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

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ABSTRACT

Greenhouse gas emissions embodied in international trade have grown rapidly as globalization has progressed and potentially threaten the efficacy of unilateral climate treaties such as the Kyoto Protocol. Consumption-based methods have been put forward as a way of overcoming this issue and help design future climate policies. We improve the Long-term Consumption-based Accounting (LCBA) model, with transfer carbon data from 1948 to 2012 by introducing country-specific import intensities and detailed bilateral trade data from UNcomtrade. Comparisons of our new “LCBA2” model with existing 4 studies show similar consumption based emission patterns both in trend and magnitude, and significant emission changes in many European countries. The results independently confirm previous findings on the efficacy of the Kyoto Protocol. The results indicate transferred emissions have contributed an historic 36 Gt CO_2 of cumulative emissions, have grown rapidly during the past 30 years (up to 8% of total emissions) and are likely to become increasingly influential in the near future as the global economy recovers. We also use the improved model to study other gases (CH_4, N_2O and SO_2) embodied in trade, and results indicate similar transfer patterns as CO_2 with comparable or even moderately larger magnitudes. Across-method result differences between LCBA2 with 3 other models are analyzed based on using common input datasets. Large emitters show moderate biases (within 10%) and about 75% of countries have differences within 25%, independent of input dataset. The LCBA2 model provides useful estimates of transferred emissions in both across-country and long-term historical contexts.
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1. Introduction

A growing number of countries have implemented policies to regulate carbon emissions within their borders. However, the true impacts of these policies have been questioned due to soaring trade interactions and emission transfers among countries (Peters and Hertwich, 2008; Aichele and Felbermayr, 2012; Andrew et al., 2013; Kanemoto et al., 2014). These phenomena are often called carbon leakage (Peters and Hertwich, 2008; Davis and Caldeira, 2010; Jakob et al., 2014) and can be induced by both “policy” (strong carbon leakage) and “consumption” (weak carbon leakage). Although strong carbon leakage and the relevant “pollution haven hypothesis” are of serious concern, ex post econometric studies do not show statistically significant evidence of them (Branger and Quirion, 2014). Weak carbon leakage, however, is broader in concept, unrelated to policies, and often triggered by comparative advantages, endowments and factor productivity in different countries (Weber and Peters, 2009; Peters et al., 2009; Jakob and Marschinski, 2013). In this study, we focus on weak carbon leakage and attempt to analyze the transferred emissions embodied in trade and their long-term patterns. These emissions are shown to be a significant factor in explaining emission changes in many countries (Nakano et al., 2009; Davis and Caldeira, 2010; Peters et al., 2011b), especially for large emitters such as China (Weber et al., 2008; Guan et al., 2009; Minx et al., 2011), the USA (Weber and Matthews, 2007) and the UK (Baiocchi and Minx, 2010; Wiedmann et al., 2010; Barrett et al., 2013). Recent studies also indicate that the Kyoto Protocol may be failing to fulfill its carbon-

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

Most empirical research on consumption-based emissions and emission transfers has been implemented using Multi-Regional Input-output (MRIO) models (Peters and Hertwich, 2004; Lenzen et al., 2004; Peters et al., 2011a; Kanemoto et al., 2014) and has focused on specific years (Peters and Hertwich, 2008; Nakano et al., 2009; Davis and Caldeira, 2010; Davis et al., 2011; Andrew et al., 2013). The very large data requirements limit the ability of the input–output framework to track changes over time (Peters et al., 2012a, 2011b; Caldeira and Davis, 2011; Miller and Blair, 2009). Due to recent advancements in constructing MRIO databases (Tukker and Dietzenbacher, 2013; Dietzenbacher et al., 2013; Andrew and Peters, 2013; Meng et al., 2013) and comparison work (Inomata and Owen, 2014; Moran and Wood, 2014; Owen et al., 2014; Arto et al., 2014; Geschke et al., 2014), some studies have transcended this limitation and conducted time series analyses at the global scale over the period from 1990 to 2010 (Peters et al., 2011b, 2012b; Caldeira and Davis, 2011; Wiebe et al., 2012; Lenzen et al., 2012, 2013; Arto et al., 2012). Peters et al. (2011b)) developed a time-series algorithm (TSTRD) to achieve long time series with trade data to estimate consumption-based emissions successfully. Wiebe et al. (2012) set up the Global Resource Accounting Model (GRAM) using linear interpolation to fill in missing data in input–output and final demand tables. Lenzen et al. (2012, 2013) developed a long term MRIO database (called EORA, which provides a completely harmonized and balanced world MRIO table) by specifying initial estimates and applying a quadratic programming approach to balance external constraint information such as merchandise trade, aggregate data and input–output tables. Kanemoto et al. (2014) further extend the EORA database to backdate consumption-based emissions to 1970. Arto et al. (2012) estimated the 1995–2008 resource use footprint of nations using the traditional MRIO method based on the World Input-Output Database (WIOD) project Timmer, 2012, Dietzenbacher et al., 2013). All these studies help backdate historical data, facilitate the establishment of regular carbon footprint monitoring schemes and provide the foundation to complement the current production-based accounting system.

Previous research based on MRIO databases constructs carbon emission transfers beginning in 1990, limiting our understanding of the spatial and temporal patterns of transferred emissions. Therefore, long term (over 60 years) transferred emission data is needed. Not only because it can display long term patterns, but also because it can be used to set up new scenarios of consumption-based emissions in contrast to the territorial ones for different countries/groups. And these scenarios can be used as external forcing data and be put into climate models in order to research the climatic impact of transfer emissions (Wei et al., 2012, 2016). To further backdate these data, Yang et al. (2015) set up a new framework called LCBA (Long-term Consumption-based Accounting model) for estimating historical emission transfers since 1948. However, the LCBA model ignored regional disparities merely assuming global averages for "importation intensity", which affects the credibility of the results. We address this problem here by grouping countries using a hierarchical clustering method based on their emissions per GDP and dynamic time warping algorithm, and increased use of bilateral trade data from the UNcomtrade database (UN, 2014). We show results for 164 countries over the period from 1948 to 2012 (Table S1–S2). Furthermore, we show that the improved LCBA model (hereinafter LCBA2) is effective in calculating transfers of non-CO_2 greenhouse gases (e.g. CH_4 and N_2O, 1970–2011, Tables S3–S4) and air pollutants (e.g. SO_2, 1948–2005, Tables S5–S6). These new results from LCBA2 independently confirm previous findings on the efficacy of the Kyoto Protocol. Although our error analysis shows that results are greatly influenced by the calculation framework even after harmonization of territorial emissions, for large emitters, differences among datasets are always within ±10%.

2. Materials and methods

2.1. LCBA2 model

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

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

Where $F_{Cr}(r,i)$ and $F_{Pr}(r,i)$ represent the consumption-based and production-based emissions for country r in year i, respectively. *Imports*(r,i) and *Exports*(r,i) are the annual trade of goods and services from each country r. $COEF(r,i)$ is the "production intensity" estimated (CO_2 emissions per unit of "Gross Productive Output") for country r in year i. This is a compound indicator which represents changes of emission factors, technology, energy uses and production method etc (SI Section 1). "Gross Productive Output" equals GDP plus imports minus "imported elements" (Yang et al., 2015). $COEF_{im}(r,i)$ refers to "importation intensity" which is calculated based on "production intensity" estimates. The constraints in Equation (1) mean that in each year the total imports equals exports of embodied emissions, and also that total territorial emissions equals consumption-based emissions. This "substance conservation" is achieved in each simulation by setting importing and consumption-based emissions to exporting and territorial ones respectively (SI Section 2). Theoretically speaking, LCBA2 resembles a simple version of EEBT-style Multi-regional input-output model (Peters, 2008) without sectoral details (SI Section 1).

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