplete data, resource constraints, and underdeveloped accounting standards, estimation steps are required and accounting practices are not uniform. This leads to a degree of inconsistency among MRIO databases4. While consumption based carbon accounts (CBCA) are often perceived as less robust than emission inventories, several studies have shown that at the national level the accuracy of CBCA results is not significantly different than production based accounts 5-7. However, there is still a huge range of results being presented as carbon footprint results.

The main source of difference between CBCA results from different models typically stems from the domestic emission inventory applied in the model8. The volume and composition of consumption (also called final demand) is another cause of variation between models9. The tracking of embodied emissions through global supply chains (i.e. trade and transformation steps) is, surprisingly, relatively robust across models9. The trade results do differ between CBCA, but this is not the main cause of divergent results4,10,11. In general, results are more significantly more robust at the country level than the product level12.

Comparison work and evaluation of robustness to date, however, has overlooked the main use of CBCA data – the tracking of whether (and by how much) emission accounts are increasing or decreasing over time, and whether these changes are synonymous or different to changes in the territorial account. By analyzing the time trend it can indicate progress toward targets and evaluate whether there has been a growth or decline in emission transfers. At least for the original Kyoto targets under the UNFCCC, they were principally based upon greenhouse gas emissions relative to a 1990 baseline. As emission estimates get revised backwards over time as better accounting methods become available, the importance lies upon having consistency in the data used to estimate change over time. Additionally, focusing on the rate of change of emissions, can partially eliminate differences due to particular modeling details (for example the allocation of bunker fuels).

The purpose of this work is to construct an indexed database across the major MRIO models used today, and to give an understanding of variability across the results. We collect results from five available MRIO models. EXIOBASE (49 regions, high product detail, 1995-2016), WIOD (41 regions, low product detail, 1995-2009), Eora (187 regions, variable product detail, 1970-2015), the OECD ICIO (61 countries, 34 industries, 1995-2011), and the use of GTAP through the results presented in the Global Carbon Project (130 regions, 1990-2015). These five databases are described in more detail below.

In section 2 we present key results in a graphical format, with a short discussion in section 3. In section 4, we outline the methods used to harmonise production based emissions, consumption based emissions and growth rates. The database of harmonised emissions is attached to this article as a supplementary MS-Excel file.

# Results

## Regional results over time

Variation in headline results for large regions are in the order of 5-10% (Figure 1, see dataset for all country results). Indexing results reduces the variation to in general below 5%.

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Figure 1 Multi-model results of production and consumption CO2 account for OECD. a) raw model results; b) after indexing to 2007. Relative standard error across the available datasets plotted on right axis. Note number of available models changes over time and other statistics (quantity and relative absolute difference are available in the dataset)

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Figure 2 Multi-model results of production and consumption CO2 account for OECD. a) raw model results; b) after indexing to 2007. Relative standard error across the available datasets plotted on right axis. Note number of available models changes over time and other statistics (quantity and relative absolute difference are available in the dataset)

## Country level results

As above, most major economies and regions had variations in the order of 5-10% before indexing, and circa 1-2% after indexing. Countries that were highly trade exposed, or with large international transport emissions (e.g. shipping of Greece) showed the highest amount of variability due to the different conceptual coverage used in different MRIO models. For such economies, raw result variability was in the order of 20-30%, and roughly halved after indexing.

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| **Region** | **Prod. Raw RSE** | **Cons. Raw RSE** | **Prod. Index RSE** | **Cons. Index RSE** | **Prod. Raw RAD** | **Cons. Raw RAD** | **Prod. Index RAD** | **Cons. Index RAD** |
| OECD | 3.7 | 4.7 | 0.9 | 0.9 | 3.0 | 3.9 | 0.7 | 0.7 |
| BRICS | 8.8 | 8.4 | 3.1 | 2.9 | 6.8 | 6.3 | 2.2 | 2.1 |
| Annex\_I | 4.8 | 5.6 | 0.7 | 0.7 | 3.9 | 4.5 | 0.5 | 0.5 |
| G8 | 3.4 | 4.1 | 0.7 | 0.8 | 2.7 | 3.3 | 0.5 | 0.6 |
| EU12 | 3.8 | 8.7 | 1.5 | 3.7 | 3.2 | 7.1 | 1.0 | 2.9 |
| North\_America | 6.1 | 4.9 | 1.9 | 1.6 | 4.3 | 3.6 | 1.4 | 1.2 |
| EU28 | 3.9 | 6.7 | 1.1 | 1.3 | 2.9 | 5.4 | 0.8 | 1.0 |
| AUS | 4.0 | 6.1 | 1.9 | 2.8 | 3.0 | 4.2 | 1.4 | 2.2 |
| AUT | 7.3 | 8.3 | 2.0 | 3.0 | 5.3 | 6.1 | 1.6 | 2.3 |
| BEL | 4.3 | 25.4 | 3.5 | 7.7 | 3.1 | 17.6 | 2.6 | 5.6 |
| BGR | 6.0 | 19.9 | 3.7 | 6.6 | 4.7 | 15.9 | 2.5 | 5.0 |
| BRA | 10.6 | 11.4 | 4.8 | 5.7 | 7.9 | 9.0 | 3.5 | 4.0 |
| CAN | 5.7 | 7.5 | 1.9 | 4.9 | 3.9 | 5.8 | 1.5 | 3.7 |
| CHN | 9.1 | 8.5 | 4.8 | 5.7 | 7.2 | 6.1 | 3.5 | 4.5 |
| CYP | 21.8 | 22.2 | 7.6 | 6.8 | 15.2 | 16.8 | 5.6 | 5.1 |
| CZE | 7.2 | 7.1 | 1.9 | 6.1 | 5.0 | 5.3 | 1.4 | 4.3 |
| DEU | 5.2 | 6.7 | 2.3 | 3.1 | 3.8 | 5.4 | 1.7 | 2.5 |
| DNK | 19.1 | 11.0 | 10.2 | 4.1 | 14.5 | 8.2 | 7.5 | 3.2 |
| ESP | 5.7 | 9.2 | 2.9 | 3.5 | 4.6 | 7.0 | 2.1 | 2.6 |
| EST | 7.0 | 15.2 | 7.7 | 8.3 | 5.2 | 11.4 | 5.5 | 6.1 |
| FIN | 4.9 | 13.4 | 2.0 | 7.1 | 3.6 | 10.2 | 1.5 | 5.4 |
| FRA | 3.2 | 8.1 | 1.7 | 2.6 | 2.4 | 5.8 | 1.3 | 2.0 |
| GBR | 4.7 | 6.6 | 2.1 | 3.0 | 3.6 | 5.2 | 1.6 | 2.2 |
| GRC | 32.2 | 26.0 | 3.4 | 9.1 | 22.7 | 20.5 | 2.5 | 6.6 |
| HUN | 4.0 | 12.3 | 2.7 | 9.6 | 3.3 | 9.6 | 2.0 | 6.6 |
| IDN | 6.6 | 5.6 | 5.2 | 5.3 | 4.8 | 4.4 | 3.7 | 4.0 |
| IND | 4.8 | 4.1 | 3.0 | 2.8 | 3.6 | 3.2 | 2.1 | 2.3 |
| IRL | 7.2 | 10.1 | 4.2 | 5.8 | 5.3 | 8.1 | 3.2 | 4.5 |
| ITA | 4.5 | 6.4 | 4.6 | 3.5 | 3.5 | 4.9 | 3.3 | 2.6 |
| JPN | 5.2 | 7.6 | 1.3 | 2.6 | 4.2 | 6.2 | 0.9 | 1.9 |
| KOR | 4.4 | 10.6 | 1.9 | 5.3 | 3.5 | 8.3 | 1.4 | 4.1 |
| LTU | 7.2 | 20.1 | 4.6 | 7.7 | 4.9 | 15.0 | 3.3 | 5.6 |
| LUX | 19.8 | 38.0 | 12.3 | 20.7 | 14.0 | 29.3 | 9.0 | 14.9 |
| LVA | 13.7 | 15.6 | 4.1 | 6.0 | 9.4 | 12.0 | 3.2 | 4.5 |
| MEX | 6.2 | 6.5 | 3.0 | 3.8 | 4.8 | 5.2 | 2.1 | 2.9 |
| MLT | 8.8 | 29.0 | 4.7 | 16.2 | 6.5 | 21.2 | 3.7 | 11.6 |
| NLD | 4.9 | 13.2 | 2.0 | 7.1 | 3.8 | 9.8 | 1.6 | 5.3 |
| POL | 3.5 | 6.8 | 2.1 | 4.1 | 2.7 | 5.3 | 1.5 | 3.1 |
| PRT | 5.5 | 11.2 | 3.5 | 4.6 | 4.2 | 8.6 | 2.5 | 3.4 |
| ROU | 5.9 | 8.1 | 3.6 | 5.7 | 4.6 | 6.2 | 2.7 | 4.2 |
| RUS | 6.1 | 13.2 | 1.6 | 6.3 | 4.3 | 10.2 | 1.2 | 4.9 |
| SVK | 9.9 | 28.1 | 3.2 | 5.9 | 7.3 | 20.5 | 2.5 | 4.4 |
| SVN | 5.1 | 7.5 | 3.4 | 3.6 | 4.0 | 5.6 | 2.4 | 2.7 |
| SWE | 5.4 | 9.2 | 4.7 | 4.2 | 4.2 | 6.8 | 3.7 | 3.0 |
| TUR | 7.1 | 10.2 | 2.4 | 3.6 | 5.8 | 7.8 | 1.7 | 2.8 |
| TWN | 5.7 | 16.8 | 3.9 | 8.3 | 4.1 | 11.8 | 3.0 | 5.7 |
| USA | 4.1 | 3.7 | 1.2 | 1.4 | 2.8 | 2.7 | 0.8 | 1.0 |

## All results

The naïve (unweighted across all regions) average of the relative standard error over all model observations was 11% for the production account, and 14% for the consumption account. This is prior to the indexing of the production emissions. After indexing to a common base year the naïve average relative standard error drops to 1% for the production account and 4% for the consumption account.

Figure 2a provides a complete plot of all observations of raw data for both production and consumption accounts (i.e. one data point per country per year), along with linear least-squares curve fitting. Outliers exist for a range of Eastern European countries in prior to 1990. Figure 2b, provides a zoom of the range of results below a relative standard error of 20%.

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**Figure** 3 Relationship between relative error and absolute emissions for 41 common regions across the MRIO models, relative error taken in comparison to the multi-model mean (1995-2015).

Comparing growth rates rather than absolute emissions there is an improved agreement across the MRIO models (Figure4). Interestingly, we obtain much higher levels of convergence for large economies after calculating growth rates and indexing to 2007. This is particularly notable for the consumption based account, where RSE of the model outcomes drops to below that of the production based account for the largest emitters.

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**Figure** 4 Relationship between relative error and absolute emissions for 41 common regions across the MRIO models, both raw model results and after indexing. Relative error taken in comparison to the multi-model mean (1995-2015).

# Discussion

This work provides a harmonized emissions database collecting CBCA results from five current leading MRIO models. Results are presented at national level for both production and consumption perspectives. All major economies available across the MRIO databases were included, as well as regional aggregates. The database is intended to help disseminate project based results, and by harmonizing across models, gives the longest time-span to date of the MRIO results. In general, the model results are in good agreement (less than 10% deviation). Exceptions to this generally occur for highly trade exposed countries, early years in the time series (prior to 1990) where only 1-2 models inform results, and in the early 1990s in countries affected by the breakup of the USSR. The database contains both harmonized values using the average growth rates of model outcomes, as well as statistical measures of variation across the models.

# Methods

## Data sources

We collected five of the current leading MRIO models that provide CBCA carbon footprint results. We focus on CO2 emissions from fossil fuel combustion, although the Global Carbon Project inventory also includes emissions from cement production. Emissions from cement production are ~2% of global CO2 emissions but can be a larger fraction in some cases, e.g. they have been estimated to account for up to 5% of total emissions in China in some years.

We compare results at the national level. The MRIOs have different degrees of sectoral detail, ranging from none (Global Carbon Project) to a heterogeneous level of detail per country (Eora), to consistent high resolution for a limited set of countries (EXIOBASE), so this is not considered in this work.

Here we summarize the five MRIOs that are included:

**EXIOBASE**

The EXIOBASE database covers 44 countries and 5 rest of world regions, and in each region has 163 industries and 200 product categories. It includes sector-specific data for gross energy use, emission relevant energy use, and gross energy supply for around 60 energy products, and has air emission data for 27 types of air emissions (combustion as well as non-combustion). It covers the years 1995 to 2011, as a basis, but has been extended to 2015 13,14. The energy and emission accounts in EXIOBASE follow Eurostat’s guidelines 15 and the UN SEEA accounting standards 16 . The energy accounts are based on data IEA’s energy balances. The IEA energy balances are given in the territorial principle but are converted to the residential principle by means of Eurostat’s bridge tables17 and auxiliary transport models. As documented in the EXIOBASE methodology papers, emissions related to combustion were calculated by multiplying emission relevant energy use data with emission factors obtained from the TNO Emission Assessment Model18

**Eora**

Eora is a global MRIO database with 187 individual countries. It uses variable sectoral resolution from 26 to ~500 sectors for a total of 15909 sectors. Using heterogeneous classifications in each country allows the system to preserve national IO table detail wherever possible. Eora covers the period 1970-2015. The monetary MRIO tables are complemented with satellite accounts containing physical data at a detail of 35 indicator groups19,20. The Eora database uses a constrained optimisation approach to construct an emissions inventory. The primary datasource is the EU JRC Emissions Database for Global Atmospheric Research (EDGAR) database of GHG emissions, but national and international data are also used as constraints where available. The emission inventory is not converted into the residence principle. The emissions are first allocated to sector groups according to emissions category, then within those groups allocated to subindustries according to industry output.

**WIOD**

The World Input-Output Database (WIOD) covers 40 countries and a single rest of the world region. It uses a homogenous sector classification with 35 industries in each country21. WIOD is built by combining information from national statistic institutes and UN COMTRADE. The WIOD database covers the period 1995-2011.

WIOD’s environmental accounts include data on energy, air emissions, materials extraction, land and water use, but cover only the period 1995-2009. Per-sector energy data is provided, in addition to gross energy use and emission relevant energy use22. The energy and emissions data is presented according to the residence principle. The construction methods and data sources for emission accounts vary by country. The preference is data from National Accounting Matrices including Environmental Accounts (NAMEA). When that is not available, inventories are constructed based on the energy-first approach, and by applying emission factors. For EU countries, emissions datasets are from Eurostat. For non-EU countries, international air emissions inventories from the UNFCCC, EDGAR and Convention on Long-Range Transboundary Air Pollution (CLRTAP) are used. For CO2, emission factors were taken from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories or the UNFCCC.

**ICIO**

The OECD inter-country input-output (ICIO) table is a symmetric input-output table covering 61 countries and the rest of the world, with 34 sectors of detail, for the years 1995-201123. ICIO’s main data sources are OECD and UN SNA data, national IO/SUTs, OECD COICOP consumption data, OECD tourism satellite accounts, UN Comtrade and OECD ITCS and trade in services estimates. ICIO uses the IEA CO2 from fuel combustion data to estimate the CO2 emissions by industries. The IEA fuel combustion data is based on IEA energy balances 24 combined with the IPCC Guideline emission factors25. In most cases emissions can be straightforwardly allocated to matching ICIO industry. In the cases that emissions categories correspond to more than one ICIO industry, those emissions are pro-rated according to sectoral gross output, in monetary terms. Emissions from autoproducers, other energy industry own use and emissions by transport are allocated to industries using emissions by fuel type information from the energy balances.

**GCP**

Global Carbon Project provides production and territorial emissions accounts for 114 countries. For production-based accounts the database covers the period 1959-2016. For consumption-based accounts the database covers the period 1990-201526 . GCP consumption based accounts are built starting from the GTAP8 database 27, and then extrapolated to estimate an emissions time series dataset28 . The construction process for this is described in detail by Peters et al.1[. GCP provides economic data for 140 countries at a resolution of 57 sectors.](#_ENREF_48) GCP also contains per-sector energy volumes and CO2 emissions from combustion for 5 emission-related energy products. GCP’s emissions data are benchmarked the CIDIAC and EDGAR emissions databases to interpolate an emissions timeseries.

## Emission calculations

Production-based emissions were extracted from the MRIO databases directly. Eora, and GCP provide CBCA results per country calculated by the authors of the MRIO. For EXIOABSE, ICIO, and WIOD, CBCA results were calculated using the standard Leontief demand model29.

The production account (emissions by country of origin) **f** can be represented as the sum of sectoral, *j*, CO2 emissions **F** plus the direct householdCO2 emissions **fy** (where for ease of manipulation, each country, *r*, emissions are represented on different rows, so Whilst the consumption account by country **d** represents emissions attributed to final demand of a country. The standard Leontief production function is used to attribute emissions to final demand:

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|  | Eq 1 |

Where **A** is the inter-industry matrix in MRIO models, and **s** is the sector specific emissions () per unit output, and **Y** is the final demand for all countries. We then obtain two databases of **D** and **F** of dimension time \* country \* model.

With five databases, the number of observations in a statistical sense is small. Nevertheless, the comparison 1) provides some indication of deviations between models in terms of absolute values and 2) allows to compare temporal trends across models. Although the absolute value might me the most general indicator available, the temporal trends are of higher policy importance as they allow to track improvements over time. The directional value can be calculated from chained growth rates, or can be taken with reference to a fixed year. In this work, we take chained growth rates which perform better further from the reference year, but are more subject to differences in annual fluctuations.

We thus define two growth rate variables, and, that relate emissions to previous year emissions:

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|  | Eq 2 |

and

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|  | Eq 3 |

For each region of interest, we then calculate mean and standard error of raw data and of growth rates. In addition, number of observations and relative absolute difference is calculated.

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| Variable: | Mean | Standard error | Comment |
|  |  |  | Production accounts, absolute value |
|  |  |  | Consumption accounts, absolute value |
|  |  |  | Growth in production accounts |
|  |  |  | Growth in consumption accounts |

Emission calculations are performed across a set of 41 countries and 7 regions (see appendix), focusing on variance in results from 1990-2016, albeit stretching back to 1960 (because of the lack of multiple model results for earlier years, exploring variance has no meaning). Whilst in general, the MRIO models provide the necessary detail for the country level results, some databases do not provide the necessary resolution for regional results (e.g. EXIOBASE misses Argentina and Saudi Arabia from the G20). In this case, the results are scaled by contribution to GDP.

The harmonized production and consumption accounts are then taken as the mean growth rate relative to the mean of the model outcomes for the benchmark year in 2007 (the year of consistent model coverage).

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| Hence, for harmonizing since 2007 (*t*>2007), | Eq 4 |
| And prior to 2007 (*t*<2007): | Eq 5 |
|  | Eq 6 |

And likewise for the production account.

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