

# The evolution of CO<sub>2</sub> emissions in international trade for major economies: a perspective from the global supply chain

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**Abstract** Employing global multi-regional input–output models, this paper revisits the carbon dioxide (CO<sub>2</sub>) emission trade (including exports and imports) and assesses their positions in the national emissions of 14 major countries with large national emissions or large emission trades during 1995–2009. It especially explores the evolution of the emission trades of these countries from both continuous time series and comparative perspectives, in order to provide an explanation for CO<sub>2</sub> emission spillovers across countries. The main findings obtained were as follows: (1) China was the largest CO<sub>2</sub> exporter to other countries, accounting for over 20 % of global exports since 2005; the CO<sub>2</sub> exports of the United States of America (USA), Germany, and Japan varied slightly over this time period, but overall, their proportions had decreased. (2) The CO<sub>2</sub> imports of the USA were the largest, occupying around 20 % of the global CO<sub>2</sub> imports; meanwhile, China's CO<sub>2</sub> imports increased rapidly and ranked the second largest. (3) For Chinese Taiwan, its proportion of CO<sub>2</sub> exports in production-based emissions ranked the highest while that of the USA ranked the lowest; highly CO<sub>2</sub> import-dependent countries with an over 40 % proportion of CO<sub>2</sub> imports in its consumption-based emissions included France, Germany, Italy, and Spain, while China, India, and Russia remained the lowest, distinguished from their physical energy imports. These results suggested that the global policy makers should take the CO<sub>2</sub> emissions in trade into consideration when carefully accounting for national emissions inventories.

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## 1 Introduction

Issues relating to climate change have received much attention worldwide due to the potential threat to humans in the future. As climate change is triggered by the global concentration of greenhouse gas (GHG), neither a single country nor a group of few countries are capable of addressing such a global issue alone. Therefore, the United Nations Framework Convention on Climate Change (UNFCCC) has proposed a “common but differentiated responsibilities” rule, urging its parties to participate in emission mitigation actions (Kiuila et al. 2016). However, international climate change negotiations have encountered tremendous obstacles due to the disagreements on the assignment of emission mitigation obligations among different countries. One particularly fierce dispute has resulted from questions concerning the accounting system boundaries and definitions contained within the territorial-based National Emission Inventories (NEIs) specified by UNFCCC.

These territorial-based NEIs are considered to be equivalent to the production-based principle (PBP) emissions, except for the allocation of international transportation<sup>1</sup> (Peters 2008). However, the PBP accounting system has received much criticism and questioning due to its ignorance of carbon leakage<sup>2</sup> issues in the international trade (Wyckoff and Roop 1994; Lenzen et al. 2004; Munksgaard et al. 2005; Peters and Hertwich 2008; Su and Ang 2014). Thus, many scholars have proposed the consumption-based principle (CBP) NEIs, which are considered as a helpful complement to the PBP NEIs (Munksgaard and Pedersen 2001; Ferng 2003; Lenzen et al. 2004; Wilting and Vringer 2007; Barrett et al. 2013; Yang et al. 2015). Basically, it is the emissions trade that causes the difference between CBP and PBP emissions, which can be demonstrated by the following relationship: consumption-based emissions = production-based emissions – exports of emissions + imports of emissions.<sup>3</sup> Here, exports of emissions and imports of emissions are the two aspects forming the basis of the emissions trade, the balance of which also determines whether a particular country is a net exporter or net importer of emissions. Since carbon dioxide (CO<sub>2</sub>) is the principal GHG, this paper will focus on the CO<sub>2</sub> emissions trades and other associated indicators.

Given the significant role of emission trade in the comprehensive assessment of NEIs, researchers worldwide have paid attention to the CO<sub>2</sub> emissions embodied in exports. From the perspective of bilateral trade, Jayanthakumaran and Liu (2016) quantified the CO<sub>2</sub> emissions embodied in bilateral trade between Australia and China using a sectoral input–output model; Guo et al. (2010) computed the CO<sub>2</sub> emissions embodied in Sino-US international trade and measured their impacts on national and global CO<sub>2</sub> emissions. From the perspective of interregional trade within one country, Su and Ang (2014) conducted a comprehensive study on China’s regional emission embodiments to try to

<sup>1</sup> Therefore, we adopt the concept of production-based principle (PBP) emissions hereafter.

<sup>2</sup> Carbon leakage is commonly defined as an emission in one geographical area resulting from a decrease in emissions elsewhere, everything else being constant, including policies applied elsewhere (Kiuila et al. 2016).

<sup>3</sup> A definition in terms of formulas of one country’s export or import of carbon emissions is presented in Sect. 2.

This is because it can be explained as production emissions from country A exports to country B, becoming imported consumption emissions.

explain how interregional trade and international trade affect China's regional domestic emissions; Zhang et al. (2014) further calculated carbon emissions embodied in trade within China for 1997–2007. From a national-level perspective, Sánchez-Chóliz and Duarte (2004) evaluated the exports and imports of the Spanish economy in terms of the direct and indirect CO<sub>2</sub> emissions (CO<sub>2</sub> embodied) generated in Spain and abroad, and Tolmasquim and Machado (2003) analyzed to what extent energy use and its associated CO<sub>2</sub> emissions in Brazil during the 1990s may be overloaded by changes in the country's trade specialization toward a more energy-intensive mix. From the above literature, it can be seen that most of the previous studies were conducted a single year or "period-wise" analysis from a bilateral trade or a national-level perspective. Although some studies concentrated on the relationship between CO<sub>2</sub> emissions and trade patterns from the perspectives of both continuous time series and cross-countries, they almost all pertain to econometric analysis (e.g., Al-mulali and Sheau-Ting 2014; Kasman and Duman 2015; Kim and Worrell 2002).

The most common tools used for calculating the CO<sub>2</sub> emissions embodied in exports, consumption, investments, etc. are environment input–output models. According to the ways of treating the imports in intermediate consumptions, these models can generally be divided into two different categories. One type of such models treats intermediate imports as a part of the total trade flow along with final consumption, without distinguishing between the domestic and overseas production technologies. This type of analysis can be achieved by using bilateral trade input–output (BTIO) or single-region input–output (SRIO) models, which have reduced data requirements. The other model type, however, treats intermediate imports differently to final products through forming a large technical coefficient matrix with distinctions between domestic goods and imports. As a result, this method involves massive data requirements for compiling the input–output table, which is usually realized within a framework named as the multiregional input–output (MRIO) model. Peters (2007, 2008) summarized the two types of methods and defined them as the emissions embodied in bilateral trade (EEBT) method and the emissions embodied in consumption (EEC) method, respectively. Following the concept of trade in value added (Johnson and Noguera 2012), Meng et al. (2013) proposed CO<sub>2</sub> emissions in trade (CEiT) and trade in CO<sub>2</sub> emissions (TiCE) to represent these two frameworks, respectively. Su and Ang (2013) stated that the former is based on the assumption of non-competitive imports while the latter is based on the assumption of competitive imports. Hubacek and Feng (2016) compared the gap between physical trade flows and MRIO approaches when using them to account for embodied land in trade.

Compared with the BTIO and SRIO models, the MRIO model provides much more accurate estimates (on condition that reliable data are available). On the other hand, as globalization deepens, cross-country supply chains have become more prevalent, not only in terms of final products but also in terms of intermediate products. From the perspective of the global supply chain, production processes are segmented into more and more countries, where the components may transfer across borders multiple times. For instance, an Apple iPhone shipped from China to the USA contains components that are produced in Japan, but these CO<sub>2</sub> emissions embodied in the components are generated in the USA. The BTIO and SRIO models cannot capture this complex relationship in the global supply chain. In contrast, a global multiregional input–output (GMRIO) framework allows for the tracing of all emissions associated with final products back to the country that generates, even if the production process passes through many countries in the global supply chain (Xu and Dietzenbacher 2014).

Empirical studies have highlighted the importance of incorporating the spillover and feedback effects within the framework of supply chains when calculating embodied emissions (Peters 2007; Weber and Matthews 2007) or considering adaptation measures (Nakano 2015). Therefore, this paper adopts the GMRIO model despite its computational complexity.

Some studies have utilized the MRIO model to calculate embodied emissions in trade or CBP emissions, but most of them still confined their scope to a specific country/region for individual years, such as China in 2007 (Feng et al. 2013; Su and Ang 2014), or 2002 and 2007 (Liu et al. 2015), and Australia in 1997 and 2004 (Muñoz and Steiner 2010). Unlike previous studies, the present study aims to offer three main contributions. Firstly, we explore the characteristics of emissions trade in terms of a continuous time series, i.e., 1995–2009. By so doing, problems such as information loss and unreliable consequents can be avoided (Ang and Lee 1994). Secondly, the paper carries out a comparative analysis between major countries simultaneously. Such a comparative analysis undertaken in the framework of the global supply chain can provide valuable information for policymakers of individual countries and also can enhance the understanding of the different positions that these countries can take in addressing the global climate change. Thirdly, by using the GMRIO model, the relationship between the global CO<sub>2</sub> emission spillovers and the global supply chain can be explained. This can help avoid double counting when measuring bilateral trade balance and the associated CO<sub>2</sub> emissions across regions, since the intermediate products may flow through a region's borders multiple times to produce final products (Meng et al. 2013).

This study, therefore, employs a GMRIO model to calculate the trade of CO<sub>2</sub> emissions and their balances for major economies during the continuous period 1995–2009. The impacts of each economy's exports and imports of CO<sub>2</sub> emissions on its production-based and consumption-based national emissions are also analyzed, respectively. We adopt the World Input–Output Database (WIOD) as the basis of our data, due to its time series and free availability.

In order to present a clear analysis, the remainder of this study is organized as follows. Section 2 explains the methodology used to estimate the emission trade of major countries, wherein a GMRIO model is depicted in detail. Section 3 provides a brief explanation of the WIOD and details of the selected countries. The results and discussions follow in Sect. 4, where the results of different economies are analyzed in turn, roughly in accordance with volume from more to less. Finally, the conclusions and policy implications are proposed.

## 2 Methodology

### 2.1 Multi-regional input–output model

The main method used in this paper is the environmental GMRIO model. Input–output model was developed by Wassily Leontief in the late 1930s, the fundamental purpose of which is to analyze the interdependence of industries in an economy. In input–output work, a fundamental assumption is that the interindustry flow from  $i$  to  $j$  and every unit of output needed a fixed amount of each input through the so-called *Leontief production function*. Then, the relationship between these input–output flows can be represented compactly in matrix form (Miller and Blair 2009).

Based on input–output technology (Peters 2008; Miller and Blair 2009; Boitier 2012; IPCC 2014; Fan et al. 2016), the basic Eq. (1) can be shown in the form of Eq. (2), which represents the framework of GMRIO.

$$X=AX+F \tag{1}$$

$$\begin{pmatrix} \mathbf{x}_1 \\ \vdots \\ \mathbf{x}_m \\ \vdots \\ \mathbf{x}_N \end{pmatrix} = \begin{pmatrix} \mathbf{A}_{11} & \cdots & \mathbf{A}_{1v} & \cdots & \mathbf{A}_{1N} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \mathbf{A}_{m1} & \cdots & \mathbf{A}_{mv} & \cdots & \mathbf{A}_{mN} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \mathbf{A}_{N1} & \cdots & \mathbf{A}_{Nv} & \cdots & \mathbf{A}_{NN} \end{pmatrix} \begin{pmatrix} \mathbf{x}_1 \\ \vdots \\ \mathbf{x}_m \\ \vdots \\ \mathbf{x}_N \end{pmatrix} + \sum_{m=1}^N \begin{pmatrix} \mathbf{f}_{1m} \\ \vdots \\ \mathbf{f}_{vm} \\ \vdots \\ \mathbf{f}_{Nm} \end{pmatrix} \tag{2}$$

where  $\mathbf{x}_m$  is the vector of total output of the country  $m$  ( $m$  and  $v$  both represent the countries,  $m = 1, \dots, N$ ;  $v = 1, \dots, N$ );  $\mathbf{A}_{mv}$  is the interindustrial matrix between country  $m$  and country  $v$ , where the elements are measured as per unit of output;  $\mathbf{f}_{vm}$  is a vector of the final demands in country  $m$  provided by country  $v$ , and its elements are the sum of the final demands of all items, including investment, household consumption, government consumption, and inventory changes.

Equations (3) and (4) can be obtained from Eq. (1).

$$X = (I-A)^{-1}F \tag{3}$$

$$L = (I-A)^{-1} \tag{4}$$

where  $L=(I-A)^{-1}$  is the Leontief inverse matrix through which the final consumption is converted into total demands of output of each industry. Using the vector of each country’s carbon emission factor  $\mathbf{E}_m$  (namely, the CO<sub>2</sub> emissions per output of industries in country  $m$ ), the CO<sub>2</sub> flow matrix can be derived. For simplicity, here we take an IO model with a dimension of three countries as an example, as shown in Eq. (5).

$$\begin{bmatrix} C_{AA} & C_{AB} & C_{AR} \\ C_{BA} & C_{BB} & C_{BR} \\ C_{RA} & C_{RB} & C_{RR} \end{bmatrix} = \begin{bmatrix} (\mathbf{E}_A)' & 0 & 0 \\ 0 & (\mathbf{E}_B)' & 0 \\ 0 & 0 & (\mathbf{E}_C)' \end{bmatrix} \begin{bmatrix} L_{AA} & L_{AB} & L_{AR} \\ L_{BA} & L_{BB} & L_{BR} \\ L_{RA} & L_{RB} & L_{RR} \end{bmatrix} \begin{bmatrix} f_{AA} & f_{AB} & f_{AR} \\ f_{BA} & f_{BB} & f_{BR} \\ f_{RA} & f_{RB} & f_{RR} \end{bmatrix} \tag{5}$$

where  $C_{AB}$  refers to the CO<sub>2</sub> emissions of country A that are embodied in the final consumption of country B, we have defined it as the CO<sub>2</sub> export from country A to country B.<sup>4</sup> Other symbols represent the similar meaning as in Eqs. (2) to (4), with the differences of the various subscripts. When extending this example to multiple countries, the CO<sub>2</sub> flow matrix  $C$  that is needed in this paper can be obtained, as described as set out in Eq. (6).

$$C = \begin{pmatrix} C_{11} & \cdots & C_{1v} & \cdots & C_{1N} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ C_{m1} & \cdots & C_{mv} & \cdots & C_{mN} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ C_{N1} & \cdots & C_{Nv} & \cdots & C_{NN} \end{pmatrix} \tag{6}$$

<sup>4</sup> This is because it can be explained as production emissions from country A exports to country B, becoming imported consumption emissions.

### 2.2 Corresponding indicators

Based on CO<sub>2</sub> flows matrix, two key indicators that reflect the impacts of international trade on CO<sub>2</sub> emissions can be deduced. On one hand, the total exported production emission from country *m* is formed by the sum of production emissions in country *m* embodied in the final consumption of all other countries along the global supply chain (see Eq. (7)). On the other hand, the total imported consumption emission into country *v* is represented by the sum of emissions from all other countries in the global supply chain (see Eq. (8)). For simplicity, we call them exports and imports of CO<sub>2</sub> emissions, respectively, as depicted in Sect. 1.

$$C_m^{\text{exp}} = \sum_{v \neq m}^N C_{mv} \tag{7}$$

$$C_v^{\text{imp}} = \sum_{m \neq v}^N C_{mv} \tag{8}$$

where  $C_m^{\text{exp}}$  means the total CO<sub>2</sub> emissions of country *m* that embodied in all other countries' final consumptions, namely exports of CO<sub>2</sub> emissions from country *m* for short;  $C_v^{\text{imp}}$  denotes the total CO<sub>2</sub> emissions of all other countries driven by the final consumption of country *v*, namely imports of CO<sub>2</sub> emissions of country *v*. It is worth noting that these two indicators are not comparable to the concepts of physical energy imports and exports.

A related indicator is then adopted to represent the difference between CO<sub>2</sub> exports and imports which can be called the CO<sub>2</sub> emission trade balance (CETB), as shown in Eq. (9).

$$C_v^{\text{net}} = C_v^{\text{exp}} - C_v^{\text{imp}} \tag{9}$$

where  $C_v^{\text{net}}$  is the CETB of country *v*. A positive CETB indicates that the amount of emissions produced by country *v* to meet other countries' consumption is larger than that produced by other countries to meet the consumption of country *v*, while a negative balance indicates the amount of CO<sub>2</sub> emissions produced by other countries to meet the consumption of country *v* is larger than that produced by country *v* to meet the consumptions of other countries. The CETB is also equal to the difference between the PBP emissions and its CBP emissions of a country. A positive value of trade balance means that a country's PBP emissions are larger than its CBP emissions.

In addition, the PBP emissions in country *m* and the CBP emissions in country *v* are represented by  $C_m^{\text{prod}}$  and  $C_v^{\text{cons}}$ , which are shown in Eqs. (10) and (11). These two indicators have been used to determine the proportion of one country's emission export in its PBP emissions (see Eq. (12)), and the proportion of emission import in its CBP emissions (see Eq. (13)).

$$C_m^{\text{prod}} = \sum_{v=1}^N C_{mv} \tag{10}$$

$$C_v^{\text{cons}} = \sum_{m=1}^N C_{mv} \tag{11}$$

$$S_m^{\text{exp}} = C_m^{\text{exp}} / C_m^{\text{prod}} \quad (12)$$

$$S_v^{\text{imp}} = C_v^{\text{imp}} / C_v^{\text{cons}} \quad (13)$$

where  $S_m^{\text{exp}}$  is the proportion of CO<sub>2</sub> emissions exports of country  $m$  ( $C_m^{\text{exp}}$ ) in its total PBP emissions ( $C_m^{\text{prod}}$ ),  $S_v^{\text{imp}}$  is the proportion of CO<sub>2</sub> emission imports of country  $v$  ( $C_v^{\text{imp}}$ ) in its total CBP emissions ( $C_v^{\text{cons}}$ ).

### 3 Data source and management

#### 3.1 Data source

As mentioned above, the data source for this study is the WIOD. The WIOD provides non-competitive world IO tables (WIOTs), relevant environmental accounts, and corresponding social economic data (Dietzenbacher et al. 2013). The scope of the yearly WIOT covers 41 economies (40 economies plus a rest of world entry) and 35 sectors during the whole period of 1995–2011. However, the environmental account that provides CO<sub>2</sub> emission data is confined to the year 2009, which constrains the time scope of this study to the year 2009. The WIOD has been successfully applied to empirical works in multiple fields (Arto and Dietzenbacher 2014; Johnson 2014; Timmer et al. 2014; Voigt et al. 2014; Jiang and Liu 2015; Kucukvar et al. 2015; Los et al. 2015; Zhang et al. 2015). Table 1 displays a microcosm of a WIOT with three economies.

#### 3.2 Boundary definition

Consistent with the data sources, the CO<sub>2</sub> emissions calculated in this paper refer to fossil energy-related carbon emissions, excluding the CO<sub>2</sub> emissions caused by non-commercial energy such as biomass energy and process emissions. Additionally, only CO<sub>2</sub> emissions caused by production are taken into consideration while those emissions caused by household direct energy consumption are excluded. Furthermore, to maintain the comparability of the results, the emission trade related indicators and the CBP emissions and PBP emissions are calculated within the same framework of the GMRIO model.<sup>5</sup>

In particular, the emission coefficients in Eq. (5) are key parameters that significantly impact the results. Tian et al. (2015) have examined the influence of carbon coefficients on emission accountings of different countries. According to their results, the CO<sub>2</sub> emissions embodied in exports in 2009 would be underestimated by 1704 million tons if the carbon coefficients of other economies are artificially fixed at the values of Chinese domestic coefficients. To avoid bias results, we adopt different carbon coefficients for the industry of different economies rather than simply assume them as the same set of coefficients.

<sup>5</sup> Using the same framework can ensure that the total global emissions remain consistent between the production-based and consumption-based accounting methods.

**Table 1** WIOD table illustration

	Intermediate use			Final use			Output
	A	B	RoW	A	B	RoW	
Industries, A	$Z^{AA}$	$Z^{AB}$	$Z^{AR}$	$F^{AA}$	$F^{AB}$	$F^{AR}$	$X^A$
Industries, B	$Z^{BA}$	$Z^{BB}$	$Z^{BR}$	$F^{BA}$	$F^{BB}$	$F^{BR}$	$X^B$
Industries, RoW	$Z^{RA}$	$Z^{RB}$	$Z^{RR}$	$F^{RA}$	$F^{RB}$	$F^{RR}$	$X^R$
Value added	$(w^A)'$	$(w^B)'$	$(w^R)'$				
Int. transp. marg.	$(tm_U^A)'$	$(tm_U^B)'$	0	$(tm_y^A)'$	$(tm_y^B)'$	0	$tm$
Output	$(X^A)'$	$(X^B)'$	$(X^C)'$				

Source: Dietzenbacher et al. (2013)

### 3.3 Selection of major economies

Of the 41 economies, 14 major economies were selected to be the key objects, based on their amounts of total emissions and total emissions trade in the global supply chain.<sup>6</sup> To be specific, we chose the individual top ten economies in terms of total CO<sub>2</sub> emissions (under both production-based and consumption-based principles, in 2009) and total CO<sub>2</sub> emissions in trade (including both exported and imported CO<sub>2</sub> emissions on average from 1995 to 2009), respectively. Through refining the four groups of top ten countries, we finally obtained 14 major economies and a newly generated “rest of world (ROW)” category. The abbreviations used for these economies are shown in Table 2. It is notable that ROW here refers to all the other countries except the 14 major economies, which differs from the initial world input–output table. In order to make the result more accurate, instead of merging the original IO table, we aggregated the accounting results of the other 27 economies (41 minus 14) after applying the 41 countries to the GMRIO model.

## 4 Results and discussions

### 4.1 Overview of the global trade of CO<sub>2</sub>

As shown in Fig. 1, both total global CO<sub>2</sub> emissions and the total CO<sub>2</sub> emissions trade (equal to the total amount of CO<sub>2</sub> exports or imports) showed an overall increase trend during the period 1995–2009, with the exception of a slight decrease in 2009 due to the economic crisis. In detail, global CO<sub>2</sub> emissions increased from 18.95 billion tons in 1995 to 24.87 billion tons in 2009, with emissions trade increasing from 4.04 billion tons in 1995 to 6.15 billion tons in 2009. This trend represents an average annual growth rate of 1.96 and 3.04 %, respectively. In particular, during the period 2002–2008, both two types of emissions experienced rapid annual growth rates of 3.45 and 5.78 %, respectively. This phenomenon was due largely to China’s participation in the world trade organization (WTO) in November 2001, which contributed to a significant promotion of international trade. Compared with global CO<sub>2</sub> emissions, the CO<sub>2</sub>

<sup>6</sup> As stated in Fan et al. (2016), the 14 economies are selected and compared with the 40 economies provided by the WIOD, thus possibly making the ranking results inconsistent with those of the whole world. According to our calculation, the total emissions of the 14 countries accounted for approximately two thirds of total global emissions.



**Table 2** The 14 selected major economies

Country	Abbreviation	Country	Abbreviation	Country	Abbreviation
Australia	AUS	Canada	CAN	China	CHN
Germany	DEU	Spain	ESP	France	FRA
The UK	GBR	India	IND	Italy	ITA
Japan	JPN	Korea	KOR	Russia	RUS
Taiwan, China	TWN	The US	USA	Rest of world	ROW

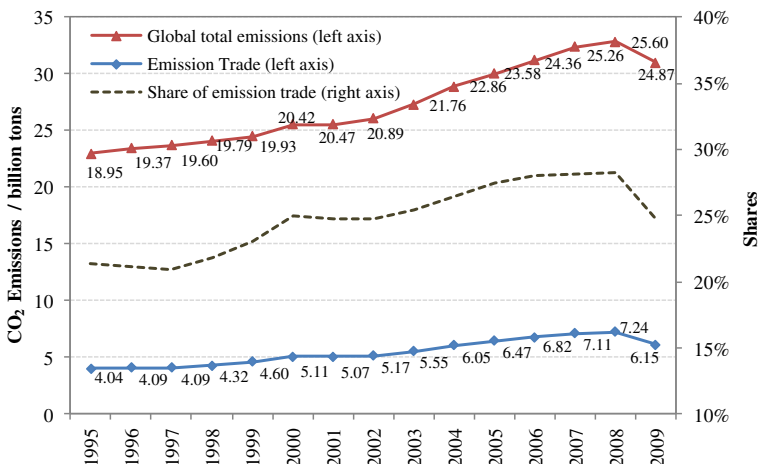
emissions trade grew more rapidly, seeing that its proportion in global CO<sub>2</sub> emissions increased from 21.33 % in 1995 to 28.28 % in 2008, and finally declined to 24.73 % in 2009, again due to the impacts of the economic crisis.

### 4.2 CO<sub>2</sub> exports and imports in major economies

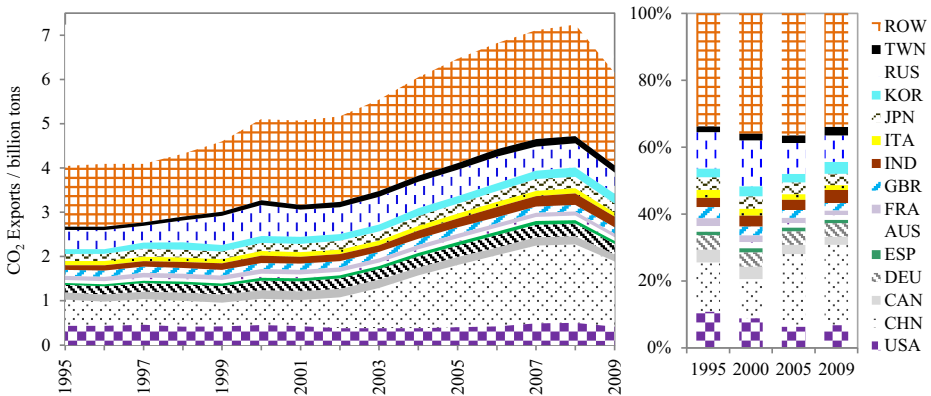
As shown in Figs. 2 and 3, both the total exports and imports of CO<sub>2</sub> emissions for the 14 major economies accounted for approximately two thirds of the global CO<sub>2</sub> trade during 1995–2009, with obvious differences existing among them.

#### 4.2.1 CO<sub>2</sub> exports in major economies

From the export volume of the production-based emissions (Fig. 2), it can be seen that, of these 14 major economies, China ranked first in general; its export volume experienced an increase trend from 0.59 billion tons in 1995 to its ultimate point of 1.77 billion tons in 2008, and then reduced to 1.48 billion tons in 2009. Meanwhile, during the period 1995–2009, China’s production-based CO<sub>2</sub> exports accounted for 11.65~24.72 % of the total global CO<sub>2</sub> exports, with its proportion continuously exceeding 20 % since 2005. The period 2002–2007 witnessed the most obvious increase trend, which exactly accorded with the period from China’s joining to the WTO in 2001 to the global economic crisis in 2008. During this period, China’s CO<sub>2</sub> exports increased from 0.69 to 1.76 billion tons, with an average annual growth rate up to



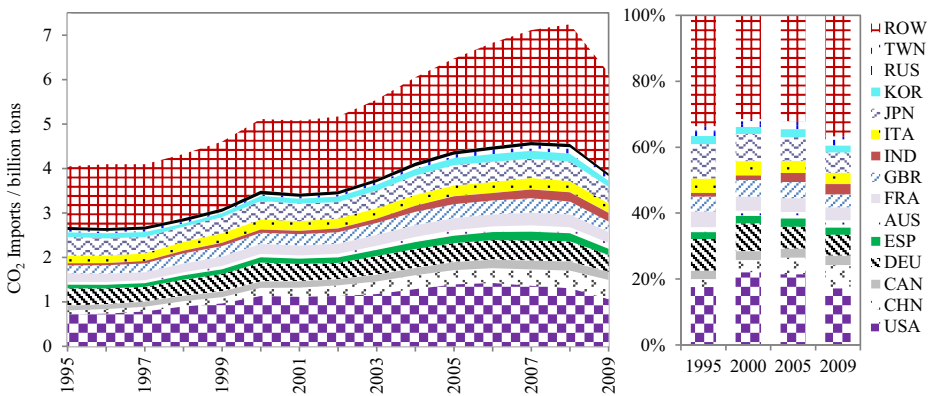
**Fig. 1** The global CO<sub>2</sub> emissions and CO<sub>2</sub> emissions trade during 1995–2009



**Fig. 2** Annual CO<sub>2</sub> exports of major economies during 1995–2009 (note: the original data of this figure can be found in Table 3 in the Appendix)

20.42 %, which makes it obvious that China’s joining in the WTO not only promoted world economic trade, but also triggered China’s CO<sub>2</sub> emissions for other countries. It is expected that China’s CO<sub>2</sub> exports is likely to continuously increase in the following several years because Chinese total exports have increased from 1578 billion United States of America (USA) dollars in 2009 to 2342 billion in 2014, with an average annual growth rate of 14 % (NBS 2015).

Russia and the USA were the two countries which also possessed high volumes of CO<sub>2</sub> exports, with an average annual export volume of 0.55 and 0.43 billion tons, respectively, during 1995–2009 (see Fig. 2). For Russia, its CO<sub>2</sub> exports were obviously higher during the period 1999–2006, with its annual volumes being 0.6–0.7 billion tons and its proportion in global CO<sub>2</sub> exports staying between 11 and 14 %. Russia’s CO<sub>2</sub> exports in the years 1999 and 2000 were the highest (0.66 and 0.70 billion tons), with its corresponding proportions being as high as 14.31 and 13.65 %, respectively. The CO<sub>2</sub> exports of the USA were relatively stable, ranging from 0.38 to 0.51 billion tons. However, as the global CO<sub>2</sub> exports increased, the corresponding shares for the USA declined with time, from 10.75 % in 1995 to 6.73 % in 2009.



**Fig. 3** Annual CO<sub>2</sub> imports of major economies during 1995–2009 (note: the original data of this figure can be found in Table 4 in the Appendix)

The average annual CO<sub>2</sub> exports for Germany and Japan during 1995–2009 were 0.23 and 0.20 billion tons, respectively, and showed an overall increase trend with time. If ignoring the impacts of the economic crisis in 2008, for the period 1995–2007 the average annual growth rates of these two countries reached 4.22 and 5.11 %, respectively. Germany's CO<sub>2</sub> exports accounted for around 3.92~4.70 % of global CO<sub>2</sub> exports, and this proportion decreased with time; meanwhile, the share of Japan's CO<sub>2</sub> exports stayed between 3.36 and 4.39 % and also declined over time, with the share in 2009 being the lowest. In addition, the volume of India's CO<sub>2</sub> exports was also relatively high and showed an obvious growth trend with time. Indeed, it grew from 0.14 to 0.24 billion tons during the period 1995–2009, with a high point in 2008, and the average annual growth rate was 5.11 %. Meanwhile, its proportion in global CO<sub>2</sub> exports experienced an increase trend from 2.81 % in 1995 to 3.93 % in 2009.

Additionally, the annual CO<sub>2</sub> exports for both Canada and the UK were above 0.1 billion tons, with the former being between 0.15 and 0.19 billion tons and the latter being between 0.13 and 0.15 billion tons. Meanwhile, their shares in global CO<sub>2</sub> exports decreased with time, with the former declining from 3.89 % in 1995 to 2.45 % in 2009 and the latter from 3.27 to 2.22 % over the same time period. The annual production-based CO<sub>2</sub> exports from Korea and Chinese Taiwan ranged between 74.89 and 221.40 million tons and increased significantly with time. The shares of these two countries in global CO<sub>2</sub> exports also increased with time, with the former increasing from 2.70 % in 1995 to 3.60 % in 2009 and the latter from 1.85 % in 1995 to 2.61 % in 2009. For Australia, Spain, France, and Italy, their CO<sub>2</sub> exports were relatively low with an annual volume of 0.1 billion tons and below.

#### 4.2.2 CO<sub>2</sub> imports of major economies

From the consumption-based CO<sub>2</sub> imports shown in Fig. 3, we can see that, among the 14 major economies, the import volume of the USA consistently ranked top during the whole period. The USA also experienced an overall increase trend, reaching the highest point of 1.42 billion tons in 2006. The CO<sub>2</sub> imports of the USA accounted for 17.21~22.08 % of the total global CO<sub>2</sub> imports during 1995–2009, indicating that approximately one fifth of the world's CO<sub>2</sub> trade was driven by the consumption of this country. For Germany and Japan, their CO<sub>2</sub> imports were also very high and comparatively stable during the period 1995–2009, with the annual volumes of both countries ranging between 0.33 and 0.46 billion tons. However, as the global CO<sub>2</sub> emissions trade increased, their shares in the global CO<sub>2</sub> imports declined over time, with the shares of Germany decreasing from 9.63 % in 1995 to 6.28 % in 2009 and that of Japan from 10.37 to 6.10 % over the same time period.

Similar characteristics existed in the cases of France, the United Kingdom (UK), and Italy, all of which also experienced a stable and slight increase trend from 1995 to 2009. Meanwhile, their annual proportions in global CO<sub>2</sub> imports ranged between 3.41 and 5.29 % and depicted a decrease trend over time. For Canada, Spain, and Australia, although their CO<sub>2</sub> imports were relatively low, with average annual amounts of 0.15, 0.13, and 0.10 billion tons, respectively, they all revealed an overall increase trend. During the period 1995–2008 (excluding the decline in 2009), the average annual growth rates for these three countries were 5.14, 6.33, and 6.48 %, respectively. Accordingly, their proportions in the global CO<sub>2</sub> imports also increased during 1995–2009, with the shares of Canada increasing from 2.62 to 2.87 %, Spain from 2.02 to 2.24 %, and Australia from 1.49 to 2.16 %.

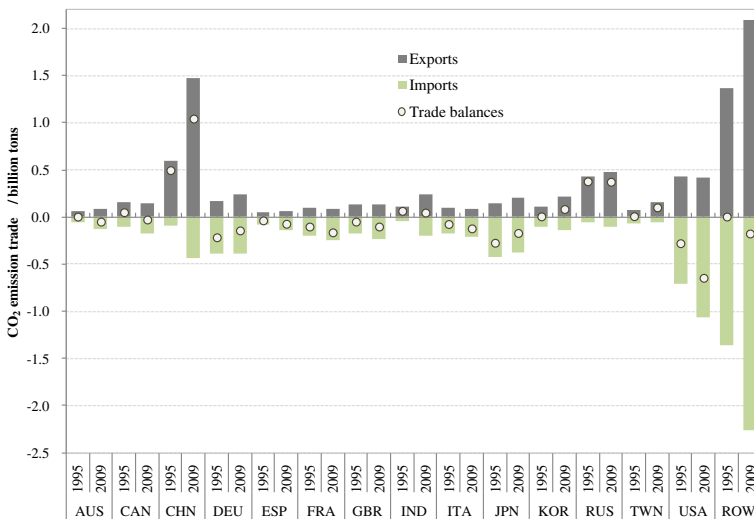
In particular, China's consumption-based CO<sub>2</sub> imports showed an obvious increasing trend from 95.47 million tons in 1995 to 433.25 million tons in 2009, with an average annual growth rate of 11.4 %. Its share in global CO<sub>2</sub> imports increased from 2.36 to 7.05 %, thus making

China the second largest CO<sub>2</sub> importer among the 14 major economies, with the USA being the largest. Similarly, although the average annual CO<sub>2</sub> imports of India and Russia were relatively low (113 and 699 million tons, respectively), they both showed an upward trend from 1995 to 2009 (regardless of the decline in 2009), with average annual growth rates being 11.99 and 7.72 %, respectively. Accordingly, India’s share in global CO<sub>2</sub> imports increased from its lowest point (1.18 %) in 1995, to its highest point (3.16 %) in 2009, and shares of Russia increased from 1.37 to 1.71 % over the same period. For Korea and Chinese Taiwan, however, their CO<sub>2</sub> imports did not show definite increase or decrease trends. During the period 1995–2009, their average annual CO<sub>2</sub> imports were 129.05 and 71.08 million tons, respectively, and the proportion of Chinese Taiwan in global CO<sub>2</sub> imports declined obviously from 1.62 % in 1995 to 0.94 % in 2009, while the share of Korea fluctuated between 1.60 and 2.79 %.

### 4.2.3 CETB in major economies

The CETB for a country can directly account for the difference between its PBP and CBP CO<sub>2</sub> emissions. As shown in Fig. 4, we can see that, in both 1995 and 2009, China was the largest net exporter of CO<sub>2</sub> emissions, and the USA was the largest net importer of CO<sub>2</sub> emissions. Moreover, the absolute volumes of the net CO<sub>2</sub> trade for both countries increased over time, with the net CO<sub>2</sub> exports of China increasing from 0.50 billion tons in 1995 to 1.04 billion tons in 2009 (increasing by 1.1 times) and the net CO<sub>2</sub> imports of the USA increasing from 0.28 billion tons in 1995 to 0.64 billion tons in 2009 (increasing by 1.33 times).

Other than China, the net exporters in 1995 and 2009 also included Russia, Chinese Taiwan, Korea and India. Of these countries, although Russia’s net export in 2009 was lower than that in 1995 (dropping from 0.38 billion tons to 0.37 billion tons), although its net export was still significantly larger than that of the other three economies, making Russia the second largest net exporter of CO<sub>2</sub> emissions. For India, as a developing country, its net exports decreased during 1995–2009 from 65.76 to 47.79 million tons. The net exports of both Chinese Taiwan and



**Fig. 4** The CETB for major economies in 1995 and 2009. ( note: After examining the values for the entire period 1995–2009, no break points exist for any of the major economies, with the exception of 1 year in the case of Korea. Therefore, the CO<sub>2</sub> trade balances for 1995 and 2009 can be said to basically represent unbiased changes during the period)

Korea increased during this period, the former increased from 9.42 to 102.88 million tons (an increase of nearly 10 times), which made Chinese Taiwan the third largest net exporter, and the latter increased from 7.45 to 85.34 million tons (an increase of 10.5 times).

In addition to the USA, there were six other net importers during the period 1995–2009. These countries, in terms of absolute volume, ranking from high to low in 1995, were Japan (273 million tons), Germany (214 million tons), France (100 million tons), Italy (73.7 million tons), the UK (47.9 million tons), and Spain (35.1 million tons). In 2009, the net imports of Japan and Germany decreased to 169 and 141 million tons, respectively, and those of France, Italy, the UK, and Spain increased to 162, 120, 100, and 70.8 million tons, respectively. As a result, the rankings of Germany and France were exchanged. Combining the case of the USA, this reflected the fact that the net imports of the USA in 2009 were significantly higher than those of the above named countries.

Furthermore, besides the ROW, two other countries (Australia and Canada) have transformed from net exporters (4.81 and 51.33 million tons) in 1995 into net importers (48.1 and 25.81 million tons) in 2009, reflecting the changes of the CO<sub>2</sub> trade pattern in these countries. Australia became a net importer in 2002 and Canada became a net importer in 2006.

### 4.3 Comparisons between CO<sub>2</sub> trade and total national emissions

Figures 5 and 6 presented the proportions of CO<sub>2</sub> exports in the total PBP emissions and CO<sub>2</sub> imports in the total CBP emissions for each economy during the period 1995–2009, respectively (i.e., relative volumes of CO<sub>2</sub> exports and imports compared with their own national emissions).

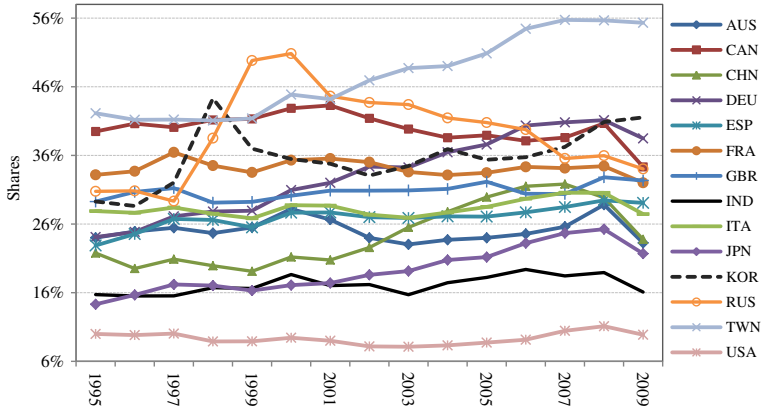
#### 4.3.1 CO<sub>2</sub> exports and proportions

As shown in Fig. 5, among the 14 major economies, the proportion of the CO<sub>2</sub> exports of the USA in its own national PBP emissions was the lowest at approximately 10 %, and thus was located at the bottom of the figure. This suggested that 90 % of the US territory CO<sub>2</sub> emissions were driven by its domestic final consumption. Contrary to this, the corresponding proportion for Chinese Taiwan was generally the highest in excess of 40 %, and hence was located at the top of the figure. Meanwhile, its proportions showed a significant upward trend, suggesting that more than 50 % of its production-based CO<sub>2</sub> emissions have been driven by the final consumption of other economies since 2005. This reflected an emission-intensive export structure for Chinese Taiwan; for this case, its CO<sub>2</sub> exports should not be ignored when taking action in terms of energy saving and emission reduction.

The curves for other countries were situated between those of the USA and Chinese Taiwan, with their proportions being between 15 and 40 %. Among these countries, the shares of India and Japan were relatively low, less than 20 %, while those of Canada and Russia were relatively high at about 40 %. Additionally, the proportions of Japan, China, and Germany experienced increase trends with time (except during the years 2008 and 2009), and shares for Russia and Korea increased at first and then decreased; the other seven countries witnessed relatively minor fluctuations, revealing an overall stable trend.

#### 4.3.2 CO<sub>2</sub> imports and proportions

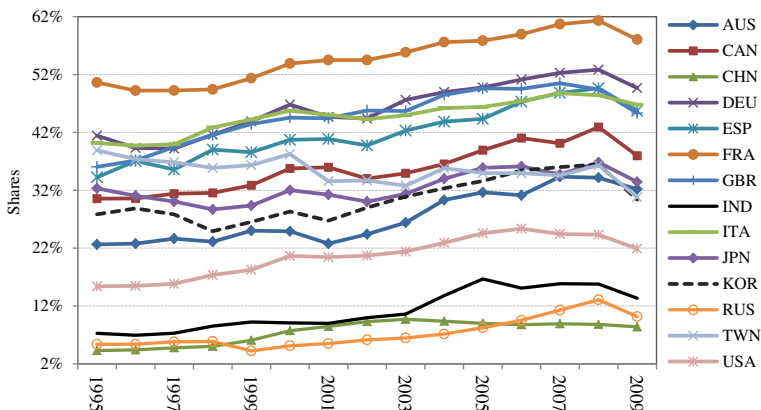
Unlike the characteristics of the proportions of CO<sub>2</sub> exports in PBP emissions, as shown in Fig. 6, the proportions of the CO<sub>2</sub> imports in the total CBP emissions for these major economies,



**Fig. 5** Proportions of CO<sub>2</sub> exports in PBP CO<sub>2</sub> emissions for major economies during 1995–2009

depicted an overall consistent increase trend during the period 1995–2009. An exception occurred in the case of Chinese Taiwan, where an obvious decrease trend was evident for the proportions of its CO<sub>2</sub> imports. Along with the significant increase trend for its CO<sub>2</sub> exports, this reflected dramatic changes in the characteristics of Taiwan’s trade pattern, and the growing impacts of trade on its CO<sub>2</sub> accounting system over time. Among other countries, the proportion of CO<sub>2</sub> imports for France remained above 50 %, with a highest point of 61.3 % occurring in 2008. This proportion was significantly higher than those of other countries, indicating that the final consumption of France depended heavily on the carbon emissions of other countries. The curves of Germany, Italy, and Spain in Fig. 6 were close with some intersections among them. As a result, these shares ranged from 40 to 50 %, rendering these countries to be categorized as the relatively high CO<sub>2</sub> import-dependent countries. Ranking in accordance with their proportions of CO<sub>2</sub> imports, from high to low, the following countries were Canada, Japan, Korea, and Australia, all of which showed a nearly parallel trend, with shares roughly between 20 and 40 %.

Compared with other developed countries, the shares of the USA were the lowest. Its share increased from 15 % in 1995 to the highest point around 25 % in 2006 and has remained above 20 % since 2000. This formed a distinct contrast with its highest volume of CO<sub>2</sub> imports, reflecting an ultra-high CO<sub>2</sub> emissions consumption pattern of this country. In other words, the



**Fig. 6** Proportions of CO<sub>2</sub> imports in CBP CO<sub>2</sub> emissions for major economies during 1995–2009

final consumption of the USA not only drove a large amount of CO<sub>2</sub> emissions in other countries but also lead to much greater CO<sub>2</sub> emissions for itself. At the bottom of the figure, there were three countries. Their CO<sub>2</sub> import shares were all distributed around 10 %, which was obviously lower than those of other countries, indicating that the final consumption of these three countries relied heavily on their domestic CO<sub>2</sub> emissions. Moreover, their proportions also increased with time. This was especially the case for India which enjoyed a relatively rapid growth rate, reflecting its gradual changes in the consumption dependence structure.

Again, it is notable that the proportion of CO<sub>2</sub> imports in CBP emissions in this paper should be distinguished from the physical imports dependency. For instance, the crude oil and natural gas consumptions of India and China are highly dependent on imports from abroad while their CO<sub>2</sub> import proportions in CBP emissions are fairly low. This is because the indicator in this paper, the proportion of CO<sub>2</sub> imports in CBP CO<sub>2</sub> emissions, is calculated based on total sectoral output driven by one country's final consumption and the emission coefficients, in a process in which the global supply chain relationships are fully considered. In this framework, crude oil or natural gas imported by one country is probably reflected by outputs of the energy mining sector in export countries; meanwhile, the energy mining sector might not be a carbon-intensive one.

## 5 Conclusions and policy implications

Based on the results and discussions above, some main conclusions and policy implications are proposed, which consist of the following.

1. Global CO<sub>2</sub> trade experienced a faster growth rate overall than that of global CO<sub>2</sub> emissions during 1995–2009, leading its proportion in global CO<sub>2</sub> emissions to increase from 21.33 % in 1995 to 28.28 % in 2008. It is clear that the global supply chain plays a significant role in accounting each country's CO<sub>2</sub> emissions. To achieve a deeper international mitigation of CO<sub>2</sub> emissions, it is necessary to introduce a broader range of policy options rather than only resorting to production and technological solutions. In addition to the volumes of emission exports and imports for different countries, the roles of these factors in their corresponding PBP and CBP emission inventories varied with time, indicating that it is of importance to relate consumption-induced emissions spillover to mitigation policy instruments to attain the ultimate objective of addressing global warming through the avoidance of carbon leakage. For example, the well-known carbon border tax adjustments may be a good choice to provide definitive knowledge concerning the effects on different countries when it is elaborately designed. In practice, however, few national governments have considered applying these philosophies when making policy, except for some state border carbon adjustments for specific goods such as electricity exports from California to Quebec.
2. Climate policy at global level should be designed and promoted by considering the huge proportion of global CO<sub>2</sub> emissions trade in total CO<sub>2</sub> emissions. For example, a global carbon emission trade system (ETS) would be an effective policy tool in mitigating CO<sub>2</sub> emissions to a considerably large extent. Currently, most emission trade systems, with the exception of European Union, are restricted to a single country level, imposing very limited influence on emission transfers among countries. If the global emission trade system is established, tradable products will be imposed a kind of price markup through the carbon pricing system, thus stimulating global emission reduction.



3. Developing and developed countries show very distinctly different characteristics in the respect of CO<sub>2</sub> imports and exports. Therefore, developed and developing countries should be distinguished with regard to making strategies for CO<sub>2</sub> emission reduction. Given that developed and developing countries basically reveal the opposite characteristics of carbon trade balance (net exporters and net imports, respectively), two different types of climate policies can be emphasized: (i) consumption-side emission reduction strategies such as reducing energy wasting at home might be a good focus for developed countries; (ii) production-oriented reduction strategies such as incentives to improve energy efficiency may be still regarded as an efficient tools for developing countries.
4. When considering individual economies, China's CO<sub>2</sub> imports increased rapidly and ranked second only to the USA. Thus, the climate policy aimed at reducing China's CBP emissions is relatively more important for the reduction of global emissions. For the USA, only 10 % of its territory CO<sub>2</sub> emissions were driven by other countries' final consumptions. However, its CO<sub>2</sub> imports ranked highest in spite of taking the lowest proportion in its total CBP emissions among the developed countries. This indicates the huge effects of the US's consumption on the global CO<sub>2</sub> emissions. It can be seen from the dramatic decrease of CO<sub>2</sub> emission trade and global emissions in 2009, which was caused to a great extent by US subprime mortgage crisis in 2008. It also reflects the huge differences between the PBP emission and CBP inventories for the USA. In this case, the global emission reduction policies should take comprehensive consideration of both principles, thus a weighted responsibility accounting principle might be a choice. More than 50 % of the PBP CO<sub>2</sub> emissions for Chinese Taiwan were driven by the final consumption of other economies since 2005. Therefore, a re-examination of its CO<sub>2</sub> emission sources should be undertaken so as to offer effective policy support for its energy saving and emission reduction.

## 6 Further perspectives

This paper offers a comprehensive accounting and discussion in relation to the trade of CO<sub>2</sub> emissions for major emitters from a continuous time series perspective and draws some interesting conclusions. However, due to the limitations of the scope of this study, many important issues need to be extended or further discussed. For example, the sector sources of the CO<sub>2</sub> imports and exports for each country, the driving factors for the changes in the CO<sub>2</sub> trade as well as the CBP CO<sub>2</sub> emissions for major economies, and the relationship between the CO<sub>2</sub> emissions trade and the corresponding value added in the global supply chain, all require further examination. Global CO<sub>2</sub> emissions increased with an average annual growth rate of 3.25 % during 2009–2013 (IEA 2015), which was much higher than that during 1995–2009 (1.96 %). The share of the total exports of goods and services based on the world gross domestic product (GDP) increased during 2009–2011 and then decreased during 2011–2015 (WB 2016). Therefore, extending the time span from 2009 to as far as possible close to the present is also important. These are meaningful topics that all deserve a place in future studies.

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## Appendix

Table 3 Total CO<sub>2</sub> exports of major economies during 1995–2009 (unit: million tons)

	AUS	CAN	CHN	DEU	ESP	FRA	GBR	IND	ITA	JPN	KOR	RUS	TWN	USA	ROW
1995	65.1	157.3	593.2	174.8	46.6	94.2	132.0	113.4	100.5	146.6	109.0	434.6	74.9	434.6	1365.4
1996	69.5	164.1	546.2	182.6	45.9	98.1	142.4	118.8	96.6	161.5	112.7	425.4	75.7	435.7	1417.1
1997	73.0	169.3	577.1	192.3	54.8	105.2	140.2	124.4	100.2	179.8	135.6	380.8	81.6	461.8	1316.0
1998	74.6	181.3	583.6	196.8	55.4	105.5	131.8	137.2	98.5	175.6	165.3	496.1	86.5	415.0	1415.4
1999	79.1	182.0	538.6	193.8	58.8	99.0	129.2	144.7	96.3	173.0	147.9	658.1	90.4	420.3	1586.9
2000	90.5	191.9	594.9	217.0	66.5	103.7	136.4	166.2	106.0	183.6	158.8	697.1	107.6	451.6	1836.1
2001	88.4	194.5	592.2	226.7	67.0	102.5	143.4	154.6	106.8	183.4	160.7	613.0	107.6	427.4	1902.2
2002	80.5	186.1	694.0	241.3	69.7	99.8	138.8	160.1	102.6	199.8	148.7	607.7	122.1	385.0	1932.1
2003	77.4	185.6	909.8	241.3	69.4	97.4	143.2	151.0	104.0	208.6	156.4	625.2	133.5	381.0	2061.7
2004	82.4	176.7	1183.1	255.2	74.6	95.6	145.1	181.2	108.0	222.5	177.9	596.9	138.7	391.7	2216.2
2005	87.2	179.3	1402.6	260.0	78.2	98.0	151.5	198.0	111.2	221.5	170.8	595.3	148.8	407.2	2358.9
2006	91.7	170.2	1609.7	284.2	77.3	97.1	141.1	226.7	116.2	243.1	175.3	603.1	168.8	421.1	2395.3
2007	93.7	183.7	1758.0	287.0	82.0	95.1	139.9	236.4	118.7	266.8	189.8	542.2	172.0	490.6	2456.3
2008	106.3	185.5	1767.7	284.0	76.9	93.9	147.4	258.9	115.6	258.0	213.2	544.8	160.9	506.2	2519.8
2009	84.7	150.7	1477.7	244.9	67.1	83.4	136.6	241.9	90.4	206.9	221.4	479.9	160.6	414.0	2088.8

**Table 4** Total CO<sub>2</sub> imports of major economies during 1995–2009 (unit: million tons)

	AUS	CAN	CAN	CHN	DEU	ESP	FRA	GBR	IND	ITA	JPN	KOR	RUS	TWN	USA	ROW
1995	60.3	106.0	95.5	389.1	81.7	194.6	179.9	47.6	174.2	419.2	101.6	55.4	65.5	711.6	1360.0	
1996	61.8	105.7	103.7	357.7	83.1	187.0	190.1	48.1	166.5	390.6	114.0	54.3	64.5	731.8	1433.4	
1997	66.1	115.8	109.3	332.9	82.9	177.9	201.2	53.2	167.9	371.7	110.9	56.5	67.9	777.9	1400.1	
1998	68.4	119.3	124.1	363.6	97.9	195.7	228.4	63.6	194.7	343.8	69.0	49.4	69.4	889.9	1441.4	
1999	77.0	126.5	147.5	390.9	107.7	207.3	240.1	73.7	208.3	368.8	91.0	29.3	73.1	957.1	1499.8	
2000	76.4	142.4	185.2	425.9	119.4	222.2	254.0	72.4	221.5	418.9	114.0	36.3	81.9	1127.9	1609.0	
2001	71.7	143.2	208.9	388.9	120.7	222.7	257.0	74.5	217.7	395.1	110.0	44.4	68.6	1108.4	1638.3	
2002	82.3	135.8	243.6	368.1	124.3	221.9	262.4	85.5	216.4	375.6	122.9	51.2	70.2	1126.7	1681.7	
2003	92.9	150.6	285.1	421.1	138.4	243.5	269.5	96.1	230.8	402.3	133.1	56.4	68.6	1172.1	1785.2	
2004	115.4	161.9	317.7	426.6	156.6	262.0	302.4	137.1	242.2	437.0	145.4	64.9	80.5	1280.8	1915.1	
2005	127.8	179.2	324.8	427.9	167.6	267.4	314.7	177.5	241.4	460.8	157.9	77.5	77.3	1386.7	2080.2	
2006	127.3	192.1	336.2	440.0	181.0	267.1	317.0	167.4	248.2	454.5	172.9	96.2	75.9	1419.0	2326.2	
2007	142.5	195.9	368.2	456.2	196.4	283.5	327.1	196.8	256.7	433.2	180.0	124.9	72.2	1360.0	2518.7	
2008	136.3	203.4	401.6	455.4	181.4	283.4	294.6	207.7	246.6	445.0	176.9	145.8	73.1	1299.5	2688.5	
2009	132.8	176.5	433.3	386.3	137.9	245.1	236.8	194.1	210.3	375.4	136.1	105.4	57.8	1058.4	2263.0	

## References

- Al-mulali U, Sheau-Ting L (2014) Econometric analysis of trade, exports, imports, energy consumption and CO<sub>2</sub> emission in six regions. *Renew Sust Energ Rev* 33:484–498
- Ang BW, Lee SY (1994) Decomposition of industrial energy consumption: some methodological and application issues. *Energy Econ* 16(2):83–92
- Arto I, Dietzenbacher E (2014) Drivers of the growth in global greenhouse gas emissions. *Environ Sci Technol* 48(10):5388–5394
- Barrett J, Peters G, Wiedmann T, Scott K, Lenzen M, Roelich K, Le Quéré C (2013) Consumption-based GHG emission accounting: a UK case study. *Clim Pol* 13(4):451–470
- Boitier B (2012) CO<sub>2</sub> emissions production-based accounting vs consumption: insights from the WIOD databases. In the final WIOD conference proceedings, Groningen, The Netherlands, April 24–26
- Dietzenbacher E, Los B, Stehrer R, Timmer M, De Vries G (2013) The construction of world input–output tables in the WIOD project. *Econ Syst Res* 25(1):71–98
- Fan J-L, Hou Y-B, Wang Q, Wang C, Wei Y-M (2016) Exploring the characteristics of production-based and consumption-based carbon emissions of major economies: A multiple-dimension comparison. *Applied Energy*, in press
- Feng K, Davis SJ, Sun L, Li X, Guan D, Liu W, Liu Z, Hubacek K (2013) Outsourcing CO<sub>2</sub> within China. *Proc Natl Acad Sci* 110(28):11654–11659
- Ferng J-J (2003) Allocating the responsibility of CO<sub>2</sub> over-emissions from the perspectives of benefit principle and ecological deficit. *Ecol Econ* 46(1):121–141
- Guo J, Zou L-L, Wei Y-M (2010) Impact of inter-sectoral trade on national and global CO<sub>2</sub> emissions: an empirical analysis of China and US. *Energy Policy* 38:1389–1397
- Hubacek K, Feng K (2016) Comparing apples and oranges: some confusion about using and interpreting physical trade matrices versus multi-regional input–output analysis. *Land Use Policy* 50:194–201
- IEA (2015) CO<sub>2</sub> emissions from fuel combustion highlights 2015. International Energy Agency, Paris
- IPCC (2014) Regional development and cooperation. In: climate change 2014: mitigation of climate change. Contribution of working group III to the IPCC AR5. In: climate change 2014: mitigation of climate change. Cambridge University Press, New York
- Jayanthakumaran K, Liu Y (2016) Bi-lateral CO<sub>2</sub> emissions embodied in Australia–China trade. *Energy Policy* 92: 205–213
- Jiang X, Liu Y (2015) Global value chain, trade and carbon: case of information and communication technology manufacturing sector. *Energy Sustain Dev* 25(0):1–7
- Johnson RC (2014) Five facts about value-added exports and implications for macroeconomics and trade research. *J Econ Perspect* 28(2):119–142
- Johnson RC, Noguera G (2012) Accounting for intermediates: production sharing and trade in value added. *J Int Econ* 86(2):224–236
- Kasman A, Duman YS (2015) CO<sub>2</sub> emissions, economic growth, energy consumption, trade and urbanization in new EU member and candidate countries: a panel data analysis. *Econ Model* 44:97–103
- Kim Y, Worrell E (2002) CO<sub>2</sub> emission trends in the cement industry: an international comparison. *Mitig Adapt Strateg Glob Chang* 7:115–133
- Kiuiila O, Wójtowicz K, Żylicz T, Kasek L (2016) Economic and environmental effects of unilateral climate actions. *Mitig Adapt Strateg Glob Chang* 21(2):263–278
- Kucukvar M, Egilmez G, Onat NC, Samadi H (2015) A global, scope-based carbon footprint modeling for effective carbon reduction policies: lessons from the Turkish manufacturing. *Sustain Prod Consumption* 1:47–66
- Lenzen M, Pade L-L, Munksgaard J (2004) CO<sub>2</sub> multipliers in multi-region input-output models. *Econ Syst Res* 16(4):391–412
- Liu L-C, Liang Q-M, Wang Q (2015) Accounting for China's regional carbon emissions in 2002 and 2007: production-based versus consumption-based principles. *J Clean Prod* 103(0):384–392
- Los B, Timmer MP, de Vries GJ (2015) How global are global value chains? A new approach to measure international fragmentation. *J Reg Sci* 55(1):66–92
- Meng B, Xue JJ, Feng KS, Guan DB, Fu X (2013) China's inter-regional spillover of carbon emissions and domestic supply chains. *Energy Policy* 61:1305–1321
- Miller RE, Blair PD (2009) *Input-output analysis: foundations and extensions*, second edn. Cambridge University Press, New York
- Munksgaard J, Pedersen KA (2001) CO<sub>2</sub> accounts for open economies: producer or consumer responsibility? *Energy Policy* 29(4):327–334
- Munksgaard J, Pade L-L, Minx J, Lenzen M (2005) Influence of trade on national CO<sub>2</sub> emissions. *Int J Glob Energy Issues* 23(4):324–336

- Muñoz P, Steining KW (2010) Austria's CO<sub>2</sub> responsibility and the carbon content of its international trade. *Ecol Econ* 69(10):2003–2019
- Nakano K, (2015) Screening of climatic impacts on a country's international supply chains: Japan as a case study. *Mitigation and Adaptation Strategies for Global Change*, in press: 1–17
- National Bureau of Statistics of China (NBS) (2015) China statistical year book 2015. China Statistical Press, Beijing
- Peters GP (2007) Opportunities and challenges for environmental MRIO modelling: illustrations with the GTAP database. In 16th International Input-Output Conference, Istanbul
- Peters GP (2008) From production-based to consumption-based national emission inventories. *Ecol Econ* 65(1): 13–23
- Peters GP, Hertwich EG (2008) CO<sub>2</sub> embodied in international trade with implications for global climate policy. *Environ Sci Technol* 42(5):1401–1407
- Sánchez-Chóliz J, Duarte R (2004) CO<sub>2</sub> emissions embodied in international trade: evidence for Spain. *Energy Policy* 32:1999–2005
- Su B, Ang BW (2013) Input-output analysis of CO<sub>2</sub> emissions embodied in trade: competitive versus non-competitive imports. *Energy Policy* 56:83–87
- Su B, Ang BW (2014) Input-output analysis of CO<sub>2</sub> emissions embodied in trade: a multi-region model for China. *Appl Energy* 114:377–384
- Tian J, Liao H, Wang C (2015) Spatial-temporal variations of embodied carbon emission in global trade flows: 41 economies and 35 sectors. *Nat Hazards*:1–20
- Timmer MP, Erumban AA, Los B, Stehrer R, de Vries GJ (2014) Slicing up global value chains. *J Econ Perspect* 28(2):99–118
- Tolmasquim MT, Machado G (2003) Energy and carbon embodied in the international trade of Brazil. *Mitig Adapt Strateg Glob Chang* 8:139–155
- Voigt S, De Cian E, Schymura M, Verdolini E (2014) Energy intensity developments in 40 major economies: structural change or technology improvement? *Energy Econ* 41(0):47–62
- WB, The World Bank (2016) World Bank Open Data, <http://data.worldbank.org/>
- Weber CL, Matthews HS (2007) Embodied environmental emissions in US international trade, 1997–2004. *Environ Sci Technol* 41(14):4875–4881
- Wilting H, Vringer K (2007) Environmental accounting from a producer or a consumer principle: an empirical examination covering the World. In: 16th International Conference on Input-Output Techniques, Istanbul
- Wyckoff AW, Roop JM (1994) The embodiment of carbon in imports of manufactured products: implications for international agreements on greenhouse gas emissions. *Energy Policy* 22(3):187–194
- Xu Y, Dietzenbacher E (2014) A structural decomposition analysis of the emissions embodied in trade. *Ecol Econ* 101:10–20
- Yang Z, Dong W, Wei T, Fu Y, Cui X, Moore J, Chou J (2015) Constructing long-term (1948–2011) consumption-based emissions inventories. *J Clean Prod* 103:793–800
- Zhang Z, Guo J, Hewings GJD (2014) The effects of direct trade within China on regional and national CO<sub>2</sub> emissions. *Energy Econ* 46:161–175
- Zhang W, Peng S, Sun C (2015) CO<sub>2</sub> emissions in the global supply chains of services: an analysis based on a multi-regional input-output model. *Energy Policy* 86:93–103