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Identifying the atmospheric and economic key drivers of global air pollution change: a combined SDA approach

Sandy Dall'erba[1], Nicole Riemer[2], Yilan Xu[1], Ran Xu[3], Yao Yu[2]

[1] Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign
[2] Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign
[3] Academy of Mathematics and Systems Science, CAS, University of Chinese Academy of Sciences, and Key Laboratory of Management, Decision and Information Systems, CAS.

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Abstract: The transmission of pollution across countries has been studied through the lens of atmospheric chemical transport or through its content in international trade. The few studies that consider both channels concurrently do not highlight what the key drivers of the change in pollution production and transmission are. Based on a structural decomposition method this paper uncovers which changes in target pollutants emanate from technological changes, structural changes, final demand changes or household activities taking place locally, in the trade partners, or in the upwind countries. We apply our approach to a five-region model and focus on carbon monoxide (CO) for its capacity to promote the formation of secondary pollutants. Our results provide solid scientific evidence for the US, the European Union and South Korea to request changes from China because the large increase of its domestic demand is the main driver of the growth in CO they experienced over 1990-2014. By providing new insights into the interconnected sources of air pollution, this paper suggests more nuanced global emission abatement policies than the consumer-focused or producer-focused approaches currently used.

Climate, Regional, Environmental and Trade Economics
65-67 Mumford Hall
1301 West Gregory Drive
Urbana, IL, 61801

1. Introduction

The world population, currently at 7.7 billion people, has doubled since 1970, which has led to an increase in global consumption and production fueled by economic specialization and decreasing transportation costs (Hummels *et al.*, 2001; Dean *et al.*, 2011). Naturally, this surge in worldwide production has caused air pollution to worsen over time. Large producers of heavy manufacturing, such as China, thus have experienced an increase in premature deaths and life expectancy losses due to the air pollution embedded in their production regardless of whether the products are consumed domestically or internationally (Yang *et al.*, 2013; Lin *et al.*, 2014; Zhang *et al.*, 2017). The distinction between accounting for pollution at the source of production or final consumption has occupied a prominent role in the academic literature and in the policy arena (Takahashi *et al.*, 2014; Jiang *et al.,* 2015). For instance, while the Kyoto Protocol allocates the full responsibility of the emissions to the producers, other approaches such as the Ecological Footprint offer to hold the consumers fully accountable (e.g. Hoekstra and Janssen, 2006; Munksgaard *et al.*, 2005; Davis and Caldera, 2010). More recent contributions have brought to the fore the need to consider shared responsibility further in order to avoid double-counting the emission footprint of consumers and producers (Lenzen et al., 2007; Dietzenbacher *et al.*, 2020; Kahjehpour *et al.*, 2021; Turner *et al.,* 2007). These contributions, like this paper, are based on input-output techniques of which system approach accounts for the amount of air pollution associated with production, trade and consumption at the sub-national and international levels. Findings based on these techniques highlight the extent to which consumption in one country relies on domestic or foreign production, and therefore generates pollution, in the home country or abroad.

However, neither ecological footprint nor environmentally extended input-output explicitly control for the international transport of pollutants through the atmosphere. Global model simulations (Liang *et al.*, 2004) and analysis of remote sensing data (Jiang *et al.*, 2007) suggest that pollution such as particulate matter (PM) or carbon monoxide produced in China can reach the US within a few days. The reach and travel speed of a pollutant depend on the pollutant's chemical nature as well as the altitude at which it travels. To our knowledge, only a handful of studies have focused on the transboundary pollution transport effect of global trade. For instance, Lin *et al.* (2016) show that the radiative climate forcing from aerosols and their precursor gases is larger in regions that produce and export emissions-intensive goods. They also note the potential for weather systems to contribute to additional aerosol forcing transported over long distances (Shindell and Faluvegi, 2009). Zhang *et al.* (2017) find that the transboundary health impact of PM 2.5 pollution (particulate matter where particle size < 2.5 micrometers) associated with international trade is greater than the impact associated with transport of pollutant through wind (Lin *et al.*, 2014). They also find that in 2007 up to 30,900 deaths in East Asian countries downwind from China were related to emissions produced in China.

Such pollution externalities call for pollution abatement responsibilities to be shared between the consuming countries, the producing countries, and the upwind countries. However, before shared responsibility can be established, one needs to identify and quantify the drivers of air pollution and the geographical origins of the transboundary inflows of air pollution. As of today, these concepts are not incorporated into any authoritative international pollution abatement effort. Part of the difficulty lies in distinguishing the factors driving the increase in emissions in upwind countries from the role of evolving wind patterns because one cannot act upon the latter. Clearly, we must understand these factors so that we can suggest a new pollution abatement responsibility sharing system that will help reduce the impact of emissions on human health (Marques *et al.*, 2012).

To our knowledge, the literature that has studied the role of trade and atmospheric flows in the effect of air pollution on health relies on a static approach only (e.g. Zhang *et al.*, 2017; Lin *et al.*, 2016), hence it does not allow to identify the changes that have taken place or the mechanisms that have led to such changes. A notable exception is Dasadhikari *et al*. (2019) who uncover that the increase in early deaths in the Asia-Pacific area over 2010-2015 is driven by growth in energy and industry production in the region. In this paper, we use the international supply-chain linkages from the EORA dataset (Lenzen *et al*., 2012, 2013) and state-of-the-art atmospheric flow modelling techniques (Bey *et al*., 2001, Chen *et al*., 2009) to perform a structural decomposition analysis (SDA, see Dietzenbacher and Los, 1998) of the changes in air emissions over 1990-2014. This approach is commonly used in the environmentally-extended input-output literature to identify how changes in factors such as technology, supply-chain linkages (structural effect) and final demand explain the total change in air pollution emission (De Haan, 2001), energy use (Su and Ang, 2012) or water withdrawals (Avelino and Dall'erba, 2020). However, in this manuscript we go beyond the traditional economic supply-chain SDAs. We plan to leverage the state-of-the-art atmospheric flow modeling techniques and introduce for the first time in the SDA literature how changes in emissions from heavy manufacturing countries affect downwind countries. Our research focuses on CO emissions because the content of CO in global production and trade has been relatively understudied in the literature (exceptions are Lin *et al*., 2014; Blanco *et al*., 2014; Zhang *et al*., 2017), yet it has a large influence on the atmospheric oxidative capacity that promotes formation of secondary aerosols.

Identifying the factors that contributed to the change in transboundary pollution transport pattern between 1990 and 2014 will allow us to go beyond the traditional pollution abatement policies where the responsibility is allocated to producers, consumers, or shared between them (e.g. Mi *et al*., 2016; Yang *et al*., 2014; Zhu *et al*., 2018). Indeed, our proposed approach accounts for the fact that a pollution abatement policy will generate benefits both in the places of production and in their downwind neighbors. For instance, a tax on the consumption of polluting goods in the US could discourage consumers from buying these goods which, in turn, could reduce their production and export wherever they are manufactured (e.g., China). This change could trickle down to third-party countries located downwind of China (e.g. South Korea) because they, too, could experience a lower pollution level. As such, our findings will fill in a research gap in the literature on pollution abatement policies and shared responsibility (Zhu *et al*., 2018; Lenzen *et al*., 2007; Creutzig *et al*., 2015; Mi *et al*., 2016).

In the next section we detail the input-output model and the atmospheric chemistry transport model to trace the carbon monoxide (CO) emissions via trade flows and wind flows, as well as the structural decomposition formulation. Our focus in this paper is CO emissions, a gas of which content in trade has been relatively understudied in the literature (exceptions are Lin *et al*., 2014; Blanco *et al*., 2014; Zhang *et al*., 2017), yet has a large influence on the atmospheric oxidative capacity that promotes the formation of secondary aerosols. Next, we describe the data, their source and the sample in Section 3. The manuscript focuses on the largest polluting economies, namely the United States, China and Europe. We add South Korea (S.K.) to the system due to its proximity and downwind position from China. Indeed, pollution leaving the east coast of China reaches South Korea within one to seven days according to Kim (2019). The rest of the world is subsumed in its own category. Its disaggregation will take place in future research. Section 4 reports the results and their discussion while Section 5 presents the conclusion and policy implications.

2. Methodology

2.1. SDA of CO embedded in production and trade

SDA is a comparative static exercise that identifies the role of several components in the overall change in pollutant creation over a period of interest. This process isolates the change in one set of parameters at a time while keeping the others fixed at the initial or final year. As a result, the specification of a structural decomposition is not unique and the number of its equivalent forms increases as the number of parameters increases (Dietzenbacher and Los, 1998). Therefore, although this methodological section shows one possible decomposition form, the results will be generated by the average effect of all equivalent decomposition permutations for each factor which, in the case of Eq. (1) below, is $\mathbf{3}! = \mathbf{6}$ forms.

Using indices 0 and 1 to indicate the first (1990) and last (2014) year of the period that we study, we start in Eq. (1) with a basic three factor decomposition of the total change in CO due to the economic activities in a country:

$$\Delta\mathbf{CO}_{\boldsymbol{eco}} = \Delta(\boldsymbol{cLf}) = \hat{\boldsymbol{c}}_1\boldsymbol{L}_1\boldsymbol{f}_1 - \hat{\boldsymbol{c}}_0\boldsymbol{L}_0\boldsymbol{f}_0 = \Delta\hat{\boldsymbol{c}}\boldsymbol{L}_0\boldsymbol{f}_0 + \hat{\boldsymbol{c}}_1\Delta\boldsymbol{L}\boldsymbol{f}_0 + \hat{\boldsymbol{c}}_1\boldsymbol{L}_1\Delta\boldsymbol{f} \tag{1}$$

Where $\hat{\boldsymbol{c}}_1\boldsymbol{L}_1\boldsymbol{f}_1$ is the total amount of CO at time 1 ($\hat{\boldsymbol{c}}_0\boldsymbol{L}_0\boldsymbol{f}_0$ is for time 0). $\hat{\boldsymbol{c}} = \boldsymbol{p}\hat{\boldsymbol{x}}^{-1}$ is the direct pollutant input coefficient where $\boldsymbol{p}$ is the pollutant vector, corresponding to the quantity of pollutant generated to satisfy one unit of production in a sector, and $\boldsymbol{x}$ the total output vector of each sector. $\boldsymbol{f}$ is the final demand vector. As usual in the input-output literature, final demand is composed of demand by consumers, the government, changes in inventory and exports. When calculated over two time periods, the structural decomposition method can be used to explore the relative contribution of the various components of demand. $\boldsymbol{L}$ is the Leontief inverse matrix. The elements of $\boldsymbol{L}$, noted $\boldsymbol{L}_{\boldsymbol{rs}}$, represent the total (direct and indirect) output of sector r that is required to satisfy one unit of final demand in sector s. The use of an interregional input-output Leontieff matrix allows us to calculate the pollution generated through the production of both intermediate and final goods whether they end up being consumed locally or abroad.

The right-hand side of Eq. (1) decomposes the changes in CO emissions due to production into three traditional elements: i) $\Delta\hat{\boldsymbol{c}}\boldsymbol{L}_0\boldsymbol{f}_0$ is the contribution of the changes in direct CO creation per unit of production in each sector/economy (the CO intensity effect); ii) $\hat{\boldsymbol{c}}_1\Delta\boldsymbol{L}\boldsymbol{f}_0$ is the contribution of the changes in the local and foreign inter-industrial linkages (structural effect, also called technological effect); iii) $\hat{\boldsymbol{c}}_1\boldsymbol{L}_1\Delta\boldsymbol{f}$ is the contribution of changes in domestic and foreign final demand (final demand effect).

If the most relevant factor turns out to be the CO intensity effect, then supporting a greener technology in the most polluting sectors of the producing countries, taxing emissions and/or implementing tradable emission permits might achieve the largest pollution reduction (Jordaan *et al.*, 2017; Beckerman and Pasek, 1995). An example of this approach is the Intended Nationally Determined Contributions signed in 1993 at the United Nations Framework Convention on Climate Change. They became Nationally Determined Contributions in the countries that ratified the 2015 Paris Agreement. However, according to Liang *et al.* (2014) and Guan *et al.* (2014), this approach would not work in a China where the country's anticipated technology improvements will "barely be able to offset pollutant emissions associated with increasing consumption" (Zhao *et al.,* 2015, p 5443). Yet, there is hope. As noted by Lin *et al.* (2016), it would cost far less for developing countries to adopt lower emission technologies than for more developed nations to support incremental improvement of their much cleaner technology.

If, however, the results of the SDA indicate that the technology effect played a major role in the change of CO emissions, then one possible strategy is the relocation of supply chains. Based on empirical evidence, the literature has mostly focused on relocation to less developed countries with less stringent pollution standards. For instance, Zhao *et al.* (2015), among others, doubt the efficiency of a relocation strategy if it is not accompanied by a change in the consumption patterns. Indeed, they expect this approach would actually lead to more emissions because production in geographically remote countries would increase the need for transportation services between them and other links of the supply chain. In addition, relocation would take place in countries with lower costs of production which are often associated with lesser regulation, less efficient technologies and higher emissions per unit of production. Furthermore, if relocation requires the construction of new infrastructures, then the new pollution emissions could be staggering. Indeed, Andrew (2018) shows that concrete processing accounted for about 4% of the global fossil fuel emissions in 2016. However, considering raising global trade tensions, the desire to create local employments and growing concerns for climate change, it is not impossible that rerouting supply chain linkages increasingly considers relocation to developed countries (Wang and Hewings, 2020).

Finally, if final demand is the main driver of CO emissions change, then consumers should be made responsible by paying, for instance, a tax on their consumption choices. This consumption-based accounting approach has generated a large amount of interest in the literature (Mi *et al*., 2016; Yang *et al*., 2014; Steininger *et al*., 2013) because importing countries benefit from the price difference in the production cost and do not bear the health effects associated with the emissions due to production (Zhu *et al*., 2018). However, a consumption-based accounting approach should not be implemented on its own as the exporting countries (the producers) benefit from the employments, technological advances and other economic advantages that exports generate (Creutzig *et al*., 2015; Liu *et al.,* 2012). As such, recent contributions offer to split the responsibility between importing and exporting countries based on their differences in terms of criteria such as pollution intensity (Zhu *et al*., 2018), income (Marques *et al.,* 2012) and value-added (Lenzen *et al*., 2007) so that all the links in the supply-chain would simultaneously contribute to pollution reduction. Note that the latter approach would also be relevant if the structural effect is the main driver of CO emission changes.

2.2. Modelling atmospheric emissions and transport

Developing modeling capabilities to predict the concentration of atmospheric trace gases and aerosol particles has a long history in atmospheric sciences research (Grose *et al*., 1987, Brasseur *et al*., 1998, Jacobson *et al*., 1996, Bey *et al*., 2001). These efforts have been motivated by the need to assess the potential impact of human activities on the chemical composition of the global atmosphere and the climate system. For this paper, our aim is not only to predict concentration fields of pollutants but also to extract information from where the pollution originates at a given location. This task is commonly known as "source apportionment". Several approaches exist for the source apportionment of trace gases and particulate matter in atmospheric models. Among them, the Lagrangian dispersion models have been used to determine source-receptor relationships and the contributions to long-range transport (Stohl *et al*., 2005). They are computationally efficient, but they allow only one receptor region to be studied at a time, and typically use simplified chemical mechanisms. Another option are the Eulerian chemical transport models. Their "Zero-out analysis" has often been used where emissions for a target source region or source sector are set to zero (Koo *et al*., 2009, Liu and Mauzerall, 2007, Lin *et al*., 2016). The attribution of pollution to a certain source is then quantified by calculating the difference between the reference simulation and the simulation with "zeroed-out" emissions. More sophisticated approaches include various tracer-based approaches (Ying and Kleeman, 2006; Wagstrom *et al*., 2008; Wang *et al*., 2014) that rely on "tagging" certain pollutants of interest, thereby allowing for determining source contributions from different sectors or regions with only one simulation. This is the approach we exploit for this paper, since we want to investigate several pairs of origin and destination countries.

The global chemistry model, GEOS-Chem, is an appropriate choice for this work as it provides several species that are "tagged" with location and sector of origin (Bey et al., 2001; Chen et al., 2009; Fisher et al., 2014) with CO being one of them. We use a horizontal resolution of 2 by 2.5 degree for our model simulations. The GEOS-Chem model relies on global emission inventory data and meteorological data. It predicts the spatial and temporal distribution of concentration fields of different chemical trace gases during transport. The full chemistry simulation includes NOx-Ox-hydrocarbon tropospheric chemistry with more than 300 reactions and over 80 chemical species and includes emissions from anthropogenic and natural sources. The emission inventory data is described in Section 3.2 in more detail. The model simulations are driven by assimilated meteorological fields from the Goddard Earth Observing System (GEOS-Chem) of the NASA Global Modeling and Assimilation Office (Gelara et al., 2017). The model itself, along with the necessary inputs is freely available to the scientific community and has a large number of users around the world.

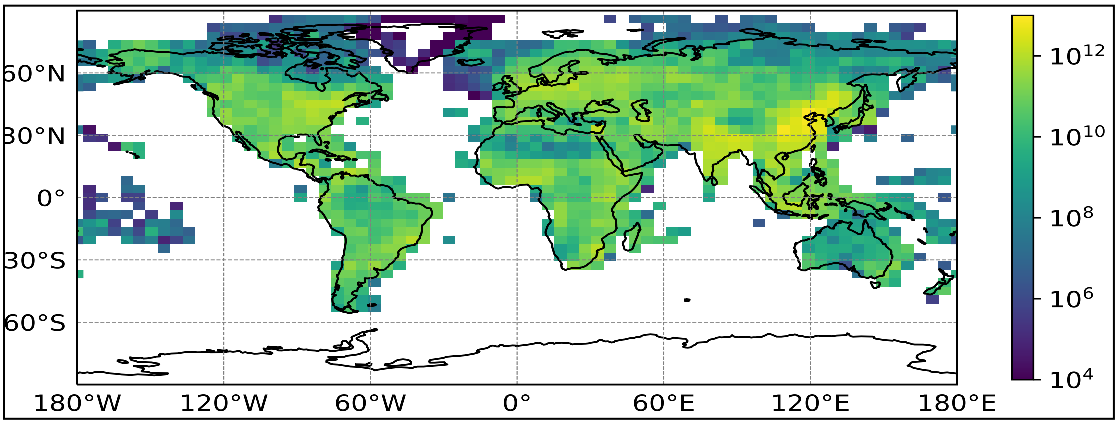


Figure 1 Spatial distribution of CO emissions (in count/cm^2/s) at 2 x 2.5 degree resolution, averaged for the year 2014.

In order to illustrate the capabilities of the GEOS-Chem model, Figure 1 shows the spatial distribution of CO emission fluxes averaged for the year 2014. These emission fluxes are ingested into the model for different chemical species following a specified annual cycle (e.g. Hoesly *et al.*, 2018). After the emissions enter the atmosphere, they are transported with the wind away from their sources.

2.3. SDA of the change in CO produced and transmitted

In addition to the CO created during the production process ($\mathbf{CO_{eco}}$) as captured in Eq. (1), CO emissions are also due to the activities of households such as when they drive their personal car, cook and heat their housing. These types of emissions, although they represent just 5-10% of the total, are not included in the interindustry transaction matrix $\boldsymbol{L}$ because they do not take place in the production site. For instance, Guan *et al.* (2009) note that 33 million metric tonnes of CO_2 have been emitted between 2002 and 2005 in China for these activities. We note them $\mathbf{CO_{hh}}$. Thus, the total change in CO produced in a country is:

$$\Delta\mathbf{CO_{prod}} = \Delta\mathbf{CO_{eco}} + \Delta\mathbf{CO_{hh}} \tag{2}$$

Yet, $\Delta\mathbf{CO_{prod}}$ is not necessarily the most relevant indicator of CO emissions when it comes to studying the impact of air pollution in a country on the health of its citizen. Indeed, $\Delta\mathbf{CO}_{\mathbf{prod}}$ does not account for any type of atmospheric flows from upwind neighboring economies. The latter can be very large for some pairs of economies. For instance, up to 31.8 and 42.4 Tg (tera-grams) of CO entering South Korea could be attributed to China in 1990 and 2014 respectively while the total emissions due to South Korean activities ($\mathbf{CO}_{\mathbf{eco}} + \mathbf{CO}_{\mathbf{hh}}$) are only 1.7 and 1.3 Tg over the same years.

Therefore, we need to account for the emissions that are blown into a country over one cycle of time (in our case, one year) minus the emissions of the same upwind sources that leave the country. They are *net* inflows of emissions and are noted $\mathbf{CO}_{\mathbf{inflow}}$. They correspond to the sum of $\mathbf{CO}_{\mathbf{eco}}$ and $\mathbf{CO}_{\mathbf{hh}}$ in upwind countries net of the similar emissions that leave the country. Their change over time can be written and decomposed as follows:

$$\Delta\mathbf{CO}_{\mathbf{inflow}} = \sum_U \Delta\mathbf{CO}_{\mathbf{U}_{\mathbf{inflow}}} = \sum_U\left(\mathbf{CO}_{\boldsymbol{U}\mathbf{0}}\Delta\mathbf{W}_{\mathbf{inflow}_{\boldsymbol{U}}} + \Delta\mathbf{CO}_{\boldsymbol{U}}\mathbf{W}_{\mathbf{1inflow}_{\boldsymbol{U}}}\right) \tag{3}$$

Where $\sum_U \Delta\mathbf{CO}_{\mathbf{inflow}_{\boldsymbol{U}}}$ denotes the sum of CO inflows coming from upwind countries (U). It can be decomposed into two elements. $\mathbf{CO}_{\boldsymbol{U}\mathbf{0}}\Delta\mathbf{W}_{\mathbf{inflow}_{\boldsymbol{U}}}$ captures how changes in wind patterns between time 0 and 1 affect the CO one country receives from upwind countries. $\Delta\mathbf{CO}_{\boldsymbol{U}}\mathbf{W}_{\mathbf{1inflow}_{\boldsymbol{U}}}$ holds the wind pattern constant (at period 1) and focuses on the change in CO produced in the upwind countries *U*, which is calculated in the same way as in (2).

Note that, as in (1), we show here one possible decomposition form. The results that will be generated will display the average effect of all equivalent decomposition permutations for each factor. In the case of Eq. (3), there are $\mathbf{2!} = \mathbf{2}$ forms. The appendix presents how the final role of each component will be based on the average of these two forms.

Because CO_U in Eq. (3) corresponds to $\mathrm{CO}_{\mathrm{eco}} + \mathrm{CO}_{\mathrm{hh}}$ in the upwind country U, Eq. (3) can be further disaggregated in order to quantify the CO intensity effect, technological effect and final demand effect of each single upwind country:

$$\Delta\mathbf{CO}_{\mathbf{inflow}} = \sum_U\left[\mathbf{CO}_{\boldsymbol{U}\mathbf{0}}\Delta\mathbf{W}_{\mathbf{inflow}_{\boldsymbol{U}}} + \left(\Delta\hat{\boldsymbol{c}}\boldsymbol{L}_0\boldsymbol{f}_0 + \hat{\boldsymbol{c}}_1\Delta\boldsymbol{L}\boldsymbol{f}_0 + \hat{\boldsymbol{c}}_1\boldsymbol{L}_1\Delta\boldsymbol{f} + \Delta\mathbf{CO}_{\mathbf{hh}}\right)_{\boldsymbol{U}}\mathbf{W}_{\mathbf{1inflow}_{\boldsymbol{U}}}\right] \tag{4}$$

Furthermore, the final demand f can be decomposed further to differentiate changes in the domestic vs. foreign demand (itself identifiable by countries).

Unlike the approaches currently available in the literature, the proposed SDA can inform the role of transboundary externalities carried out by the wind. If our SDA reveals that the elements of Eq. (4) play a major role in the changes in CO emissions, then a country should be seeking the CO emissions in the upwind countries *U* to reduce as much as possible. While an upwind producer-based responsibility attribution approach such as a Pigouvian tax (Barnett, 1980; Yu *et al.*, 2020) is the most straightforward mechanism, consumers in *U* are also responsible as part of *U*'s production is for domestic demand. In addition, a transfer of technology from downwind to upwind countries could also help the later improve its emission intensity standard and would have a direct positive impact on the downwind countries. None of these approaches would be considered if wind flows were disregarded as is usual in the literature. Only by carrying out the work will we be able to identify clearly which pollution abatement policy is the most appropriate for each country of our sample.

3. Data

3.1. Input-output data

The multi-regional input-output tables and air pollution coefficients we use are available from the recently released EORA dataset (Lenzen *et al*., 2012, 2013). It provides a comprehensive list of trace gases and aerosols (31 types) for 189 countries, 26 economic sectors, for each year over the 1990-2015 period. In this paper, we will focus on five regions: the United States (US), the European Union (EU), China mainland (CHN), South Korea (SK) and a Rest of the World region (ROW) as described in Figure A of the appendix. The model creates separate tracers diagnostics for the CO emitted from these regions. The initial and final years are 1990 and 2014 as atmospheric fluxes cannot be derived from GEOS-Chem beyond 2014. Although carbon monoxide is not directly an aerosol precursor, we focus on its emissions because of its influence on the atmospheric oxidative capacity that promotes the formation of secondary pollutants.

As described in Lenzen *et al.* (2013), the emission data contained in EORA come from the European Commission's Joint Research Center EDGAR (Emission Database for Global Atmospheric Research) database. The calculation of emissions relies on a technology-based emission factor approach that is consistently applied for all world economies (Janssens-Maenhout *et al*., 2015).

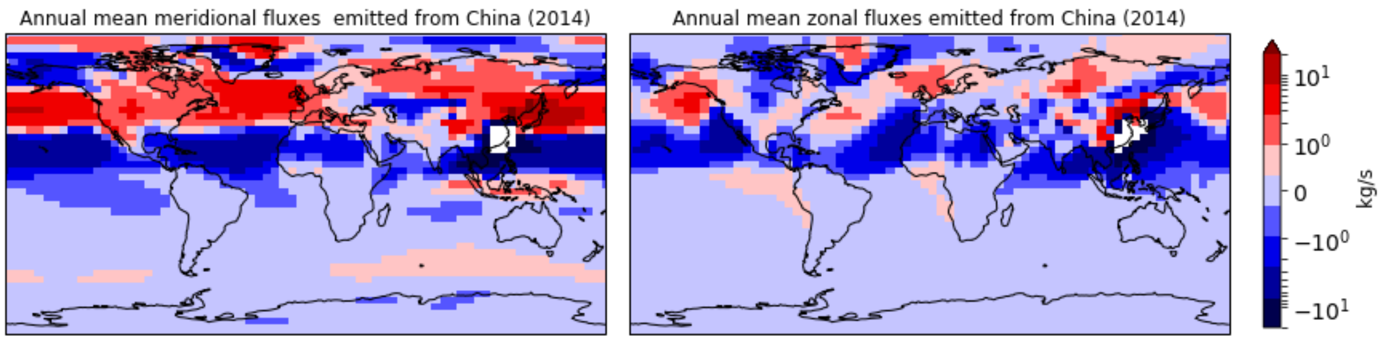
Due to the current lack of information on industrial and final demand deflators used in the construction of the dataset, we deflate the tables to 2010 constant prices using the procedure and data from the World Input-Output Database (WIOD) 2013 release (Timmer *et al*., 2015). This procedure involves deflating the entire EORA system for a given year using price deflators in national currency and then adjusting for exchange rate variations with the U.S. dollar (Dietzenbacher *et al*., 1998; 1999).

Controlling for inflation in a system combining trade- and atmospheric-based flows is new in the literature as, to our knowledge, recent contributions such as Zhang *et al*. (2017) and Lin *et al.* (2016) focus on one year only and on data up to 2007. Focusing on more timely data and on the change between time periods allow us to identify the key drivers of the change in air emissions. Hence, another important contribution of this paper is to provide more recent information about air emissions.

3.2. Data for the atmospheric flux analysis

The emission data used for our current simulation is from the Community Emissions Data System (CEDS) (Hoesly *et al*., 2018). This is the most comprehensive inventory option for the model which provides annual emission data of different gases and aerosol species from 1750-2014 for 225 countries/regions. In this inventory, five major sectors are included: Energy production, Industry, Transportation, RCO (residential, commercial, other), and Agriculture and Waste.

Since our goal is to identify the changes between two years, we simulate the years 1990 and 2014. Monthly-averaged tagged CO fluxes of these two years are saved as output for the analysis. Figure 2 shows as an example the flux distribution of CO for the model layer near the surface that was emitted from China, averaged for the year 2014 and separated into meridional and zonal fluxes. As expected, the CO fluxes originating from China are mostly distributed over the northern hemisphere. As for the zonal fluxes, more than 25 kg/s of CO are transported eastward out of northern China and reaches as far as the west coast of the United States and beyond. Large westward fluxes transport CO to southern China.


Annual mean meridional fluxes emitted from China (2014)

Annual mean zonal fluxes emitted from China (2014)

Figure 2: Global annual meridional (left) and zonal CO fluxes (right) emitted from China in 2014, for the model layer near the surface. Flux values are positive when transport occurs eastward and northward respectively.

Because CO fluxes are tagged by the source country, we can analyze the fluxes into and out of a country that originated from any source country, including itself. The calculation principle is illustrated by Figure 3. For simplicity, we choose 3 grid points in both the vertical and horizontal directions for country k. Fluxes vary with latitude, longitude and altitude even though the latter dimension is included in the calculations but not shown in the illustration. Fluxes from the surface to a 72 km altitude are included in order to capture the inflow and outflow within the entire atmospheric column. Note that the highest fluxes are frequently located at several kilometers above the surface since the windspeed increases with altitude.

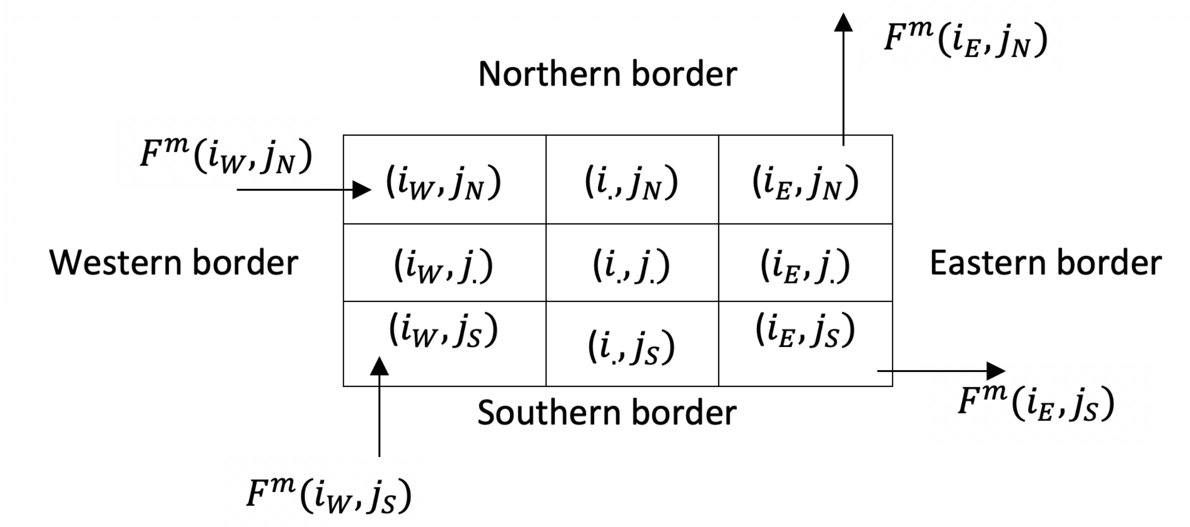


Figure 3: Illustration of the flux calculation for a given domain. i and j are location indexes for the grid boxes in the country k. F^m represents the flux of CO that originated from country m. i_W and i_E are the latitude indices of the western and eastern borders. j_S and j_N are the longitude indices of the southern and northern borders. A dot represents any region between these borders.

Influxes into and outfluxes from country k are calculated separately. For the western and southern borders, positive flux values are counted as influxes and negative values are outfluxes. Fluxes over the eastern and northern borders are just the opposite: negative values represent influxes and positive values represent outfluxes. Combining all the influxes and outfluxes along the borders of the domain from the surface $l = 0$ up to 72 km of altitude, we can obtain the total fluxes from country m to country k through the following equation:

$$I_k^m = \sum_{l=0}^{72}[\sum_{j=j_S}^{j=j_N}(\max(F_k^m(i_W, j.), 0) - \min(F_k^m(i_E, j.), 0)) + \sum_{i=i_W}^{i=i_E}(\max(F_k^m(i., j_S), 0) - \min(F_k^m(i., j_N), 0))] \tag{5}$$

Similarly, the fluxes of CO emitted in region m flowing out of region k are:

$$O_k^m = \sum_{l=0}^{72}[\sum_{j=j_S}^{j=j_N}(\max(F_k^m(i_E, j.), 0) - \min(F_k^m(i_W, j.), 0)) + \sum_{i=i_W}^{i=i_E}(\max(F_k^m(i., j_N), 0) - \min(F_k^m(i., j_S), 0))] \tag{6}$$

While the fluxes for the US, China, Europe and South Korea can be calculated based on the border fluxes described above, the ROW region which encompasses all the remaining countries does not have real borders. As a result, the influxes and outfluxes from country m into ROW and out of ROW as well as from ROW to any m country can be calculated from the other four countries. Details are reported in the appendix.

3.3. 4×4 table of international and transboundary CO flows over 1990 and 2014

The data of CO transport embedded in trade and atmospheric flows is reported in table 1. The results show that global CO emissions caused by economic and household activities have decreased by 11.6% while trade-embedded CO emissions have increased by 26.8% between 1990 and 2004, which is in line with the figures of Zhong *et al.* (2017). This process comes from the relocation of many heavy industries from developed to developing countries (Jänicke, 1997) and from the increasing role of China as a major trade and supply chain partner following its membership to the World Trade Organization.

Our findings indicate also that, for any country, the CO embedded in production destined to its domestic market is the largest flow. This result meets our expectations. For instance, the domestic production of the US corresponded to 99.5 terra grams (Tg) and 41.3 Tg of CO in 1990 and 2014 respectively. Moreover, we note that the CO emissions due to domestic production decline in the US and Europe while the role of CO embedded in imports (off-diagonal elements) increases, particularly for China. It represents the large increase in purchasing power the country experienced over the study period. We also note that the CO associated to the production and export capacity of China has almost doubled over 1990-2014 (off-diagonal row elements).

When it comes to the atmospheric transport of CO flows, we note that the off-diagonal elements are, in most cases, larger than the diagonal elements. This difference reflects the role of transboundary CO transport. In addition, we note that the large-area countries emit more than the smaller ones, which is expected. In the case of China, the atmospheric CO flows are completely disconnected from the trade-embedded CO flows. For instance, in 2014 South Korea receives 42.4 Tg of CO from China because of its downwind location while, through its imports, it is responsible for 0.8 Tg of CO produced in China only. The increase in CO flows emanating from China to any other country is notable and worrisome: + 41.5% to the US, + 21.2% to the EU, + 33.3% to South Korea. This trend took place at the same time that the US, Europe, and South Korea decreased theirs to any other country. These drastic shifts illustrate the major role that $\Delta \mathrm{CO}_{\mathrm{inflow}}$ plays in explaining the changes in CO experienced in a country as stated in equation (4). Yet, determining which factors played the largest role in CO emission changes for each country can only be achieved through an SDA.

Table 1- 4×4 table of international and transboundary CO transport (in Tera grams) embedded in trade and atmospheric flows

(in Tg)	Trade-embedded CO flows in 1990						Trade-embedded CO flows in 2014					
Into From	USA	China	EU	S. K.	ROW	SUM	USA	China	EU	S. K.	ROW	SUM
USA	**99.5**	0.1	7.4	0.7	17.8	125.6	**41.3**	0.7	2.5	0.4	6.6	51.5
China	1.9	**35.0**	2.2	0.2	5.9	45.2	4.6	**66.1**	4.9	0.8	10.1	86.5
EU	3.7	0.2	**122.3**	0.3	9.5	136.0	1.9	1.1	**31.3**	0.2	4.7	39.2
S.K.	0.2	0.0	0.2	**2.4**	0.7	3.5	0.3	0.7	0.2	**1.6**	0.7	3.5
ROW	18.9	1.5	21.0	2.4	**426.0**	469.9	29.7	14.9	30.6	4.6	**428.6**	508.4

(in Tg)	Atmospheric CO flows in 1990				Atmospheric CO flows in 2014			
Into From	USA	China	EU	S. K.	USA	China	EU	S. K.
USA	**63.4**	50.0	143.7	14.4	**26.3**	19.4	45.4	5.5
China	78.3	**30.4**	70.6	31.8	110.8	**53.6**	85.6	42.4
EU	57.4	35.9	**65.4**	10.3	26.9	16.7	**25.3**	4.7
S.K.	7.1	3.5	6.8	**1.7**	4.7	2.4	3.9	**0.9**
ROW	570.9	439.2	611.7	116.7	651.5	494.4	562.2	126.7
Inflow-SUM	777.1	559.0	898.2	174.9	820.2	586.5	722.4	180.2
Production	130.0	133.1	75.0	1.7	40.4	192.6	27.8	1.3
Outflow	878.5	687.6	899.0	180.2	832.4	779.4	687.1	184.9

Note: the atmospheric fluxes of the ROW are not displayed because the tagged fluxes are origin-specific and need to go through clearly delimited boundaries, which is not possible for a bloc representing the ROW.

4. Results

We start with the results of Eq. (1). They are reported in table 2 below. For each cell, the first element represents the absolute change while the element in parenthesis is the share of that element in the total change in CO emissions. The results indicate that, in the US, the EU and South Korea, the emissions have reduced over 1990-2014. This decrease has benefited mostly from a decrease in the CO intensity effect, reflecting how these economies adopted greener technology over that period. We also note in the case of the EU and the US that the technology effect contributed, although by a lower extent, to the overall CO reduction. This result shows that the inputs used in the production process, whether they come from the domestic or foreign markets, are polluting less. This finding can be explained, in part, by the relocation of the more polluting industries from developed to developing countries and the adoption of increasingly greener production processes abroad. This point is confirmed by a reduction in the CO intensity effect in China for instance. In addition, we find that the CO emissions associated to final demand and to household activities have respectively increased and decreased in all countries. As expected, the latter is just a fraction of the former. The increase in final demand has therefore hampered the CO emission reduction in the US, the EU and South Korea, while it has acted as a major driver of the increase in CO emissions China experienced over 1990-2014. From table 3, it is obvious that the increase in final demand in China is primarily domestic (+82.2%), as in the other economies, and as we would expect from a growing and increasingly wealthy population. We also note from this table that the EU and South Korea have experienced a change in final demand that is more driven by foreign markets (+ 30.2% and +40.3% respectively) than what it is in other countries, including China (+ 17.8% only).

Table 2- SDA for the pollution emission due to local production and trade in 1990 and in 2014

	ΔCO Coefficient	**ΔTechnology Effects**	**ΔFinal Demand**	**ΔHH**	**ΔCO Emission (Tg)**
USA	-138.8 (177.6%)	-13.1 (16.8%)	77.8 (-99.6%)	-4.0 (5.1%)	**-78.1**
CHN	-299.5 (-767.0%)	66.1 (169.2%)	274.7 (703.5%)	-2.2 (-5.7%)	**39.0**
Europe	-82.1 (77.0%)	-52.0 (48.8%)	37.4 (-35.1%)	-9.8 (9.2%)	**-106.6**
South Korea	-5.7 (674.9%)	0.9 (-112.3%)	4.8 (-569.4%)	-0.9 (106.7%)	**-0.8**
ROW	16.5 (-42.6%)	-126.6 (326.6%)	148.6 (-383.4%)	-77.3 (199.4%)	**-38.7**

Table 3- SDA of the change in final demand

To From	**USA**	**CHN**	**Europe**	**Korea**	**ROW**	**Export**
USA	**83.4%**	2.1%	3.4%	1.3%	9.8%	16.6%
CHN	4.6%	**82.2%**	3.6%	0.8%	8.8%	17.8%
Europe	7.4%	5.9%	**69.7%**	1.2%	15.7%	30.2%
South Korea	6.6%	16.2%	4.1%	**59.5%**	13.4%	40.3%
ROW	11.7%	10.8%	7.9%	2.4%	**67.2%**	32.8%

Figure 4 illustrates the results of the geographic, atmospheric and economic sources of the change in CO inflows for each country. As expected, South Korea (panel 4a) has received a large amount of CO inflows from upwind China (+ 10.6 Tg). This amount is as large as the inflow amount from the rest-of-the-world bar the EU and the US. Further details about the factors driving the change in inflows from China indicate that changes in wind patterns have reduced the increase in inflows (-1.7 Tg). As a result, the latter is principally due the large increase in CO emissions from the Chinese economy (+12.3 Tg). That increase was already captured in table 2. Like in table 2, we also find that that increase is primarily driven by an increase in final demand (+ 85.6 Tg), itself predominantly dependent on local demand (+ 71.1 Tg). Still, foreign demand is responsible for approximately 17.8% of the final demand, which means that demand from consumers beyond China has led to additional production and emissions in China which, later on, were experienced in South Korea. That change over 1990-2014 (+10.6 Tg, panel 4a) is much greater than the decrease in CO emissions (-0.8 Tg, table 2) South Korea has control over since it is based on domestic activities.

We also find that the reduction in CO emissions in the US and in the EU has reduced the amount of CO inflows going through South Korea. These amounts, -8.9 Tg and -5.6 Tg respectively, are still greater in absolute value that the changes in CO emissions South Korea has a direct control over. As such, our results indicate that if the South Korean government were to set CO emissions reduction as a mechanism to improve the health of its citizens, its best efforts could focus on lowering CO emissions primarily in China but also in the EU and the US.

None of this "loss of national control" over the change in CO emissions experienced locally is found for the rest of the sample except for the change in emissions that the ROW blows to China (panel 4c). They are larger (+55.2 Tg) than the emissions made in China (+ 39 Tg, table 2).

Another interesting finding is that developed economies such as the EU and the US may have become greener by relocating their most polluting industries to China (Zhao *et al.,* 2015; Jänicke *et al*., 1997), a phenomenon observed in the decrease in their CO emissions (Table 2) and in their negative inflows to any other country (figure 4), but is has not been devoid of externalities. Indeed, both the EU and the US experienced an increase in CO inflows coming from China and most of it was driven by an increase in Chinese demand for Chinese-made goods and services.

5. Conclusion

This paper studies the factors contributing to the change in CO emissions and transboundary flows in the US, the EU, China and South Korea between 1990 and 2014. Given the well-established detrimental effect of air pollution on health outcomes, identifying the sources of air pollution is a necessary goal. This paper starts with a traditional environmentally-extended structural decomposition analysis to uncover the role of four factors - the intensity effect, the technology effect, final demand, household activities – in the change in local emissions. Results indicate that the first effect and the third one are the primary drivers across all countries. We also uncover that foreign demand plays only a minor role in local emissions because it is never greater than 40% of the final demand. Based on these results, one would assume that any country is "in charge" of any possible pollution abatement policy it might consider in order to improve the health conditions of its citizens. As such, were governments willing to assign responsibility between consumers and producers, they would mostly keep their directives within the country's boundaries.

However, when we perform a SDA of the change in the net flows of CO emissions a country receives from abroad, the results shatter the previous conclusions for one country: South Korea. Indeed, we find that the changes in CO emissions made in South Korea are just a fraction of the emissions the country receives from its upwind neighbor China (-0.8 Tg vs +10.6 Tg). We conclude that improvement in the CO experienced in the South Korean territory is much more in the hands of China than in South Korea's, a phenomenon that the environmentally-extended input-output and responsibility attribution literatures have overlooked so far. Further investigation indicates that the increase in domestic demand in China due to a larger and wealthier population is the primary driver of the increase in emissions that emanate from the country. The country's technology has become greener over the study period but not enough to compensate for the general trend. Based on our scientific evidence, South Korea could either request from China a Pigouvian tax that would compensate for the additional health cost the country bears or it could consider a technology transfer to help China improve its emission intensity standard further. The relative cost and advantages of each option is left for future research.

We also find that the relatively large amount of emissions transmitted through the atmosphere means that developed countries like the US and the European Union are not completely cleared from the decision they took years ago of relocating their most polluting activities to developing countries such as China. The link between consumption-production-emission-health is therefore more complex than previously thought and requires to consider the transmission of emissions through more than one mechanism. As a result, pollution abatement policies, whether at the national or international level, urgently need to include the direction and intensity of the atmospheric fluxes in the current debate about consumers vs. producers responsibility attribution.