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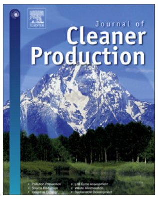

Constructing long-term (1948–2011) consumption-based emissions inventories

Zhiyong Yang [a], Wenjie Dong [a], Ting Wei [a], Yuqing Fu [a], Xuefeng Cui [a], John Moore [b,c], Jieming Chou [a,*]

[a] State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing 100875, China
[b] State Key Laboratory of Earth Surface Processes and Resource Ecology, College of Global Change and Earth System Science, Beijing Normal University, Beijing 100875, China
[c] Arctic Centre, University of Lapland, PL122, 96100 Rovaniemi, Finland

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ABSTRACT

Accompanying the boom in the global economy, CO_2 emissions have soared over the past several decades, with the developing world exhibiting higher emission growth rates than the developed world. Emissions transfers between regions, which represent a significant fraction of total emissions, are assumed to be a primary factor contributing to this difference. It is important to understand these transfer figures and the resulting consumption-based emissions in order to evaluate the emissions drivers and establish climate policies. Existing studies, however, have merely estimated figures over a 20 years span (post-1990) using a traditional input–output analysis (IOA) framework. To broaden the data coverage (to pre-1990) of these transfer figures and to further analyze their impacts on total emissions in the long term, a new model called the Long-term Consumption-based Accounting model (LCBA), which is directly based on statistics, is developed to span the period from 1948 to 2011. The results are consistent with the magnitudes and trends of existing studies over the validation (post-1990) period. We use Monte Carlo methods to calculate upper and lower bounds on the LCBA for each country and year, and find that 3 existing time series are almost fully included within these boundaries from 1990. Furthermore, the LCBA model is succinct enough to be easily expanded for future GHG estimations or to analyze other ecological footprints related to "the flow of materials". It can be assumed that the soaring emissions transfers will seriously jeopardize the current climate policies such as Kyoto Protocol. The Durban Platform for Enhanced Action (ADP) under which all parties are legally bound will require a consumption-based accounting method together with the territorial one in order to achieve an equitable agreement. However, more researches are still needed to facilitate the use of these figures to better support decision making.

1. Introduction

Accompanying the surge of international trade and the booming global economy is a heavy burden of GHGs that jeopardizes the natural system. International trade-links (global supply chains) reveal that geographical separation between production and consumption can be useful for companies to gain maximum profit. Related concepts, such as "ecological footprints" (Turner et al., 2007), "emissions embodied in trade" (Kanemoto et al., 2011; Peters et al., 2012a), and "consumption-based emissions" (Peters, 2008; Davis and Caldeira, 2010; Davis et al., 2011; Vetőné Mózner, 2013) have been widely studied over the past decade. Researchers have claimed that a portion of the production-based emissions in developing and emerging economies has been exported to developed regions as consumption, which ignites concerns about the efficiency of current climate policies and challenges the traditional carbon accounting system by substituting a production view with a consumption one. A production view or territorial view merely accounts for emissions that are produced within sovereign territories, while a consumption view also encompasses emissions conveyed through international trade.

In order to assign the GHGs emission responsibility to each agent or region, one need to know its contribution to this phenomenon in accordance with the benefits it receive through historical economic activities (Shue, 1999). Currently, several indicators have been used to quantify this (Gallego and Lenzen, 2005; Lenzen et al., 2007; Lenzen, 2008; Lenzen and Murray,

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[*] Corresponding author. Tel.: +8613683236612.
E-mail address: choujm@bnu.edu.cn (J. Chou).

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2010; Rodrigues et al., 2006; Rodrigues and Domingos, 2008a). Production-based indicator is emissions directly generated through production processes. Consumption-based indicator is emissions originated upstream along the supply chain to deliver goods and services to final demand (Kanemoto et al., 2011; Lenzen and Murray, 2010; Peters et al., 2012a); Income-based indicator accounts for all emissions generated downstream along the supply chain due to the supply of primary factors of production (Marques et al., 2012, 2013); Shared indicators are trade-off of the above indicators (Gallego and Lenzen, 2005; Lenzen et al., 2007; Lenzen, 2008; Rodrigues et al., 2006; Rodrigues and Domingos, 2008a,b). Although there are empirical studies on the global (Marques et al., 2012, 2013; Rodrigues et al., 2010), regional (Lenzen and Murray, 2010; Zhang, 2010, 2013) and corporate level (Petherick, 2012; Schücking et al., 2011) using these indicators, there exists little agreement about how to share the burden. Preferred suggestion is to use specific indicators for certain policy discussions (Andrew and Forgie, 2008; Rodrigues and Domingos, 2008a). These disputes have laid down a foundation for clarifying historical responsibilities and proposed a beneficial guide for future mitigation policies, especially for the Durban Platform for Enhanced Action (ADP) under which all partners will be restricted by one legally binding commitment. And since "common but differentiated responsibility" (UNFCCC, 1992) should still be held as a fundamental belief under the ADP scheme, long-term datasets in production-based view, consumption-based view or shared view are further needed to clarify responsibilities and to guide policy making. In this paper, we mainly focus on consumption-based view.

Most of existing studies on consumption-based emissions are initiated based on theoretical frameworks of input–output models (Miller and Blair, 2009). Research has evolved from focusing on one country and its major partners over specific years to one country over time, then to various countries over specific years and finally to global analyses over time (Davis and Caldeira, 2010). Various studies on consumption-based accounting have recently been implemented at a multi-regional (global) scale (Peters and Hertwich, 2004; Lenzen et al., 2004; Peters et al., 2011a) using MRIO (Multi-regional Input–output model) or EEBT (Multi-regional Input–output model based on emissions embodied in trade) techniques, or at a national scale using SRIO (Single-regional input–output model) methods (Wiedmann et al., 2007, 2009). Multi-regional models are commonly used because they are consistent with global climate policies; however, most of them merely focus on specific years (Ahmad and Wyckoff, 2003; Peters and Hertwich, 2008; Nakano et al., 2009; Davis and Caldeira, 2010). This is because such studies are usually limited by data availability (Miller and Blair, 2009) which make it hard to track changes over time using input–output frameworks. Currently, only 3 studies partially transcend this limitation and enable time-series analyses at a global scale over 1990–2010 (Lenzen et al., 2012; Peters et al., 2011b; Wiebe et al., 2012). Based on a modified TSTRD (an algorithm to achieve long time series with trade data) method (Peters et al., 2012b), the Global Carbon Program (GCP) nowadays is able to offer preliminary estimates of consumption-based emissions successively, with only a one-year delay. Nevertheless, when the question — "How can one backdate consumption-based data before 1990?" arises, there exists no answer due to the data constraints in the current calculating framework. Since long term historical data in the consumption view is crucial for the development of future climate policies and international negotiations under the rule of "common but differentiated responsibility", theories and methods for historical estimation are further needed. This study set up a clear and succinct algorithm for estimating historical consumption-based emissions and incorporated data going back to 1948 from 164 countries (see Appendix A).

2. Materials and methods

2.1. Accounting method

Territorial emissions inventories which are commonly used in climate change researches and negotiations are emissions taking place within national territory and offshore areas over which the country has jurisdiction (IPCC, 2006). By combining these inventories with international trade data, consumption-based emissions inventories are derived from adding emissions associated with imports and subtracting emissions associated with exports. However, in contrast to the traditional consumption-based accounting method using Input–output models (e.g. MRIO & EEBT) which are limited by data availability, our study set up a new framework using Equations (1):

$$F_{\mathrm{Cr}}(r,i) = F_{\mathrm{Pr}}(r,i) + \mathrm{COEF}_{\mathrm{im}}(i)^{*}\mathrm{Imports}(r,i) - \mathrm{COEF}(r,i)^{*}\mathrm{Exports}(r,i) \qquad \text{s.t.} \quad \sum_{r} F_{\mathrm{Cr}}(r,i) = \sum_{r} F_{\mathrm{Pr}}(r,i) \tag{1}$$

where $F_{\mathrm{Cr}}(r,i)$ and $F_{\mathrm{Pr}}(r,i)$ represent the consumption-based and production-based emissions for region r in year i, respectively. Imports(r,i) and Exports(r,i) are the annual trade of goods and services from each region r. COEF(r,i) is the "production intensity" estimated (CO_2 emissions per unit of "Gross Productive Output") for region r in year i. Here, "Gross Productive Output" means GDP plus imports and subtracts "imported elements" which will be discussed later. $\mathrm{COEF}_{\mathrm{im}}(i)$ means "importation intensity" which is calculated based on all of the "production intensities" estimated for year i. We use a global average value to represent the "importation intensity" which is the same for all countries because we do lack detailed imports flow data among countries. The constraints in equation (1) reveal that total production-based emissions in a specific year must equal those of the consumption-based emissions in the same year over all 164 countries.

There are 2 crucial points in LCBA model. The first is to estimate the "production intensities" for each of the 164 countries over 64 years. The second is to calculate the "importation intensities" for each year based on these data. In contrast to the popular concept "emission intensity," which merely provides estimates of CO_2 emissions per GDP, COEF(r,i) generates a more accurate concept — "production intensity" — and estimates its intervals for each region and each year.

When calculating GDP using an expenditure approach, GDP is a sum of Consumption (C), Investment (I), Government Spending (G) and Net Exports ($X - M$) as expressed in Equation (2):

$$\mathrm{GDP} = C + I + G + (X - M) \tag{2}$$

In the input–output model, C, I, G, X (exports) and M (imports) can be treated as basic elements in final use. Apart from X and M, all of the other 3 items are satisfied by both the domestic elements (C_1, I_1 and G_1) and the imported elements (C_2, I_2 and G_2), as shown in Equation (3):

$$\mathrm{GDP} = (C_1 + I_1 + G_1) + (C_2 + I_2 + G_2) + (X - M) \tag{3}$$

Furthermore, the imports (M) are usually consumed for both intermediate use and final use, which means that M is larger than $(C_2 + I_2 + G_2)$. Since production-based emissions should only account for emissions from "Gross Productive Output" $((C_1 + I_1 + G_1 + X))$, which excludes imports (M) and imported elements (C_2, I_2 and G_2) from the GDP, it is the CO_2 emissions per "Gross Productive Output" that should be treated as the accurate meaning of "emission intensity". However, "Gross Productive Output" can only be estimated because it is hard to separate C_2, I_2

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and G_2 from statistics data C, I and G. So GDP is supposed to be the lower-bound of "Gross Productive Output" while ($GDP + M$) can be treated as its upper-bound. Combining these data with production-based emissions, the estimated intervals of "production intensity" for 164 countries over 64 years are then obtained.

Due to the absence of the exact figures for "production intensity", we use a Monte Carlo approach with simulations from 50 to 10,000 to estimate the real conditions. Within each country, production intensities are chosen from the same proportion between the upper-bound and the lower-bound values over 64 years to avoid impractical economic fluctuations. Among different countries, however, the proportions are different due to the use of a uniform distribution for data generation. After completing one sampling trial, a set of production intensities can be generated among which some of the data might be absent due to the availability of GDP and production-based emissions data.

Since the source of imports is often unknown in the traditional aggregated statistics data and it is painstaking or nearly impossible to arrange these detailed trade-link (imports or exports) data in a timely manner, average values for each year's production intensities are selected. Within each sampling trial, 134 countries are chosen to estimate the "importation intensities" from 1948 to 2011. This excludes 5 countries with apparent abnormal results (North Korea, Qatar, Brunei, Vietnam, Singapore) and 25 countries with time series no longer than 20 years (most of these are partners of the Former Soviet Union (FSU), Yugoslavia or small island countries) from the total of 164 countries. The resulting COEF(r,i) for a specific year is not normally distributed. For example, ±3 standard deviations exclude only 3% of the realizations, showing the fat-tailed nature of the distribution. To further eliminate the influence of outliers, only COEF(r,i) that lay between ±3 standard deviations for each year are chosen. Mean values of these final selected data are treated as the estimated importation intensity for those years.

Combining COEF(r,i) intervals and $\mathrm{COEF_{im}}(i)$ estimated with statistics data — $F_{\mathrm{Pr}}(r,i)$, Imports(r,i) and Exports(r,i), a set of consumption-based emission intervals for each of the 164 countries in all years from 1948 to 2011 could be achieved. By repeating the calculation procedures and enlarging the sample size from 50 to 10,000, the mean values of those sets show a type of convergence to constant values (as shown in Fig. 1) and 10,000 is chosen as the final sampling size for demonstration. A total of 164 * 64 vectors are calculated and each vector has 10,000 separate realizations representing the range of consumption-based emissions. Within each vector, the mean value of the 10,000 data is regarded as the optimal level. And the 2.5–97.5% range is chosen to be the 95% confidence interval, namely the upper and lower bounds of the consumption-based emissions, since the 10,000 data are not normally distributed.

We name this new model "Long-term consumption-based carbon accounting" (LCBA). The similarity between Input–Output (I–O) model and the LCBA model means that LCBA can be regarded as a simple version of the EEBT model in which all industries and commodities are aggregated into one sector. However, the differences between the models are much starker. The I–O model embraces detailed sectors and coefficients that can be used to trace inter-relationships among countries (trade links) and sectors (structural path analysis) for each year (Davis et al., 2011). The LCBA, though, is incompetent in sector details, however, it is succinct and long-time-series analysis is achievable. These traits enable the LCBA model to be easily extended to do future projections. What is more, LCBA model also can be used for ecological footprints analysis if data are available, such as analyzing physical flows (e.g., fossil fuels, biomass, water, etc.) and GHGs other than CO_2.

2.2. Sources of data

Merchandise trade data from 1948 to 2011 were obtained from time series in WTO (World Trade Organization) based on the "general trade" recording system (WTO, 2013). The departure point of 1948 was chosen for 2 reasons. First, trade volume before 1948 was much smaller compared to the current amount, which means consumption-based emissions and terrestrial emissions do not vary

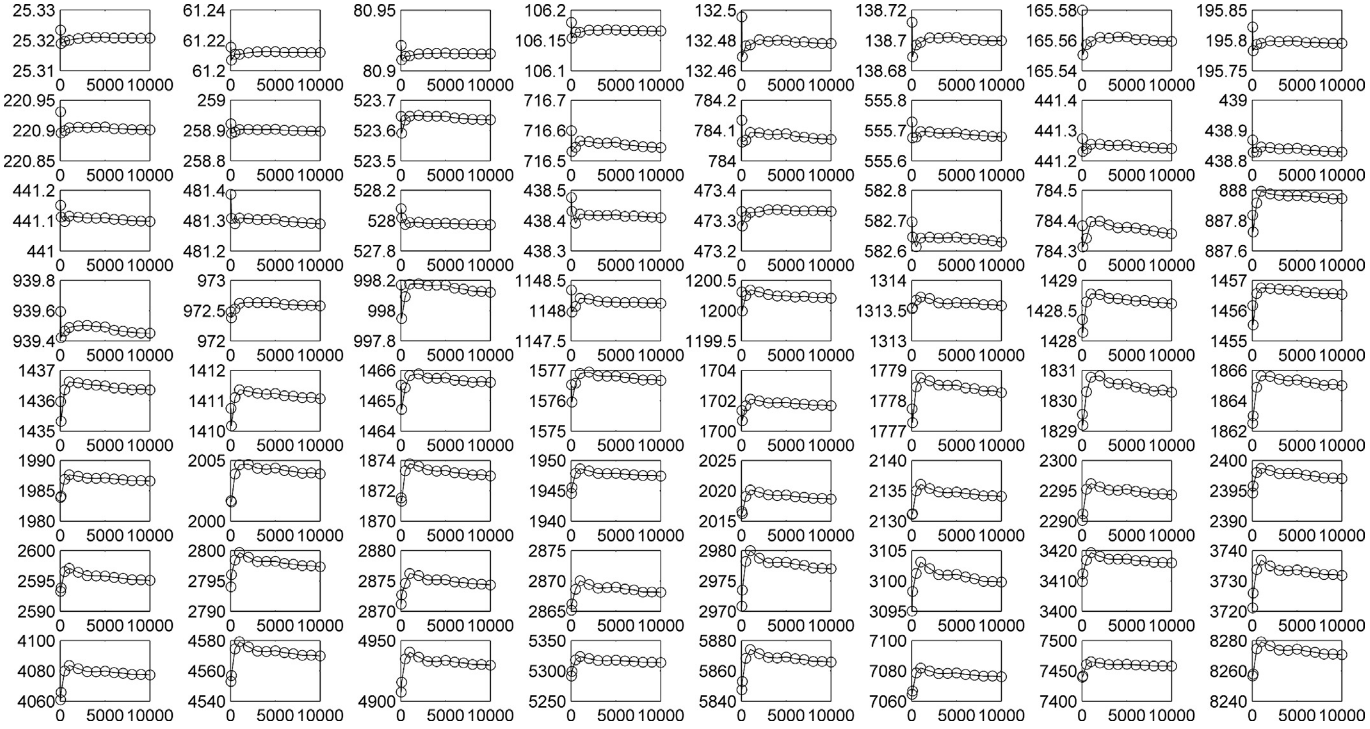

Fig. 1. Fluctuations of the LCBA (optimal level) mean values from 1948 to 2011 (from left to right and top to bottom) with a changing sampling size from 50 to 10,000 in China.

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widely at that moment. Second, the GATT (General Agreement on Tariffs and Trade, predecessor of the WTO) was founded in 1948, before which long-term and consistent statistics are not available. Exports were valued at FOB (free on board) price and imports at CIF (cost insurance and freight) price, which were all counted in current US dollars. Services trade data came from WTO too and were supplemented by BPM 5 and BPM 6 (balance of payment, version 5 and version 6) datasets in IMF (international monetary fund).

Production-based CO_2 emissions included 2 parts: emissions from fossil fuels combustion and from cement production. Fossil fuels and cement production data between 1980 and 2011 were taken from EIA and CDIAC, respectively (Boden et al., 2013; EIA, 2013). Since cement production data for CDIAC ends in 2009, average values of the past 3 years were chosen to extrapolate the data for 2010 and 2011. Emissions values before 1980 (1948–1979) were supplemented with total values from CDIAC due to the lack of energy data from EIA.

Nominal GDP and imports of goods and services in current US dollars (1960–2011) were selected from World Bank WDI (World Development Indicators) database (World Bank, 2013). GDP before 1960 were calculated using 2 methods: (1) For the 52 largest emitters of which the average consumption-based emissions between 1990 and 2008 are higher than 50 Mt were chosen (Peters et al., 2011b). For most of these countries, 1948–1959 GDP were backdated using the real growth rates, the per capita growth rates and the population growth rates based on specific historical studies (see Appendix B) in order to achieve the best accuracy. (2) For other countries, the real growth rates come from Maddison's historical PPP data (Maddison, 2010).

What should be emphasized was that there were 2 types of imports data. Those from World Bank WDI dataset were merely used to estimate "production intensities" in pursuit of data consistency with GDP data from the same source. While the other imports data came from WTO and IMF datasets and were used for calculating the final consumption-based emissions.

3. Results and discussion

3.1. Validation

Since the exact consumption-based emissions are unknown, all 3 existing long-term datasets (Lenzen et al., 2012; Peters et al., 2011b; Wiebe et al., 2012) are merely estimations. In order to validate our results and make a comparison with 3 existing studies, two indicators are chosen: the "mean values" of LCBA optimal data in certain time span (e.g.1995–2005) and "correlation coefficients" of those series for each of the 164 countries. Due to the length of time in the 3 existing studies (Lenzen, 1990–2010; Glen, 1990–2008; Wiebe, 1995–2005), 2 different time spans are selected, namely, 1990–2008 and 1995–2005 and only 1995–2005 is used for further illustration. For each year, global emissions in these 3 studies are calibrated to equal that of LCBA and total emissions for each country are scaled proportionately in order to conduct rough comparisons.

The 15 largest emitters in 2011 and 2 other groups are selected for demonstration. Table 1 shows that most "mean values" are similar to the other 2 or 3 sets and that all of these values share a similar magnitude. Although discrepancies exist (positive figures indicate greater values than the LCBA, for instance, Japan and Iran have lower values, South Africa and Canada have higher values in LCBA), they can be ascribed to discrepancies both in their own calculation frameworks and the original data. However, no direct conclusion can be drawn as to which one contributes more due to their variations among different studies. As for correlation coefficients, we find that most of our series resemble existing studies at the 0.01 significance levels. For certain countries, such as China, US, India and Russia, the correlation coefficients are extremely high. It is also found that at least one of the existing researches is highly correlated with LCBA results. The optimal values of LCBA in Russia Federation, for instance, are highly correlated with those from Lenzen and Wiebe (95.2% and 92.6%); at the same time, poorly correlate with Peters (71.6%). This might be ascribed to the algorithm and the original data selection in Peters, not to LCBA. In summary, all of these facts suggest that our model results are moderate and consistent with earlier studies (see Table 2).

As shown in Fig. 2, the territorial emissions and consumption-based emissions are nearly the same before the late 1970s. The gaps, namely emissions embodied in trade, have grown since then. Furthermore, the AX1 group (Kyoto Annex 1 signature countries) show larger values for both figures with moderate growth rates which have declined dramatically since 2008 financial crisis, while emissions from the NX1 group (Non-Annex 1 signature countries) continue to soar. The LCBA optimal values in NX1 group surpass those of AX1 in 2011, and this trend is expected to continue due to

Table 1
Contrasts between LCBA (optimal level) and 3 other studies (Lenzen et al., Peters et al. and Wiebe et al.) in the period of 1995–2005 for the top 15 emitting countries and 2 other groups in 2011.

1995–2005	Mean				Correlation coefficient		
	LCBA (Gt CO_2)	Lenzen et al. (%)	Peters et al. (%)	Wiebe et al. (%)	Lenzenet al.	Peterset al.	Wiebeet al.
China	3218.54	2.80%	3.38%	−16.56%	0.974	0.983	0.947
United States	6149.95	1.74%	−1.50%	4.62%	0.983	0.978	0.985
India	952.76	3.95%	15.45%	−6.19%	0.977	0.959	0.970
Russia Federation	1111.49	8.76%	2.16%	−11.20%	0.952	0.716	0.926
Japan	1428.38	4.65%	5.78%	11.78%	0.856	0.883	0.851
Germany	1129.12	−11.55%	−7.66%	−3.33%	0.615	0.628	0.376*
South Korea	465.81	−2.04%	−3.48%	39.65%	0.965	0.892	0.930
Iran	285.80	19.38%	23.99%	–	0.953	0.900	–
Canada	575.22	−16.01%	−12.70%	−10.91%	0.869	0.972	0.961
Saudi Arabia	228.55	−8.16%	–	–	0.876	–	–
United Kingdom	774.04	−4.44%	−15.08%	1.51%	0.965	0.954	0.978
Brazil	369.05	0.65%	−8.67%	−10.09%	0.959	0.865	0.777
Mexico	405.37	−1.33%	4.06%	−5.39%	0.990	0.949	0.915
South Africa	329.94	−13.26%	−18.29%	−21.61%	0.963	0.883	0.939
Indonesia	238.11	11.10%	3.20%	17.37%	0.975	0.986	0.986
AX1	15,747.340	−3.65%	−4.08%	−1.22%	0.972	0.973	0.987
NX1	9350.925	6.15%	6.88%	2.06%	0.987	0.990	0.987

Notes: The first column shows the optimal values of the LCBA model, and the next 3 columns are percentage comparisons with the LCBA values (positive indicates greater values than the LCBA). The correlation coefficient is unmarked if it is significant at the 0.01 significance level and marked * if it is not significant at the 0.05 level.

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Table 2
Average relative errors between LCBA model and 3 existing studies for both production-based emissions and emissions embodied in trade.

Countries	Production-based emissions	Emissions embodied in trade/emissions transfers
Hungary	2%	2290%
Argentina	4%	1979%
Canada	6%	1309%
Australia	3%	1085%
Turkey	5%	521%
Singapore	33%	371%
Philippines	2%	202%
Greece	8%	90%
Indonesia	3%	75%
Netherlands	17%	75%
Denmark	7%	66%
Ireland	4%	62%
Belgium	11%	60%
Brazil	7%	52%
Sweden	6%	49%
United States	1%	46%
Malaysia	7%	45%
Austria	3%	45%
Thailand	7%	42%
South Africa	8%	41%
India	9%	37%
Germany	1%	34%
Norway	7%	33%
Spain	5%	33%
Mexico	3%	33%
Hong Kong	24%	33%
Japan	4%	30%
Poland	3%	29%
France	2%	26%
Romania	4%	26%
Finland	11%	25%
United Kingdom	1%	24%
Switzerland	6%	18%
Russian (Federation of)	3%	18%
Portugal	3%	17%
China	4%	15%
Italy	2%	13%

probable similar growth rates in the future. This phenomenon can seriously jeopardize the effectiveness of the current climate policies, such as Kyoto Protocol. Therefore, the future ADP scheme, in which all partners are legally bound, is reasonable and insightful considering the increasing contribution of NX1 group. What is more, the LCBA optimal results resemble those from Peters et al. (2012b). The differences, however, mainly lie in the time span and the boundary estimates, which are the two strengths of LCBA model.

The 37 regions that are covered both by LCBA and the other 3 datasets are further analyzed. The relative errors for LCBA optimal values in production-based emissions and emissions transfers are calculated separately according to the 3 existed studies (positive indicates greater values than the LCBA). The absolute values of the 3 relative errors are then averaged to reflect the mean level for each of the 37 regions, and this mean value is named as the "average relative error". Although average relative errors can be greatly influenced by large values in the original 3 errors, as in the case of the US, the tendency can be roughly shown. It is found that the average relative errors for emissions embodied in trade are normally larger than those for production-based emissions. For most regions, the average relative errors in production-based emissions remain low, but those regions that are highly dependent on trade show abnormally large values, such as Singapore, Hong Kong and Netherlands. This can be explained by their huge values of trade in contrast to GDP in those economies. As for average relative errors in emissions transfers, most of the top emitters show moderate results (China, 15%; Russia, 18%; Japan, 30%; Germany, 37%). The abnormal value in Canada (1300%), for example, might be ascribed to the different calculation frameworks of the 4 models and different original trade data since they share similar production-based emissions and all 3 original errors are much smaller than 0. So does it to US (46%), of which the original errors vary from −9.3% to 63%. To further clarify these average relative errors, specific regions, namely US, China, India, Singapore, Hong Kong and 2 other groups (AX1 and NX1), are selected for illustration.

In Fig. 3, the optimal values in LCBA resemble at least one of 3 existing series. The discrepancies among production-based emissions are moderate, as predicted, and emissions embodied in trade show starker differences with similar trends among the 4 datasets. Most of the 3 existing series lie between upper and lower boundaries and the optimal LCBA values almost lie among the 3 existing results. The AX1 and NX1 groups in Fig. 3 show a significant distribution of the emissions embodied in trade, in which the AX1 group occupies the lower parts of the picture, while NX1 dominates the upper ones. This finding can be explained as a result of international trade which mainly occurs among developed economies, especially for manufactured goods and services. Since the AX1 group usually has lower production intensity, the importation intensity of this group could be lower if higher weight is given to AX1 group, which can then result in lower consumption-based emissions.

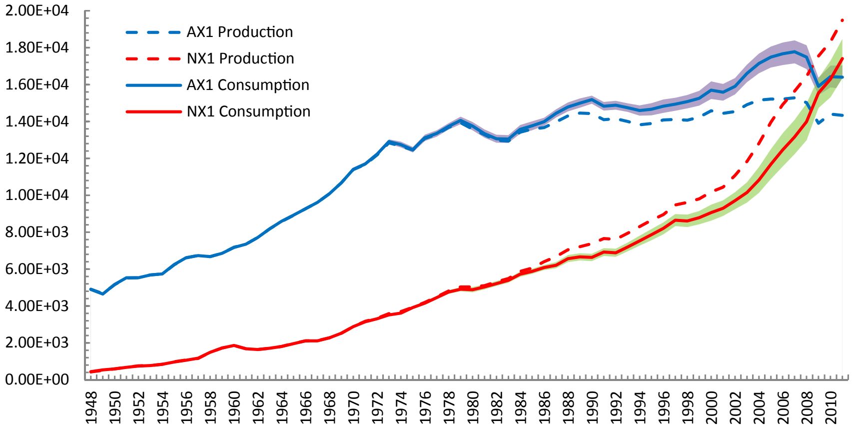

Fig. 2. Historical territorial emissions and consumption-based emissions from 1948 to 2011 for 2 groups (AX1 and NX1). The shaded areas are the boundaries of consumption-based emissions estimated.

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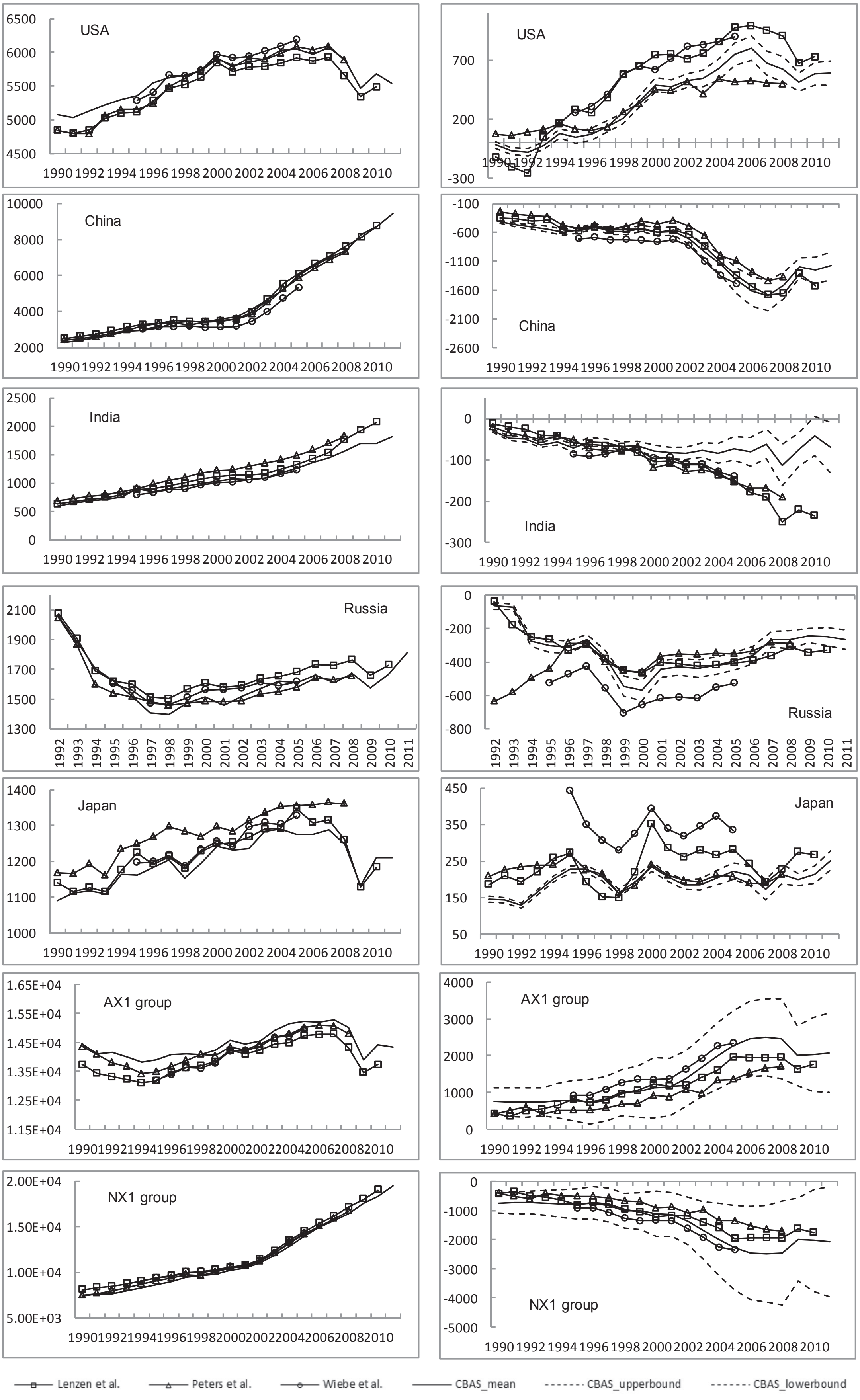

Fig. 3. Terrestrial emissions and Embodied emissions in trade among CBAS estimates and other 3 researches (US, China, India, Russia, Japan, AX1 and NX1 group from top to bottom).

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Furthermore, of the top 3 emitters, only India shows abnormal trend in trade. However, its growth in net imports combined with its declining production intensity through technical progress in recent years, suggest that India will be a net importer of CO_2 in the near future. Thus, the trend reveals by our results may be reasonable, although they differ from existing studies. As for small countries that are highly dependent on trade, such as Singapore and Hong Kong, the differences in production-based emissions are starker (as shown in Fig. 3), at the same time, emissions embodied in trade show a greater importance due to the similar magnitude to production-based ones.

In summary, most of the 3 existing model series for consumption-based emissions lie between the upper and lower boundaries of LCBA and the optimal LCBA values almost lie among the 3 existing results. The LCBA optimal results are similar to them both in magnitude and trend for most regions, especially for the top emitters. By further separating the consumption-based emissions, we find that emissions embodied in trade show larger average relative errors than the production-based ones, and for most top emitters, both of the errors are moderate.

3.2. Uncertainties

There are two main sources of uncertainty. One is from the framework of the LCBA model, and the other is from the original data selections. In the LCBA framework, the scope of COEF(r,i) is estimated, upon which the importation intensity $\mathrm{COEF}_{\mathrm{im}}(i)$ is derived. However, these two factors are rough estimates because different countries should embody different production and importation intensities of their own. What is more, further uncertainties are introduced into the framework through the use of a sampling method in each trial to achieve the final consumption-based emissions.

As for the selection of the original data, both the territorial emissions and the trade data can cause discrepancies. A comparison of different sources of production-based emissions has been carefully discussed in Peters et al. (2012a), and similar results are found in LCBA, indicating that large emitters are mainly subjected to production-based data. As for trade data, most uncertainties lie in the valuation methods (CIF or FOB) and re-export elements in bilateral trade data. Existing studies are mainly based on datasets, such as OECD, GTAP and EORA. GTAP reconcile UN Comtrade data using Gehlhar's method and optimization procedures (Gehlhar, 1996; Narayanan and Walmsley, 2008). All of its results in GTAP are displayed in market price, which is equivalent to basic price and CIF valuation method, at the same time, with the re-export matters solved. OECD STAN datasets display I–O tables and bilateral trade in basic price with valuation problems and re-export matters resolved (Yamano and Ahmad, 2006; Zhu et al., 2011). EORA datasets, however, tackles these two conflicts using quadratic programming with disturbance parameters in order to achieve balance among various data and displayed the results in 5 price forms including the basic price (Lenzen et al., 2012, 2013). Estimations in LCBA deviate for two reasons. First, re-export and re-import are included in WTO merchandise trade data, which can lead to “fictitious” emissions in our framework due to the differences between importation and production intensities; second, imports are valued at CIF price and exports at FOB price, which might exaggerate the final results. These flaws can be settled as long as detailed data processing and a consecutive series of CIF/FOB ratios are available.

3.3. Limitation

LCBA model is mainly designed for national analysis and is different from MRIO/EEBT model which concentrate more on sectors using input–output relationships. The preferred model is a matter for policy discussion. We could choose LCBA model to quickly derive national consumption-based data in the global scale, and use MRIO/EEBT model to do further sectoral discuss for specific countries.

Although LCBA model merely delivers rough estimates due to its uncertainties, as previously mentioned, it can be modified to be more accurate. For instance, we can replace the single global average importation intensity with regional importation intensities for East Asia, West Europe, North Africa, North America etc. These data can be further separated into importation intensities for each country when detailed importing source data available. Frankly speaking, the main limitation for LCBA model is data availability, which is the same for MRIO/EEBT models using I–O framework.

4. Conclusions

The consumption-based emissions inventories in the global scale can be useful supplements to the traditional production-based inventories, which embodies the advantages of clarifying historical responsibilities, differentiating reduction commitments, and harmonizing trade and climate policies. However, due to the constraints of input–output models and data availability, long-term time series starting before 1990 cannot be achieved. In this study, a new model (LCBA) is set up to meet this demand. Although many uncertainties exist, the results are consistent over the validation period. Estimations (optimal, upper-bound and lower-bound) for each of the 164 countries and each of the 64 years are given. What is more, LCBA model is succinct enough, which indicates that the results can be improved and extrapolated once the data are available. Although production-based emissions inventories will continue to dominate in the near future, owing to their lower level of uncertainty, easier implementation and widespread use, it is reasonable and insightful to balance both production-based and consumption-based inventories in the long run, especially for post-2012 climate policies, such as the ADP scheme. This is because the current climate policies such as Kyoto Protocol can be seriously jeopardized by the soaring emissions transfers and increasing contribution of the NX1 group. It is supposed that LCBA is good at estimating consumption-based emissions in the national scale, while traditional I–O models specialize in sectoral analysis and supply chain analysis. Together with LCBA model and I–O model, consumption-based emissions inventories can play an increasing role in future climate negotiations and can help to achieve solid progress in future climate policies.

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Appendix A. Supplementary material

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2014.03.053.

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