



# A new consumption-based accounting model for greenhouse gases from 1948 to 2012



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## ABSTRACT

Greenhouse gas emissions embodied in international trade have grown rapidly as globalization has progressed and potentially threaten the efficacy of unilateral climate treaties such as the Kyoto Protocol. Consumption-based methods have been put forward as a way of overcoming this issue and help design future climate policies. We improve the Long-term Consumption-based Accounting (LCBA) model, with transfer carbon data from 1948 to 2012 by introducing country-specific import intensities and detailed bilateral trade data from UNcomtrade. Comparisons of our new “LCBA2” model with existing 4 studies show similar consumption based emission patterns both in trend and magnitude, and significant emission changes in many European countries. The results independently confirm previous findings on the efficacy of the Kyoto Protocol. The results indicate transferred emissions have contributed an historic 36 Gt CO<sub>2</sub> of cumulative emissions, have grown rapidly during the past 30 years (up to 8% of total emissions) and are likely to become increasingly influential in the near future as the global economy recovers. We also use the improved model to study other gases (CH<sub>4</sub>, N<sub>2</sub>O and SO<sub>2</sub>) embodied in trade, and results indicate similar transfer patterns as CO<sub>2</sub> with comparable or even moderately larger magnitudes. Across-method result differences between LCBA2 with 3 other models are analyzed based on using common input datasets. Large emitters show moderate biases (within 10%) and about 75% of countries have differences within 25%, independent of input dataset. The LCBA2 model provides useful estimates of transferred emissions in both across-country and long-term historical contexts.

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## 1. Introduction

A growing number of countries have implemented policies to regulate carbon emissions within their borders. However, the true impacts of these policies have been questioned due to soaring trade interactions and emission transfers among countries (Peters and Hertwich, 2008; Aichele and Felbermayr, 2012; Andrew et al., 2013; Kanemoto et al., 2014). These phenomena are often called carbon leakage (Peters and Hertwich, 2008; Davis and Caldeira, 2010; Jakob et al., 2014) and can be induced by both “policy” (strong carbon leakage) and “consumption” (weak carbon leakage). Although strong carbon leakage and the relevant “pollution haven

hypothesis” are of serious concern, ex post econometric studies do not show statistically significant evidence of them (Branger and Quirion, 2014). Weak carbon leakage, however, is broader in concept, unrelated to policies, and often triggered by comparative advantages, endowments and factor productivity in different countries (Weber and Peters, 2009; Peters et al., 2009; Jakob and Marschinski, 2013). In this study, we focus on weak carbon leakage and attempt to analyze the transferred emissions embodied in trade and their long-term patterns. These emissions are shown to be a significant factor in explaining emission changes in many countries (Nakano et al., 2009; Davis and Caldeira, 2010; Peters et al., 2011b), especially for large emitters such as China (Weber et al., 2008; Guan et al., 2009; Minx et al., 2011), the USA (Weber and Matthews, 2007) and the UK (Baiocchi and Minx, 2010; Wiedmann et al., 2010; Barrett et al., 2013). Recent studies also indicate that the Kyoto Protocol may be failing to fulfill its carbon-

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reduction purpose (Aichele and Felbermayr, 2012; Peters et al., 2011b; Kanemoto et al., 2014) due to these ever growing emission transfers. Although there are doubts and critiques regarding the use of transferred and consumption-based emissions in future policy design, such as efficiency (Steckel et al., 2010), insourcing nature (Liu, 2015), justice and cost-effectiveness (Steininger et al., 2014), responsibility attribution (Jakob and Marschinski, 2013) and leakage settlement (Jakob et al., 2013, 2014), the accounting method itself is a useful complement to the current production-based system and can provide a solid foundation upon which to settle these debates in the future.

Most empirical research on consumption-based emissions and emission transfers has been implemented using Multi-Regional Input-output (MRIO) models (Peters and Hertwich, 2004; Lenzen et al., 2004; Peters et al., 2011a; Kanemoto et al., 2014) and has focused on specific years (Peters and Hertwich, 2008; Nakano et al., 2009; Davis and Caldeira, 2010; Davis et al., 2011; Andrew et al., 2013). The very large data requirements limit the ability of the input–output framework to track changes over time (Peters et al., 2012a, 2011b; Caldeira and Davis, 2011; Miller and Blair, 2009). Due to recent advancements in constructing MRIO databases (Tukker and Dietzenbacher, 2013; Dietzenbacher et al., 2013; Andrew and Peters, 2013; Meng et al., 2013) and comparison work (Inomata and Owen, 2014; Moran and Wood, 2014; Owen et al., 2014; Arto et al., 2014; Geschke et al., 2014), some studies have transcended this limitation and conducted time series analyses at the global scale over the period from 1990 to 2010 (Peters et al., 2011b, 2012b; Caldeira and Davis, 2011; Wiebe et al., 2012; Lenzen et al., 2012, 2013; Arto et al., 2012). Peters et al. (2011b) developed a time-series algorithm (TSTRD) to achieve long time series with trade data to estimate consumption-based emissions successfully. Wiebe et al. (2012) set up the Global Resource Accounting Model (GRAM) using linear interpolation to fill in missing

it can be used to set up new scenarios of consumption-based emissions in contrast to the territorial ones for different countries/groups. And these scenarios can be used as external forcing data and be put into climate models in order to research the climatic impact of transfer emissions (Wei et al., 2012, 2016). To further backdate these data, Yang et al. (2015) set up a new framework called LCBA (Long-term Consumption-based Accounting model) for estimating historical emission transfers since 1948. However, the LCBA model ignored regional disparities merely assuming global averages for “importation intensity”, which affects the credibility of the results. We address this problem here by grouping countries using a hierarchical clustering method based on their emissions per GDP and dynamic time warping algorithm, and increased use of bilateral trade data from the UNcomtrade database (UN, 2014). We show results for 164 countries over the period from 1948 to 2012 (Table S1–S2). Furthermore, we show that the improved LCBA model (hereinafter LCBA2) is effective in calculating transfers of non-CO<sub>2</sub> greenhouse gases (e.g. CH<sub>4</sub> and N<sub>2</sub>O, 1970–2011, Tables S3–S4) and air pollutants (e.g. SO<sub>2</sub>, 1948–2005, Tables S5–S6). These new results from LCBA2 independently confirm previous findings on the efficacy of the Kyoto Protocol. Although our error analysis shows that results are greatly influenced by the calculation framework even after harmonization of territorial emissions, for large emitters, differences among datasets are always within ±10%.

## 2. Materials and methods

### 2.1. LCBA2 model

This study improves the original LCBA model described in Yang et al. (2015):

$$\begin{aligned}
 F_{Cr}(r, i) &= F_{Pr}(r, i) + COEF_{im}(r, i) * Imports(r, i) - COEF(r, i) * Exports(r, i) \\
 s.t. \sum_r (COEF(r, i) * Exports(r, i)) &= \sum_r (COEF_{im}(r, i) * Imports(r, i)) \\
 \sum_r F_{Pr}(r, i) &= \sum_r F_{Cr}(r, i)
 \end{aligned} \tag{1}$$

data in input–output and final demand tables. Lenzen et al. (2012, 2013) developed a long term MRIO database (called EORA, which provides a completely harmonized and balanced world MRIO table) by specifying initial estimates and applying a quadratic programming approach to balance external constraint information such as merchandise trade, aggregate data and input–output tables. Kanemoto et al. (2014) further extend the EORA database to backdate consumption-based emissions to 1970. Arto et al. (2012) estimated the 1995–2008 resource use footprint of nations using the traditional MRIO method based on the World Input-Output Database (WIOD) project Timmer, 2012, Dietzenbacher et al., 2013). All these studies help backdate historical data, facilitate the establishment of regular carbon footprint monitoring schemes and provide the foundation to complement the current production-based accounting system.

Previous research based on MRIO databases constructs carbon emission transfers beginning in 1990, limiting our understanding of the spatial and temporal patterns of transferred emissions. Therefore, long term (over 60 years) transferred emission data is needed. Not only because it can display long term patterns, but also because

Where  $F_{Cr}(r, i)$  and  $F_{Pr}(r, i)$  represent the consumption-based and production-based emissions for country  $r$  in year  $i$ , respectively.  $Imports(r, i)$  and  $Exports(r, i)$  are the annual trade of goods and services from each country  $r$ .  $COEF(r, i)$  is the “production intensity” estimated (CO<sub>2</sub> emissions per unit of “Gross Productive Output”) for country  $r$  in year  $i$ . This is a compound indicator which represents changes of emission factors, technology, energy uses and production method etc (SI Section 1). “Gross Productive Output” equals GDP plus imports minus “imported elements” (Yang et al., 2015).  $COEF_{im}(r, i)$  refers to “importation intensity” which is calculated based on “production intensity” estimates. The constraints in Equation (1) mean that in each year the total imports equals exports of embodied emissions, and also that total territorial emissions equals consumption-based emissions. This “substance conservation” is achieved in each simulation by setting importing and consumption-based emissions to exporting and territorial ones respectively (SI Section 2). Theoretically speaking, LCBA2 resembles a simple version of EEBT-style Multi-regional input-output model (Peters, 2008) without sectoral details (SI Section 1).

Instead of using a globally uniform “importation intensity”  $COEF_{im}(i)$  for all countries as in original LCBA model (Yang et al., 2015), we first classify 164 countries into 3 groups (SI Section 3) using a hierarchical clustering method based on a dynamic time warping (DTW) algorithm. The “importation intensities” for the 22 largest importing countries (SI Section 4) are then weighted using their import distribution between these 3 groups, while the remaining countries are weighted according to their mean global imports share. These 22 countries are all large developed or developing countries and they contribute 60%–77% of total imports each year during 1948–2012. What is more, their bilateral imports data are recorded much better and normally over a longer time span in the UNcomtrade database than those for other countries.

Therefore, two crucial issues in the LCBA2 model are to estimate the “production intensities” and the “importation intensities”. Because it is difficult to separate the various imported elements that comprise final use items, GDP is treated as lower-bound of “Gross Productive Output” (domestic elements in final use items plus exports, see Yang et al., 2015) and GDP plus imports is treated as the upper-bound. Combining these boundaries with production-based emissions gives bands of estimated “production intensities”. We implement a Monte Carlo approach to choose particular  $COEF(r,i)$  from within these bands and calculate consumption-based emissions for all 164 countries and 64 years in each trial simulation. We typically run 10 000 simulations in the Monte Carlo ensemble and use the 2.5% and 97.5% quintiles as upper and lower bounds of the 95% confidence interval of the median estimate.

Using these  $COEF(r,i)$  estimates, we replace globally uniform mean  $COEF_{im}(i)$  with weighted group averages  $COEF_{im}(r,i)$  via three steps. Firstly the DTW algorithm separates the countries into 3 groups. Group 1 consists mainly of developed countries in North America and Western Europe. Group 2 includes developing countries in Eastern Europe, Central Asia and China. Group 3 comprises the remaining countries. Secondly, the “production intensity” for each group is calculated as the group mean based on  $COEF(r,i)$  estimates in each simulation. Thirdly, the importation intensities for each of the 22 largest importers are weighted based on their shares of imports among these 3 groups. Other countries are weighted using the global average imports shares.

Fig. 1 demonstrates that the uniform importation intensities, as used in the original LCBA model, differ from the new intensities in LCBA2. Group 1 intensities are dramatically underestimated prior to 1980 and then slightly overestimated. Group 2 emission intensities are greatly underestimated for much of the period after 1950. Group 3 emission intensities are overestimated until approximately 1970 and are subsequently slightly underestimated.

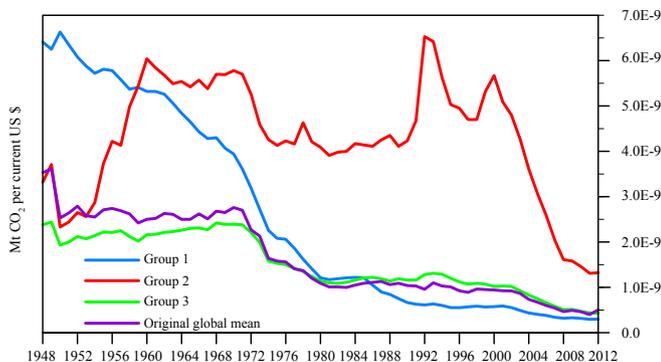


Fig. 1. Comparison of Average Emission Intensities (Mt CO<sub>2</sub> per GDP in current US \$) in 3 Groups and the Original Global Mean. Original Global Mean is the uniform importation intensity for all countries used in the original LCBA model (Yang et al., 2015).

These obvious differences suggest utilizing grouping improves the LCBA2 model.

## 2.2. Sources of data

Merchandise trade data from 1948 to 2012 and service trade data from 1980 to 2012 were obtained from the World Trade Organization (WTO) based on the “general trade” recording system (WTO, 2014). Services trade data before 1980 were supplemented by BPM 5 (Balance of Payments, version 5) datasets from the International Monetary Fund (IMF, 2014). The departure point of 1948 was chosen because the GATT (General Agreement on Tariffs and Trade, the predecessor of WTO) was founded in that year, which marks the start of long-term and consistent trade statistics. Exports were valued at FOB (free on board) price, imports at CIF (cost insurance and freight) price and they were all counted in current US dollars. Detailed bilateral trade data between countries comes from the UNcomtrade database (UN, 2014).

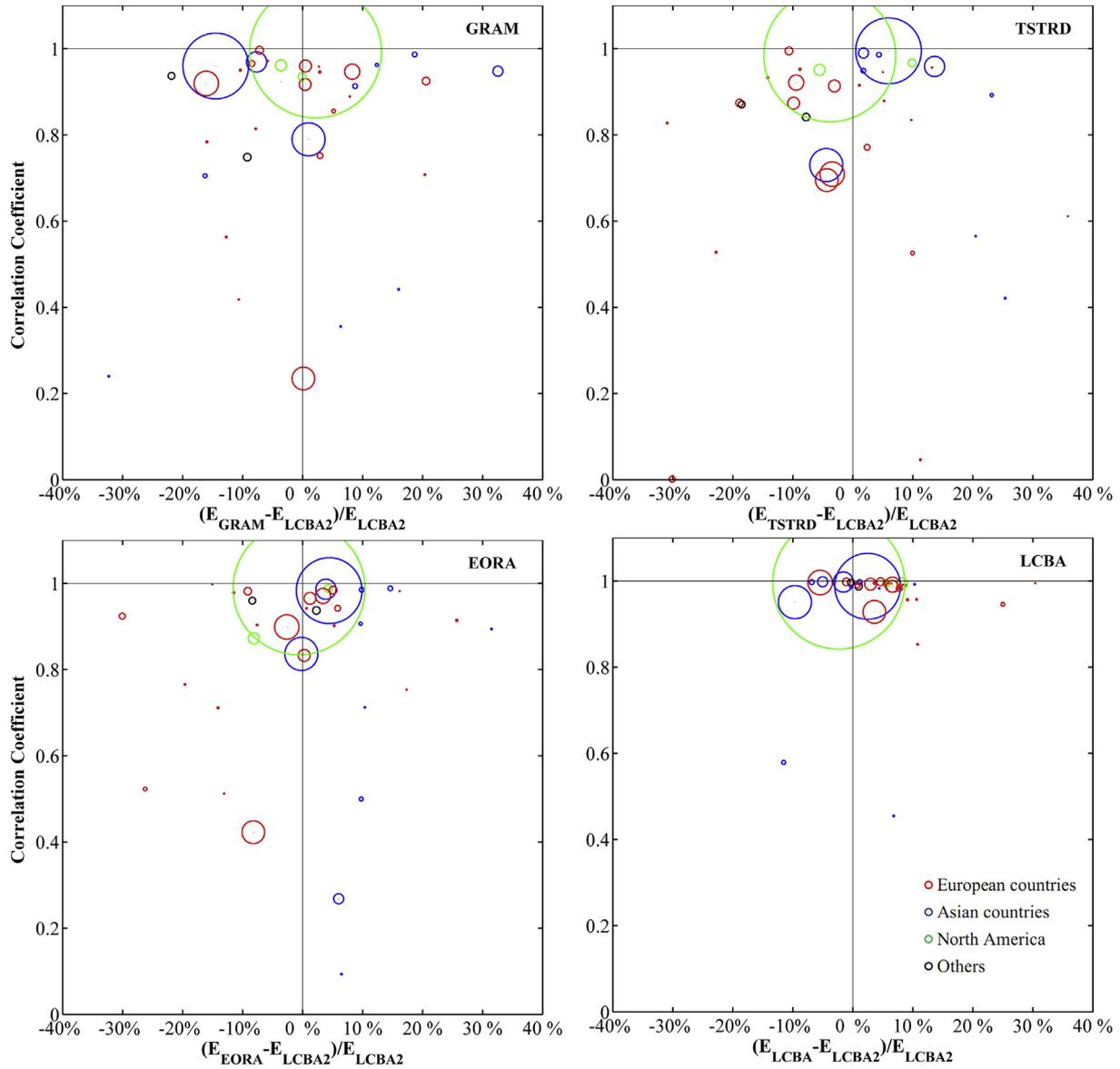
Nominal GDP (gross domestic product) in current US dollars (1960–2012) was derived from the World Bank WDI (World Development Indicators) database (World Bank, 2014). GDPs before 1960 were calculated using 2 methods: (1) For the 52 largest emitters, which had an average consumption-based emissions between 1990 and 2008 greater than 50 Mt (Peters et al., 2011b), 1948–1959 GDPs were backdated using the real growth rates, the per capita growth rates and the population growth rates based on specific historical studies (Yang et al., 2015). (2) For the remaining countries, the real growth rates are estimated from Maddison’s historical PPP GDP (GDP converted to international dollars using purchasing power parity rates) data (Maddison, 2010).

Production-based CO<sub>2</sub> emissions comprised those emitted from fossil fuel combustion and cement production. Data on fossil fuels and cement production from 1980 to 2012 were taken from the U.S. Energy Information Administration (EIA) and the Carbon Dioxide Information Analysis Center (CDIAC), respectively (Boden et al., 2013; EIA, 2014). Because cement production data from the CDIAC ends in 2010, average values for the past 3 years were used to extrapolate the data for 2011 and 2012. Data before 1980 were supplemented with total emissions from the CDIAC. Production-based emissions of CH<sub>4</sub> and N<sub>2</sub>O came from the EORA database (Lenzen et al., 2012, 2013). SO<sub>2</sub> emission data have 2 sources: the Socioeconomic Data and Applications Center (SEDAC, Smith et al., 2011a, b) and EORA database. All the details in data sources are fully listed in SI Section 5.

## 3. Results and discussion

### 3.1. Comparison of transfer emission results with the other 4 methods

The 37 largest most significant countries included in all 5 methods (GRAM, TSTRD, EORA, LCBA and LCBA2), are compared in Fig. 2 and Table S7. It is clear that most data points in TSTRD and GRAM are within ±20% of LCBA2 with smaller differences of about ±10% for EORA and LCBA. The differences between LCBA2 and LCBA are the smallest, as may be expected. Both TSTRD and EORA show lower emissions than LCBA2 for European countries. LCBA2 gives smaller emissions than EORA, GRAM and TSTRD for south-east Asian countries (Indonesia, Philippines, Thailand and Malaysia). LCBA2 gives smaller emissions for most European countries, and larger values for five important trade partners in China (namely the US, Japan, India, South Korea and Russia) than those in LCBA. Time series correlations between LCBA2 and the other methods are above 0.85 for most countries ( $p < 0.05$ ;



**Fig. 2.** The differences between LCBA2 results and those in 4 other methods (EORA, GRAM, TSTRD and LCBA) for 37 countries over the period 1995–2005. The horizontal axis represents the average emission (for 1995–2005) percentage differences, while the vertical axis indicates the time series correlation coefficients. Colors represent geographical country location and the size of the circle is proportional to the average consumption-based emissions in LCBA2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

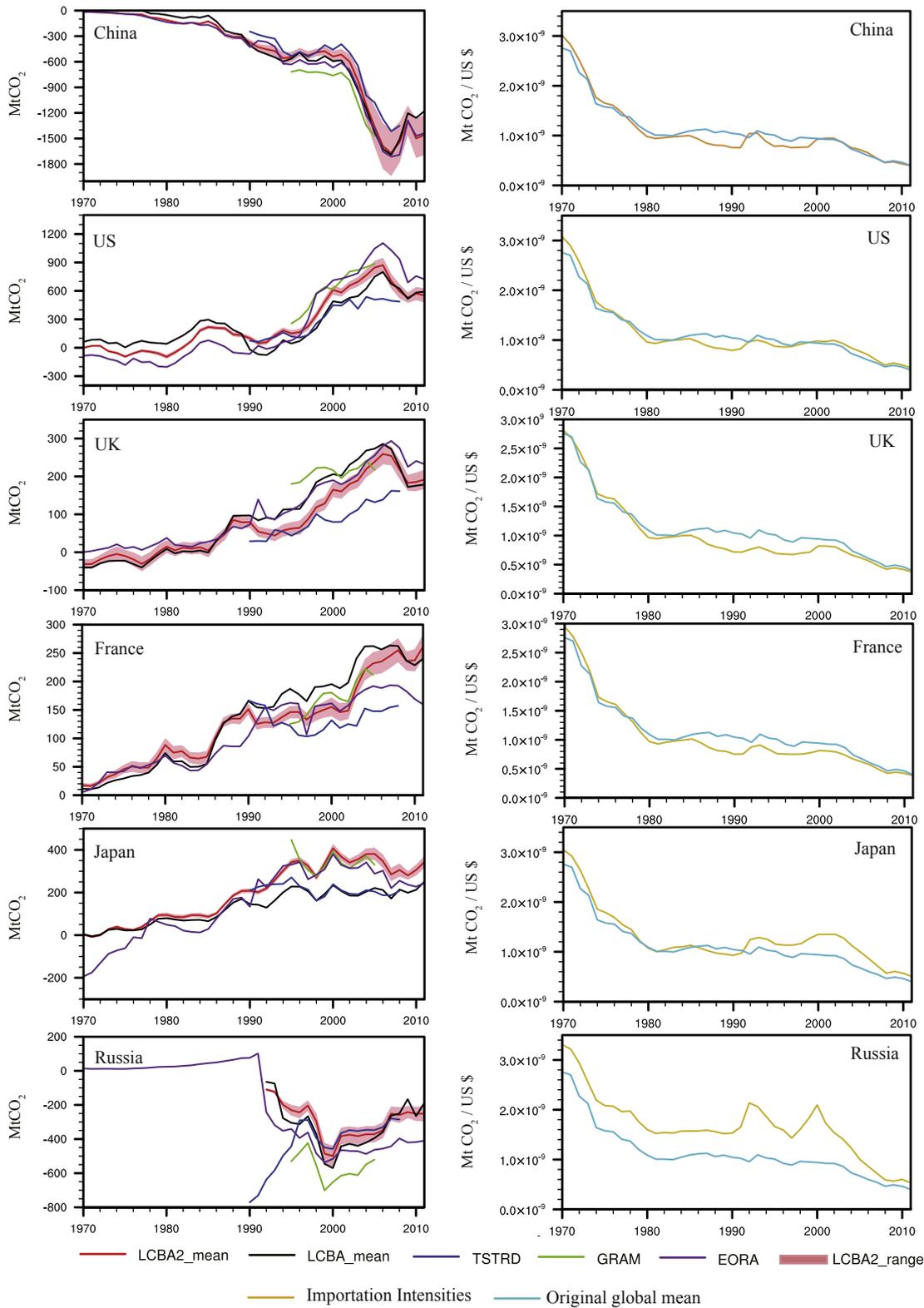
Table S7). In short, the new results in LCBA2 are similar to the existing four methods for large trading economies, but differences of  $\pm 20\%$  both in trend and magnitude are commonplace among the wider set of countries.

Patterns over 1995–2005 for six countries and each method are shown in Fig. 3. Changes in the times series of LCBA2 compared with LCBA reflect similar time variability in importation intensity for China's important trade partners (e.g. Russia and Japan) and many European countries (e.g. UK and France), as shown in Fig. 3. Disparate patterns between the two variables do also occur, for example China around 1995 and the US in 1990–2000 (Fig. 3). The changes in importation intensities in these cases should have increased the transfer emissions whereas the opposite occurred; this may be explained by the “conservation condition” applied in LCBA2 (Equation (1)). LCBA2 time series are very similar to LCBA except for Hong Kong and Singapore (two main trading economies) which changed dramatically. The main differences between LCBA2

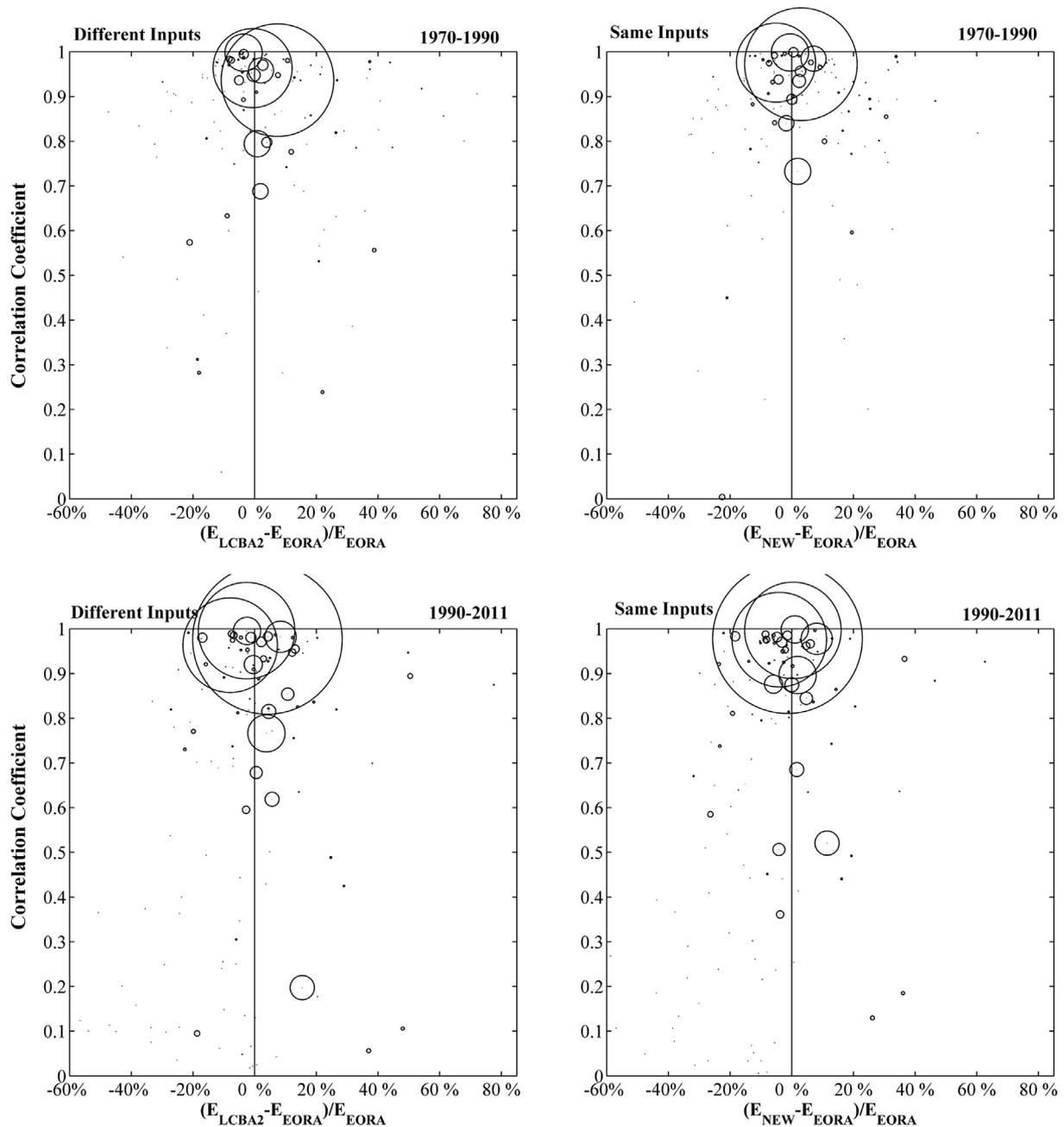
and LCBA emissions are due to the new group method and use of the UNcomtrade bilateral data.

### 3.2. Across-method differences

Because the executable files for the EORA, TSTRD and GRAM methods are not publically available, we assess the across-method differences by using each of their input territorial emission datasets in the LCBA2 method. For instance, consumption-based emissions for 127 countries over the period 1970–2011 and 1970–1990 have been estimated using EORA territorial emissions and can be compared with the results from the LCBA2 (Fig. 4 and Table S8). While using the same emission data does reduce the relative differences in the results, and improves the correlation between the time series, large differences still exist for many countries. Using the same input, 45% countries have differences below 10% including all the largest



**Fig. 3.** Emission transfer (left column) and Importation intensity (right column) changes for six countries since 1970. The emission transfers come from the LCBA2 model (mean values and ranges), the original LCBA model (mean values) and 3 earlier models (TSTRD, GRAM and EORA). The importation intensities are the original global mean in LCBA and new ones in LCBA2.



**Fig. 4.** The differences between LCBA2 results and those in EORA for 127 countries for 1970–2011 (top row) and 1990–2011 (bottom row), with the left column having different method input datasets and the right sharing the same EORA dataset. The horizontal axis shows the average emission percentage biases, while the vertical axis indicates the time series correlation coefficient.

emitters, and around 70% show average emission differences within  $\pm 20\%$  (Table S8). Correlation coefficients (Fig. 4), rise when using the same inputs, especially in the period 1970–1990 for the smaller countries. Whether use the same inputs or not, correlations are always above 0.8 for most countries and the values are above 0.9 for many large economies in both periods. From the single year perspective, 2005 is used as example to demonstrate the country-by-country distribution of consumption-based emission differences in Fig. 5, and does not significantly change with the same input datasets. Over 80% countries have differences between methods within  $\pm 25\%$ , and for the largest emitters (such as the US, China, India and Russia) the biases are often below  $\pm 10\%$  whether the same input data is used or not.

Similar analyses can be done for TSTRD with 92 countries over the period 1990–2008 (SI Section 6 and Table S9). The average emission differences between LCBA2 and TSTRD are within  $\pm 10\%$  for half of the countries, especially for large emitters, and below  $\pm 20\%$  for 70% countries. Many big emitting country differences in 2005, are improved after using the same inputs, however, the whole distribution pattern is not changed: nearly 3/4 countries have differences less than  $\pm 25\%$  and the large economies are within  $\pm 10\%$ . For GRAM, 51 countries over the period 1995–2005 (see SI Section 6 and Table S10), nearly all the countries are within  $\pm 25\%$  of LCBA2, and all large emitter have differences below  $\pm 10\%$  except for Russia (20%) and South Korea (24%). No significant improvement in correlation coefficients occurs for common input data. Large emitters tend to have correlation coefficients around 0.9 and

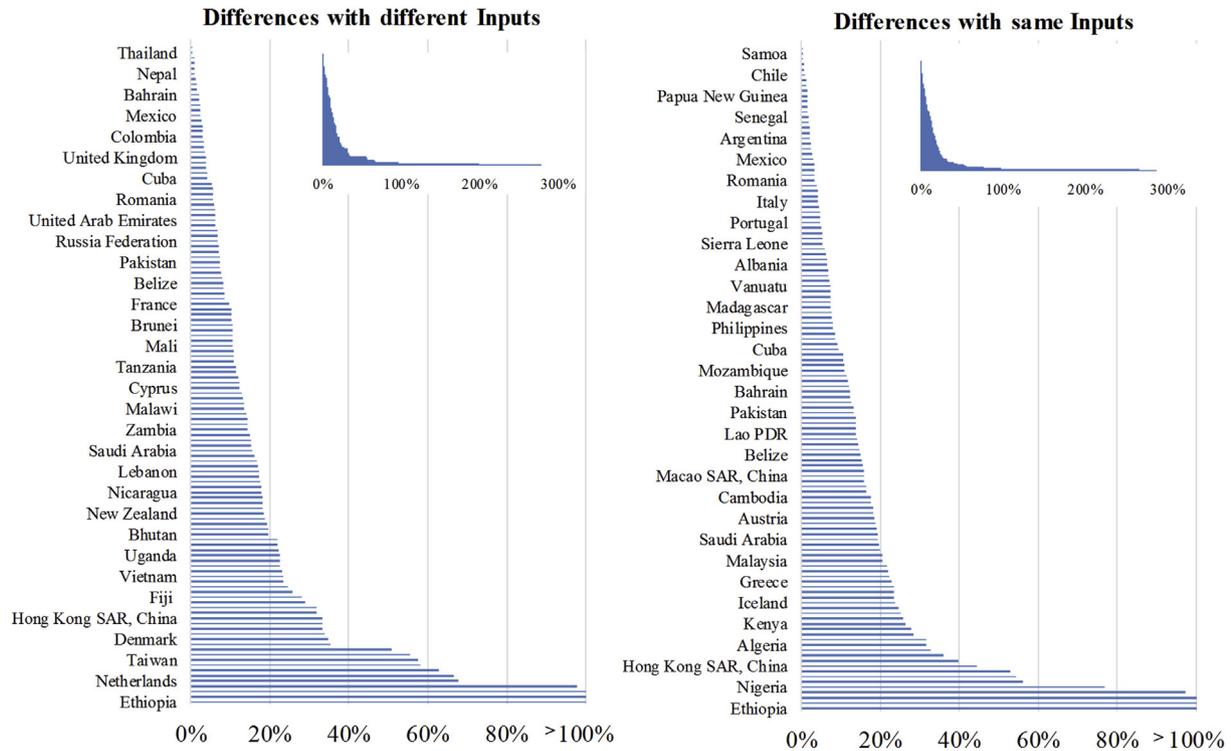


Fig. 5. The distribution of differences in consumption-based emissions for EORA and LCBA2 using different (left) or the same (right) input territorial emissions for 2005. The inset figures demonstrate the whole range while the main plots reveal the distribution within 100%.

70% countries have correlations above 0.7 whether the using the same data or not, and the 2005 year analysis share similar responses as TSTRD and EORA.

In summary, using the same input data in 3 methods reduces emissions differences between methods, but is relatively minor compared with intrinsic across-method differences both as time series and for single years. Large emitters tend to have average emission differences within  $\pm 10\%$  and 70% or more countries have values within  $\pm 25\%$ . Therefore, it is the calculation framework (the matrix in GRAM, EORA, TSTRD and the GDP, trade data in LCBA2) that causes the primary differences among different methods.

### 3.3. Transfer CO<sub>2</sub> emissions estimates over the long term

Since 1948, strikingly large increases in transferred emissions steadily occurred except for 2009, contributing 6.5%–28.6% of

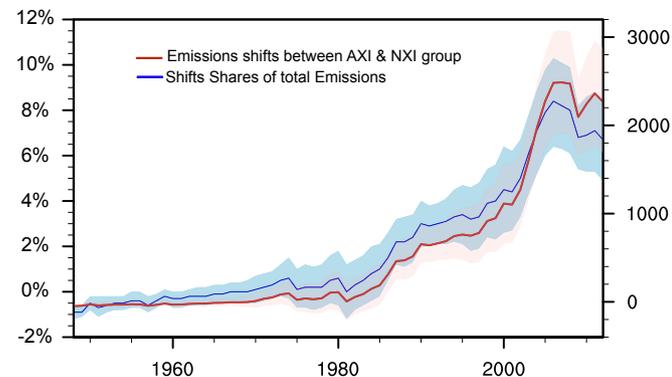
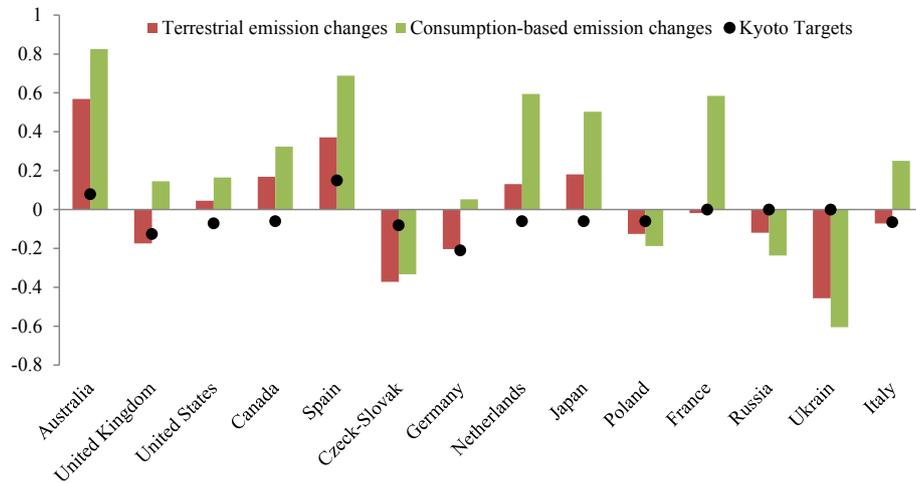


Fig. 6. Shift in share (left vertical axis) of total emissions and CO<sub>2</sub> emission transfers (in million metric tons, right vertical axis) between AXI and NXI parties from 1948 to 2012.

annual territorial emissions. The LCBA2 results indicated that cumulative emissions transferred between ANNEXI (AXI) and non-ANNEXI (NXI) group (as declared in Kyoto Protocol) reached as much as 36 [22–49] Gt in 2012. Transferred emissions for the 1948–1990 period contribute approximately 8% [–7% ~ 15%] to this cumulative volume. This share indicates that transferred emissions in 1948–1990 period cannot be simply ignored in future historical emission accounting even though trade volumes were relatively limited in that period. This is especially true when we try to simulate climate impacts of transfer emissions using long term emission inventories. Moreover, because trade volumes before 1948 were much smaller than current volumes, earlier transferred emissions can be safely assumed to be negligible. Therefore, long term (1850–2012) consumption-based emissions before 1948 can also be derived using territorial emissions as substitutes.

Annual emission transfers between AXI and NXI parties have increased sharply since the early 1980s, as has the traded fraction of total emissions (see Fig. 6). Although the Great Recession and the following European Debt Crisis essentially halted growth, transferred emissions continued to represent approximately 7% of global carbon emissions. Furthermore, the slowly reviving economy since 2010 has marked a renewed growth of transferred emissions despite a declining share. Generally speaking, transferred emissions have contributed an historic 36 Gt CO<sub>2</sub> of cumulative emissions to AXI countries and have grown rapidly during the past 30 years (up to 8% of total emissions). It is likely to continue to be influential in the near future as shown by the rebound in transfer amounts in 2011 and 2012.

Furthermore, the LCBA2 results independently confirm previous findings regarding the efficacy of the Kyoto Protocol. Fig. 7 compares changes in territorial and consumption-based emissions from 1990 to 2012 with the Kyoto Protocol reduction commitments. Ignoring transfer emissions, the United States has increased territorial emissions by 4%, despite its pledged 7% reduction. This



**Fig. 7.** Percentage changes of emissions for large emitters in different accounting perspectives. The Kyoto Protocol reduction targets are shown with black dots. Percentage changes in territorial and consumption-based emissions from 1990 to 2012 are shown with red and green bars. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

percentage change soars to 17% when taking emission transfers into consideration. Similar trends can be seen for Australia, Canada, Spain, Netherlands and Japan, all of which fail in both accounting perspectives. The picture in the UK is different. The UK appeared to be succeeding (−17% in contrast to its −14% target) from the territorial perspective. However, taking transfer emissions into account shows this to be an illusion (15% increases). The results are similar for France, Germany and Italy. In the case of those countries that have done better than their Kyoto targets (Russia, Poland and Ukraine), factoring in trade further increased their success by 6%–100%. In short, emission transfers can be significant and may be comparable in magnitude to territorial emissions as shown in Fig. 7.

#### 3.4. Non-CO<sub>2</sub> and regional pollutant transfers

Using the LCBA2 model, we also calculated the 1970–2011 consumption-based emissions for N<sub>2</sub>O, CH<sub>4</sub> and SO<sub>2</sub> (as shown in Fig. 8) based on territorial data in the EORA (Lenzen et al., 2012, 2013) and SEDAC database (Smith et al., 2011a, b). The ratios of transferred emissions to annual totals in NO<sub>2</sub> (13%–34%), CH<sub>4</sub> (9–29%) and SO<sub>2</sub> (11%–31% for both EORA and SEDAC) are all higher than CO<sub>2</sub> (9%–27%) during 1970–2012. We find similar results for the shift shares between AXI group and NXI group of non-CO<sub>2</sub> GHG emissions, namely NO<sub>2</sub> (6–10%), CH<sub>4</sub> (8–12%) and SO<sub>2</sub> (8–12% for EORA and SEDAC) comparing to CO<sub>2</sub> (4%–8%) since the year 2000. Consumption-based emissions for CH<sub>4</sub> were nearly the same as those in EORA, while results of N<sub>2</sub>O differed. Territorial emissions of CH<sub>4</sub> in the AXI group started to decline after approximately 1990 and remained nearly constant in recent years, while emissions from the NXI group continued growing (by 1.9% on average per year since 2000), enlarging the gap between the two groups. When we considered transferred emissions, the gap was greatly reduced in both the LCBA2 and EORA estimates. Embodied CH<sub>4</sub> emissions transferred to AXI countries account for 32% [25–39%] of AXI total emissions and 4%–12% of annual total emissions in LCBA2, indicating an important contribution from trade. We must also mention that territorial emissions given by Kanemoto et al. (2014) based on EORA database are considerably smaller than expected for all 3 gases (by nearly an order of magnitude for N<sub>2</sub>O, but only 15% for CH<sub>4</sub>), which may cause some confusion (SI Section 7). In the case of N<sub>2</sub>O, EORA results indicated always larger consumption-based emissions for the NXI group than the AXI

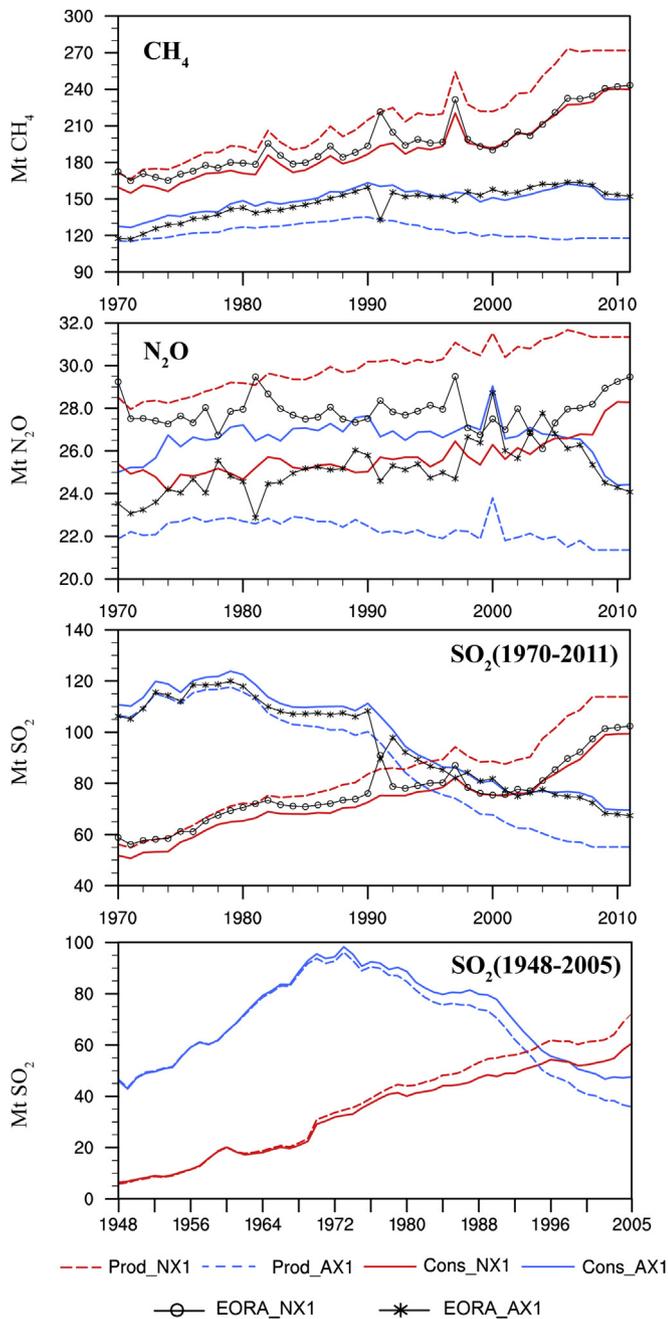
group except for 2000 and 2004. However, the LCBA2 results showed more significant transferred emissions and indicate that the AXI group had higher consumption-based emissions than the NXI group before the mid-2000 s. Since then, both results (LCBA2 and EORA) displayed an apparently growing gap with emissions rising in the NXI group (1.0% per year) and declining in the AXI group (−1.5% per year). The large fluctuations for CH<sub>4</sub> and N<sub>2</sub>O in 1991 (see Fig. 8) can be explained by the abnormally emissions embodied in exports from the former USSR (see EORA database), which is a result of EORA's optimization and input–output calculation procedures (SI Section 8). Moreover, spikes in N<sub>2</sub>O and CH<sub>4</sub> emissions from the NXI group in 1982 and 1997 were due to sudden emission changes in Indonesia (SI Section 8) and spikes in N<sub>2</sub>O emissions from the AXI group in 1981 and 2000 can be ascribed to the sharp fluctuations in territorial emissions in the USA, the UK, Japan and Australia.

The regional pollutant SO<sub>2</sub> (1948–2005) based on SEDAC database (Smith et al., 2011a, b) displays a similar pattern as CO<sub>2</sub>, in which emissions (both terrestrial and consumption-based) in the NXI group continued growing while those from the AXI group have been declining since the late 1970 s. SO<sub>2</sub> emission transfers were minor before 1970 and have been rapidly growing ever since. Using different data sources, LCBA2 and Kanemoto et al. (2014) give similar territorial and consumption-based SO<sub>2</sub> emissions since 1970, although again confusingly results in Kanemoto et al. (2014) are always smaller than EORA despite them sharing the same data source (SI Section 7).

In summary, the ratios of transferred emissions to annual totals in NO<sub>2</sub> (13%–34%), CH<sub>4</sub> (9–29%) and SO<sub>2</sub> (11%–31% for both EORA and SEDAC) are all higher than CO<sub>2</sub> (9%–27%) for 1970–2012. And so are the relative changes in share between AXI and NXI groups. The emission gaps between the AXI and NXI group for all 3 gases grew in both territorial and consumption-based perspectives. Comparisons of CH<sub>4</sub>, N<sub>2</sub>O and SO<sub>2</sub> in LCBA2 with EORA are in general consistent despite some difference before the mid-2000 s for N<sub>2</sub>O. Since EORA and LCBA2 have very different calculation framework, the similarity in results validates LCBA2, at least for CH<sub>4</sub> and SO<sub>2</sub>.

#### 4. Conclusions

This work focuses on improving the original LCBA model and backdating historical emissions with enhanced resolution. Several



**Fig. 8.** Historic emissions based on territorial (Prod) and consumption-based accounting (Cons) of CH<sub>4</sub> (1970–2011), N<sub>2</sub>O (1970–2011) and SO<sub>2</sub> (1948–2005) from for both developed countries (AXI parties) and developing countries (NXI parties). The dotted lines represent territorial emissions from EORA and SEDAC without any changes while the marked black lines are consumption-based emissions from EORA.

key findings can be drawn. (1) Using LCBA2, one can estimate transfer emissions with improved accuracy for 164 countries from 1948 to 2012. The new results in LCBA2 are in general reasonably close to the 3 other existing methods with similar trends and magnitudes, especially for the largest emitters. Significant changes from the original LCBA arise for European countries and China's important trade partners. These large changes are due to bringing imports structure into account. (2) Results reflect that cumulative emissions transferred between the AXI and NXI groups are up to 36 Gt CO<sub>2</sub> since 1948 and 8.3% of these emissions occurred in the period of 1948–1990. Since 1990, transfer emissions rose

dramatically (from 2% to 8% of annual total emissions) and recent data in 2011–2012 indicate a rebounding trend along with the reviving global economy. (3) LCBA2 results independently confirm previous findings regarding the efficacy of the Kyoto Protocol. (4) The ratios of transferred emissions to annual totals in NO<sub>2</sub> (13%–34%), CH<sub>4</sub> (9–29%) and SO<sub>2</sub> (11%–31% for both EORA and SEDAC) are all higher than CO<sub>2</sub> (9%–27%) in 1970–2012. Their relative changes in share between AXI and NXI groups are also higher. (5) LCBA2 results are comparable for CH<sub>4</sub>, N<sub>2</sub>O and SO<sub>2</sub> with those from EORA despite a difference before mid-2000 s for N<sub>2</sub>O. Since EORA and LCBA2 have very different calculation methods, this similarity provides some validation for LCBA2. (6) Across-method error analysis shows that it is the calculation framework that causes the differences among different methods rather than choice of input territorial emissions.

In general, the LCBA2 model indicates significant emissions shifts occur through international trade, which have grown in recent decades, not only for CO<sub>2</sub> but also for other pollutants. And the LCBA2 model provides a useful and succinct method of estimating historical transfer and consumption-based emissions. These emissions could be used as external forcing for future climate modeling that targets at investigating countries responsibility for historical climate change and climatic effect of transferred GHGs emissions.

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#### Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jclepro.2016.05.134>.

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