Drivers of fluctuating embodied carbon emissions in international services trade

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Summary

Service industries are always considered "green" because of the marginal direct emissions although they account for 65% of the world GDP and over 20% of total global trade in 2019. Here, we quantify the evolution of carbon emissions embodied in services trade from 2010-2018 and identify the driving factors of emission change at the global and regional scales. The annual growth rate of embodied emissions exported from the global South (2.0%) is double that of the global North (1.0%), with a different trade structure. We further identify three trade patterns of service export in the global South based on the bilateral trade partnership and annual growth rate. Three kinds of specific emission mitigation policies are proposed based on the characters of services trade and different trade structures between different regions. The results provide quantitative evidence currently lacking and critical to policy decision making.

Keywords: CO_2, emissions embodied in trade, services trade, structural decomposition analysis

Introduction

Rapid growth in international trade has resulted in a large portion (more than 20%) of global CO_2 emissions embodied in trade (EET) since 2000[1-3]. A major driver of this result has been the increasing trade in goods and services produced in developing countries and exported to developed countries (so-called South-North trade). As a result, developing countries have generated additional CO_2 emissions to satisfy increased consumption levels in developed countries – in other words, the emissions are redistributed to developing countries due to the shift of the production activities from developed countries. As most carbon emission targets and policies focus on emissions within territorial boundaries without considering the spillover effect described above, they could fail to limit emissions and indeed they could lead to an increase in global emissions[4,5]. Against this backdrop, the role of international trade in carbon transfer has received increasing attention[6-8], with EET becoming a critical component in a national carbon mitigation strategy.

The services trade contributed over 20% to world trade in 2019, up from just 9% in 1970[9]. More specifically, the share of services trade by developing economies has increased by more than 10% since 2005[9], reflecting the growing role developing countries are playing in the evolution of the global services trade. Although the service industries have been always considered green and therefore have attracted only marginal attention in terms of climate change mitigation[10,11], from a consumption perspective, energy consumption and carbon emissions along the services supply chain should be considered[12,13].

Previous studies have looked at the underestimation of energy consumption and carbon emissions in the services industries but have not considered the spillover effect outside the territory[14,15]. Meng et al touched a little on the issue of emissions embodied in services trade but did not separate it from the trade of goods[16]. More recently, studies have analyzed the footprint and bilateral embodied carbon flow of tourism, which has some overlap with services trade, and have concluded that they play an important role in driving global carbon emissions[17,18]. Given the growth of services trade, it is necessary to analyze how changes in both direct and indirect emissions embodied in the services trade and, in particular, what the drivers behind that change are.

This study fills the gap by using the latest CO_2 emissions data from the International Energy Agency (IEA)[19] and multi-regional input-output table (MRIO)[20] to track the change of carbon emissions embodied in the services trade from 2010–2018 (In this study, the services trade is defined as the intermediate and final use offered by the service sectors of an economy to other economies, or international services export). Specifically, our analysis covers 59 regions (58 regions are individual countries) and 35 sectors, among which 19 are service sectors (**See Table S1-S2**). We find that a rapid growth of both trade volume and CO_2 emissions embodied in services trade by 2010-2018 at annual average growth of 4.71% and 1.4%, separately. Although the total volume of the emissions embodied in services trade is smaller that in merchandise trade[21,22], the annual growth rates of both trade volume (4.0%) and the embodied emissions (1.1%) in merchandise trade in 2010-2018 are smaller than services trade. We also explore the drivers behind the change using Structural Decomposition Analysis (SDA)

(See Methods). Furthermore, we discuss three main trade patterns of service in the global South and separately analyze their services trade structure and their service supply chains.

Results

Emission change and services trade pattern in 2010-2018

Fig 1 presents the change of global services trade and associated trade emissions from 2010 to 2018. The volume of trade in services has experienced rapid growth at 4.71% per year. However, emissions embodied in the services trade have only been growing by 3.47% (from 2.05Gt-2.35Gt) during 2014-2018, as shown in Fig 1a.

We have witnessed the largest growth in services trade. The volume of services trade from developing countries (South) to developed countries (North) has grown 57.7% from 728.6 billion US dollars in 2010 to 1148.9 in 2018. The associated embodied emissions in trade have grown 29.2%. The volume of services trade among North-North countries has shown a rapid growth at a rate of 45.3%, but the associated trade emissions have only increased by 8.4%, which means that North-North trade contributed less to the rapid increase of CO_2 emissions embodied in global services trade. The growth of services trade between South-South countries is also significant - an increase by 49.2% from 534.0 US billion dollars in 2010 to 805.5 in 2018. Similarly, the volume of services trade among North-South countries has grown on average 36.3% while the embodied emissions of North-South trade have increased by 7.8%. The North-South trade patterns are different during 2010-2014, when the embodied emissions in services trade between developing countries and developed countries decreased slightly except for the case of North-South trade with a positive average annual growth rate of 0.35% (**Figure 1A**).

Regarding the types of service exports, we selected a number of countries showing different directions of emissions in Fig 1a, which are based on the amount of the trade volume and the embodied CO_2 emission volume between different countries. The tourism sector is the main source of service exports from the global South. According to the Statistics Department of Vietnam, the number of Japanese visitors has increased sharply by 87.0% from 442.1 thousand people in 2010 to 826.7 in 2018. Therefore, the air transportation and the wholesale trade, which is closely connected to tourism, registered rapid growth of 23.1% and 16.5%, respectively, during 2010-2018 (**Figure 1B**).

The professional services trade contributed largely to the North-North trade. Fig 1c shows that services trade between the Netherlands and Germany was dominated by renting and other business services, with an annual growth rate of 8.23% during 2014-2018. In 2018, the Netherlands exported 185 billion US dollars' worth of services with the top services in 2018 being other business services (83.9 billion US dollars), showing an increase of 165% compared to 2010 (31.7 billion US dollars). Part of those exports is represented by the trade volume exported to Germany that went up to 8.01 billion US dollars (UN Comtrade). And because the emissions embodied in renting and other business services are relatively low, we find a high

growth rate of services trade and a relatively low growth rate of embodied emissions between the Netherlands and Germany, respectively20.7% and 8.0% annually.

The main accelerator of the emissions embodied in services trade across the Global South is the increasing trade of transportation. For example, Thailand increased the use of oil in inland transport, especially after 2014, by 29.8% from 17.5Mt in 2014 to 22.7Mt in 2018. Therefore, the emissions embodied in inland transport from Thailand to Indonesia increased sharply by an average annual growth rate of 10.0% in 2014-2018, while the growth of inland transport volume was only 0.6% (**Figure 1D**). Moreover, emissions drivers vary in the case of the trade from developing to developed countries (from Vietnam to Japan) with respect to trade between developing countries (from Thailand to Indonesia) and the difference would depend on the modes of transportation in the countries involved. For example, Vietnam and Japan mainly use air transport whereas Thailand and Indonesia mostly use inland waterway transport.

However, in the case of North-South trade, business services and business travel transportation are the main drivers of the growth in services trade volume and embodied emissions. For example, in the services trade from the USA to China, air transportation has increased rapidly at an annual growth rate of 8.7% during 2010-2018, especially high over 2010-2014 (18.0%). According to the Transportation Safety Administration report, the largest U.S.-international country gateways for freight were in China in 2018. Total Freight from the USA to China was up to 0.98 Mt for the year-ended December 2018. Therefore, the emissions embodied in air transport have increased at the annual rate of 9.0% over 2010-2018.

The determinants of the change in emissions

Looking at the trend of emissions embodied in the global services trade during 2010-2018, it appears that the biggest driver of rising emissions is the growing volume of trade, which overall contributed 277.7 million tonnes (Mt) carbon emissions in 2018. This amount is comparable to CO_2 emissions from the USA's annual services export in 2018 (282.6Mt).

The patterns of trade volume vary across different regions and different periods. Before 2016, world trade grew at a low speed and consumption in major developed economies was depressed. Therefore, exports of services from the global North were growing slowly (South-North trade) and even decreased (North-North trade) during 2012-2016. For example, the volume of services export from the USA to Japan decreased by 8.8 billion dollars during 2012-2016, which contributed to the reduction of embodied emissions in services trade from the USA to Japan by 6.3Mt. Moreover, during the same period, the volume of services exports from Vietnam to Japan also decreased by 5.2% while emissions declined by only 0.09Mt. Due to the relatively small impact of the international financial crisis on the developing economies, both emerging and developing economies recovered rapidly and maintained strong trade growth. During the years 2012-2016, the volume of South-South trade and North-South trade increased to 50.7 billion dollars and 251.2 billion dollars, respectively. And the volume of exports to the global South went up to 118.5Mt in 2016. For example, the USA exported more services to China with the value of such exports going from 20.3 billion US dollars in 2012 to

23.1 in 2016, an increase of 14.0%. As a result, the emissions embodied in the services trade increased by 3.0Mt. Similarly, the volume of trade in services going from Vietnam to China and from India to China also increased, by 23.6% and 36.0% respectively, during 2012-2016, with a corresponding increase in embodied emissions of 0.09Mt and 0.61Mt.

When consumption in developed countries recovered after 2016, trade volume became the main driver of embodied emissions again (North-North trade and South-North trade) (**Figure 2A**). The trade volume from the USA to Japan increased to 10.3 billion dollars, which caused an increase in embodied emissions by 0.66Mt over 2016-2018. At the same time, Vietnam also increased services exports to Japan from 2.21 billion US dollars in 2016 to 2.47 in 2018. The growth of the trade volume between Vietnam and Japan also contributed 87.6% (0.23Mt) growth in embodied emissions. As for South-South trade, the growth rate of the volume of services trade remains relatively lower than that of North-North and South-North patterns, but the increasing trend has led to an increase in embodied emissions. During the years 2016-2018, the volume of South-South services trade increased enormously and gave rise to embodied emissions by almost 65.2Mt. (**Figure 2A**). For example, the increase of trade volume from Thailand to Indonesia was up to 1.0 billion US dollars and contributed 0.82Mt of embodied emissions over 2016-2018. Moreover, India increased the exports of services to China at a rate of 26.5% and up to 7.68 billion US dollars in 2018, which resulted in a growth of 0.50Mt emissions embodied in services trade. North-South trade also experienced a rapid increase in trade in services from 2016 to 2018. After a slight decrease in trade volume, over 2016-2018 the USA increased exports of services to China from 23.1 billion US dollars in 2016 to 26.6 in 2018 and consequently, emissions embodied in services trade increased by 4.56 Mt.

Although still dominated by fossil fuels, from 2010 onwards the fuel energy mix saw the fastest growth in the proportion of renewable sources[23]. Therefore, Figure 2A reflects the effect of the transformation of the fuel mix on the supply chain of services trade[11] by showing that emission intensity is the main decelerator of the global CO_2 emission reduction in 2010-2018, However, in the global south, such as Vietnam and Thailand, emission intensity remains a significant driver of the increase in emissions embodied in the services trade (South-South trade, South-North trade). After 2014, the emission intensity of the supply chains of services trade from Vietnam to Japan increased and contributed to growth of 0.31Mt in embodied emissions over 2014-2016. Similarly, the emission intensity of services trade from Thailand to Indonesia increased continuously and led to an increase of 0.90Mt in embodied emissions during the years 2014-2018. Therefore, with developing countries playing a more important role in international trade[8], we should pay more attention to the efforts and measures taken by developing countries in terms of carbon emission intensity reduction in the international services trade in the future.

The pattern of services trade in the global south

During 2010-2018, the annual growth rate of both services trade volume and emissions embodied in services trade from the global South (5.5% and 2.0%) is larger than the global North (4.4% and 1.0%). Especially, in South-North trade, the annual growth rate of embodied

emissions up to 3.3% during 2010-2018. Therefore, we pay more attention to the services trade of the global South, which increase largely **(Figure S1)**. Figure 3 shows that there are three main trade patterns of services trade in developing countries, whose annual growth rate is positive (**Table S4**). In Pattern 1, the global South has a closer bilateral trade relationship with the global North. For example, due to the poor infrastructure base, Ethiopia needs to import more transport equipment from developed countries **(Figure S2)**. During 2010-2018, Ethiopia imported an enormous amount of transport equipment from developed countries corresponding to an annual growth rate of 77.9% - the trade volume went from 8.75 million US dollars in 2010 to 878.5 million US dollars in 2018, especially with USA, Germany and France. In particular, Ethiopia imported 5.9 million US dollars of railways and tramways from France and 825.5 million US dollars of Aircraft from the USA in 2018. Because these kinds of equipment need to be fitted with corresponding ICT services at the same time, Ethiopia imported most ICT services, public and welfare services from developed countries, increasing by 31.3% and 25.0%, respectively. At the same time, more than 70% of the increase in air transport is due to exports to developed countries.

Similarly, in recent years Peru signed bilateral trade agreements with large economies including the USA, Canada, the European Union and Japan. The overall share of financial and business services Peru imported grew by an average annual growth rate of 8.4% over 2010-2018. Of this share, 98.9% is imported from developed countries. Moreover, Peru's tourism exports have been growing rapidly (8.8%), 54% of which are going to developed countries. In 2018, the share of foreign tourists coming from the USA went up to 15%.

In Pattern 2, developing countries import services mainly from other global South countries while establishing better trade cooperation with the global North. These countries (i.e. Philippines and Vietnam) export more to developed countries and import more services from developing countries. Tourism contributed 13% of the GDP of the Philippines. During the years 2010-2018, the export of tourism in the Philippines increased by 10.1% per year and the share of developed countries' visitors went up to 70%. Japan became the largest source of tourists to the Philippines over 2010-2018, with exports of tourism from the Philippines to Japan increasing from 1.2 billion US dollars in 2010 to 1.4 billion US dollars in 2018 by 12.7%. Moreover, given the strategic position, the Philippines are a potential gateway for investors to enter Southeast Asia and South Asia and therefore many multinational companies have their headquarters or representative offices in the Philippines. As a result, the imports of financial and business services in the Philippines increased largely by 19.5% per year over 2010-2018, 53% of which is imported from developing countries. For example, in 2018, China became the largest source of foreign investment in the Philippines. According to the official statistics of the Philippines, China's investment in the Philippines reached 50.69 billion Philippine pesos (about 975 million US dollars) in 2019, increasing by 20.72% from 2017.

In 2018, Vietnam's national shipping company saw a strong growth of volume of shipping, which is more than 13% and reach 24.3 million tons. More than 99% of Vietnam's water transportation was imported from developing countries. From 2010 to 2018, the growth rate of water transportation of Vietnam's imports went up to 25.7%. In addition, the health and medical services import in Vietnam increased by 17.4% per year during 2010-2018. Such trade

pattern has attracted many developing countries, especially China, to invest. In recent years, Vietnam has invested in the healthcare and telemedicine services system, which has increased exports of health services to other countries in the world. During the years 2010-2018, Vietnam's exports of health services to Australia increased by 41.7% from 130 million US dollars in 2010 to 184 million US dollars in 2018.

In Pattern 3, the focus is mostly on South-South cooperation. The countries in pattern 3 (i.e. Mongolia and China) have stronger trade partnership with other global south countries. As Mongolia is a land-locked country bordering China, the trade between Mongolia and China is very close, which means that China has become the largest import and export country of Mongolia. Although Mongolia's current imports from China are mainly grain agriculture and machinery industry, Figure 3 shows that, in recent years, with the continuous improvement of Mongolia's economy, Mongolia's demand for services, especially health services, is rising rapidly. During the years 2010-2018, Mongolia's GDP has grown by 81.9%from 7.2 billion US dollars in 2010 to 13.1 billion US dollars in 2018. And Mongolia's imports of public and welfare services and health services grew at an average annual rate of 40.5% and 45.1%, respectively.

During the years 2010-2018, China's imports of tourism resources from other developing countries grew by 12.3% per year. According to a report released by the World Tourism Organization, the outbound tourism spending of Chinese tourists reached 277 billion US dollars in 2018. At present, China is the world's largest exporter of tourists. Most tourists in the Asian developing countries such as Thailand, Vietnam and Malaysia are Chinese. At the same time, China and neighbouring developing countries have closer economic cooperation. Over 2010-2018, China's exports of financial and business services increased by 7.7% per year, with almost 81% of such exports going to developing countries.

Discussion

Services trade is becoming increasingly important for global economic growth and its role is likely to grow substantially over the next few years[24]. Services sectors, largely contributed by the transportation, tourism and financial services, are more sensitive to the change in the socioeconomic environment than merchandise trade. For example, the restriction of mobility during the global pandemic will cause a huge drop in tourism and air transportation[25]. However, they are likely to rebound faster than other manufacturing industries once the epidemic is under control[26]. The service industry is generally downstream of the supply chain, which means the related carbon emissions embodied in services trade are contributed by the upstream productions of supply chains. For the bilateral trade within global North, services trade is mainly professional services (i.e. Renting and other business services) and requires carbon emission reductions along the whole supply chain. Therefore, we need to advocate financial institutions not only to reduce their own carbon emissions, but also push upstream industries to green their production, such as using more renewable energy. Therefore, we should design emission mitigation policies of services trade based on the whole supply chain.

In addition, the financial sector can advocate and formulate relevant low-carbon preferential policies, such as increasing the convenience of lending to green industries and granting low-interest loans to green and low-energy-consuming industries[27]. This can reduce the production cost of the green industries and get better business performance, which can promote the construction of a low-carbon supply chain[28,29].

It has been acknowledged that regional cooperation can help to accomplish global mitigation objectives and it is easier for regions sharing common economic development structures, common cultural backgrounds or even geographical proximity to decide on mitigation policies or agreements[30-32]. Therefore, the global South countries tend to have closer bilateral cooperation with each other, which needs to strengthen regional cooperation to achieve collaborative emission reduction among South-South trade. There are some national policy-oriented factors, such as China's "One Belt, One Road" policy, which is representative of South-South cooperation. Services trade constructs a more close linkage between the "Belt and Road" regions, and creates opportunities for cooperation and development[33,34]. Moreover, reducing the trade cost between the "Belt and Road" regions will help different industries to further optimize the layout in the "Belt and Road" regions, quickly form a new pattern of cross-border industrial division of labour and spatial agglomeration, which will contribute to the emission mitigation of the "Belt and Road" regions. Moreover, the South countries should not only strengthen the trade relationship with the Global North but also introduce relevant low carbon technology, such as electrification and energy efficiency improvement. At the same time, the North-South services trade should not only stop at the merchandise trade and low-tech services trade (such as tourism), but also facilitate the technical innovation and knowledge transfer services from global North countries , which can help the capacity building of emerging countries and improve competitiveness of the global South countries to participate in the global supply chain divisions. Therefore, a focus on environmental initiatives at the regional cooperation is crucial.

Compared with merchandise trade, the intangible, non-storable, and contract-intensive characteristics of services determine that services trade is more sensitive to differences in systems, policies, laws and regulations among different trading countries[35-37]. The characteristics of technology, knowledge and human capital intensiveness determine that services trade is increasingly affected by information and communication technology[38]. Therefore, the application of information and communication technologies in developing countries should be further strengthened to provide transnational service to the upstream and downstream. As the bilateral trade between global North and global South are mainly contributed by transportation and tourism. For example, the USA has growing business travel by air to China, with a growth rate of 95.2% during the years 2010-2018. Therefore, the policies and measures of changing trade pathways should be taken to reduce the emissions embodied in North-South trade, such as, reducing the volume of business travel through more online transactions. Moreover, it is worth noting that, during 2000-2017, trade costs in services have declined at the rate of around 9%, which is about the same as in manufacturing[39,40]. With the rapid development of digital technologies and online sales, service sectors that have high trade costs (i.e. real estate activities, retail trade) witnessed a precipitated decrease in trade costs. Therefore, countries will probably be able to both reduce

the embodied emissions and cut down trade costs in services trade by developing a digital economy. At the same time, the digital economy shortens the supply chain, which makes the supply chain more effective and reduces intermediate transactions[41,42].

There are some potential limitations in our results due to data availability. To reflect the latest services trade pattern of developing economies, there are no MRIO databases available but the one from Asian Development Bank (ADB[43], see details in the Method section), which can provide the data of 2010-2018 time series. Therefore, despite the extensive spatial extent in our study, especially the developing countries in Asia-Pacific region, we are not able to include all developing regions in the world—for example, large parts of Africa and South America—due to a lack of single country coverage of the MRIO database (ADB) we used.

Experimental Procedures

Resource availability

Lead contact

Further information requests should be directed to the Lead contact Jing Meng (jing.j.meng@ucl.ac.uk).

Materials availability

This study did not generate new unique materials.

Data and code availability

The time-series Multi-regional input-output tables (MRIOTs) are obtained from the Asian Development Bank (ADB) Multi-Regional Input-Output Tables Database. Because ADB MRIO table in 2018 has not been published publicly, the original MRIO data only is available from the corresponding leader in ADB database upon request. CO2 emissions from fuel combustion and energy consumption at the sectoral level in each region are from the IEA (International Energy Agency) database, which can be found by accessing the referenced studies. The Matlab code for reproducing the SDA analysis and source data for main figures presented in this study are available at Github: https://github.com/Jingwenhuo/Services_Trade.git.

Data sources

Time-series Multi-Regional Input-Output Tables (MRIOTs) are obtained from the Asian Development Bank (ADB) Multi-Regional Input-Output Tables Database[20]. The economic data from the ADB database are in current prices (US dollars). To remove the impact of inflation on the monetary output, we use the appropriate producer price index (PPI, National Accounts

Main Aggregates Database[43]) to adjust all of the monetary data to provide a consistent analysis from 2010 to 2018.

CO_2 emissions from fuel combustion and energy consumption at the sectoral level in each region are from the International Energy Agency (IEA) database[19]. Our analysis is global and includes 19 service sectors (**Table S2**) and 59 regions.

Because ADB MRIOTs did not include Ethiopia and Peru (Figure 3), we obtained their services trade data in 2018 from WTO[44] and their share data of trade with the global North from GTAP 10 MRIOT in 2014[45]. Other Asian developing countries services data and share data all come from ADB MRIOT in 2018. The mapping between the WTO services data and GTAP MRIOT can be found in **Table S3**.

Scope of the services trade in this research

According to the *Manual on Statistics of International Trade in Services 2010* (MSITS 2010), services are defined as "heterogeneous outputs produced to order and typically consist of changes in the condition of the consuming units realized by the activities of the producers at the demand of the customers." The conventional statistical meaning of international trade in services defines it as being between residents and non-residents of an economy, while the MSITS 2010 extends the definition to include the value of services provided through foreign affiliates established abroad. Based on these definitions, international trade in services are divided into the following four models:

Mode 1: Cross-border Supply
from the territory of one economy into the territory of any other economy;
A user in country A receives services from abroad through its telecommunications or postal infrastructure. Such supplies may include consultancy or market research reports, telemedical advice, distance training, or architectural drawings.

Mode 2: Consumption abroad
in the territory of one economy the services are offered to a consumer of any other country;
The consumer consumes the services, such as tourist activities (tourists), learning courses (students) or receiving medical treatment (patients) outside his/her home territory.

Mode 3: Commercial presence
by a service supplier of one economy, through commercial presence in the territory of any other economy;
The service is provided within A by a locally-established affiliate, subsidiary, or representative office of a foreign-owned and — controlled company (bank, hotel group, construction company, etc.).

Mode 4: Movement of natural persons
by a service supplier of one economy, through the presence of natural persons of an economy in the territory of any other economy;

A foreign national provides a service within A as an independent supplier (e.g., consultant, health worker) or employee of a service supplier (e.g. consultancy firm, hospital, construction company).

In this research, the international trade in services we studied mainly covers the first two models of trade in services in the classification of GATS (General Agreement on Trade in Services)[46]. The third model was excluded as it was not cross border activities. In addition, services in some sectors - such as construction in the fourth model - were also not included in this study because they were offered by non-service sectors.

Emissions embodied in the services trade

Environmental input-output analyses (EIOs)[35] have been widely used to evaluate the linkages between economic activities and triggered environmental impacts. By environmentally extending input−output (IO) analysis to multi-regional input-output (MRIO) analysis[47], the emissions embodied in bilateral trade (EEBT) can be used to analyze bilateral interconnection between industries in different regions due to trade-adjusted emission changes[48-50] and assess attributions of environmental changes both from production and consumption[51]. Compared with MRIO, which only considers imports to final consumption and calculate intermediate consumption endogenously, EEBT considers exports from each country covering both intermediate and final products[1,52,53]. Therefore, EEBT is suitable to analyse the interconnection of sectors in bilateral relationship[50]. Here, we estimate the emissions embodied in services traded by using the global MRIO tables of 2010-2018. The monetary balance of total outputs $\mathbf{x}^r$ of region r is:

$$\mathbf{x}^r = \mathbf{A}^r\mathbf{x}^r + \mathbf{y}^r + \mathbf{m}^{rs} - \mathbf{m}^{sr} \quad (1)$$

where $\mathbf{x}^r$ is a sectoral output vector in region r; $\mathbf{A}^r$ represents the coefficients of requirements in a region to produce per unit of output; $\mathbf{y}^r$ is the final demand (household, government and investment) in region r. $\mathbf{m}^{rs}$ and $\mathbf{m}^{sr}$ are the bilateral exports and imports from r to region s. In this study, we only consider the exports of service-sectors. EEBT removes the imports required to produce the bilateral trade separating $\mathbf{x}^r$ into domestic and traded parts to pay attention to domestic production[53]:

$$\mathbf{x}^r = \mathbf{A}^{rr}\mathbf{x}^r + \mathbf{y}^{rr} + \mathbf{m}^{rs} \quad (2)$$

Where A^{rr} is the technical coefficient matrix of transactions within region r; $\mathbf{y}^{rr}$ is the domestic final demand within region r.

In EEBT, the total CO_2 emissions produced in region *r* are as follows:

$$\mathbf{T}^r = \mathbf{F}^r \mathbf{x}^r = \mathbf{F}^r (\mathbf{I} - \mathbf{A}^{rr})^{-1} (\mathbf{y}^{rr} + \mathbf{m}^{rs}) \quad (3)$$

where $\mathbf{F}^r$ is the direct emission vector to produce one unit output in region *r* [54]. As this study focuses on the direct and indirect emissions related to the service industry along the supply chain, emissions from all the sectors are considered, which means not zero here. In addition, $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix. $(\mathbf{I} - \mathbf{A}^{rr})^{-1}$ considers only the domestic supply chain in region r. Again, the supply chains including all the industries are considered.

$\mathbf{T}^{r}$ can be decomposed into two components for the domestic demand $\mathbf{T}^{rr}$ (eq. (4)) and the total emissions $\mathbf{T}^{rs}$ embodied in exports from region r to region s (eq. (5)):

$$\mathbf{T}^{rr} = \mathbf{F}^r (\mathbf{I} - \mathbf{A}^{rr})^{-1} \mathbf{y}^{rr} = \mathbf{F}^r \mathbf{L}^{rr} \mathbf{y}^{rr} \quad (4)$$

$$\mathbf{T}^{rs} = \mathbf{F}^r (\mathbf{I} - \mathbf{A}^{rr})^{-1} \mathbf{m}^{rs} = \mathbf{F}^r \mathbf{L}^{rr} \mathbf{m}^{rs} \quad (5)$$

Structural Decomposition Analysis

To analyze and quantify the driving factors behind the change of socio-economic indicators or environmental economic system (i.e. energy consumption and CO_2 emissions), the two most common decomposition methods used at the sectoral level are Index Decomposition Analysis (IDAs) and Structural Decomposition Analysis (SDAs)[55]. Both IDA and SDA can decompose these dependent variables into various independent determinants, with the main difference between these two methods focusing on the model used. IDA uses only sectoral aggregation data, while SDA uses the input-output framework[55]. Because the input-output model includes indirect demand information captured by the Leontief inverse matrix, SDAs enable us to distinguish a range of production effects and total final demand effects, such as structural, production and socio-technical effects[23,54] and can assess both direct and indirect effects where IDAs include direct effects only. In our analysis, we divided the change of embodied emissions into four constituent parts: emission intensity, trade structure, production structure, and trade volume effect[56].

The total CO_2 emissions embodied in producing the products exported from region r to region *s* can be decomposed as follows:

$$\begin{aligned}
\mathbf{T}^{rs} &= \mathbf{F}^r (\mathbf{I} - \mathbf{A}^{rr})^{-1} \mathbf{m}^{rs} \\
&= \sum_i \sum_j \sum_k \frac{c_i^r}{m_i^r} L_{ij}^{rr} m_j^{rs} \\
&= \sum_i \sum_j \sum_k \frac{c_i^r}{m_i^r} L_{ij}^{rr} \frac{m_j^{rs}}{m^{rs}} m^{rs} \\
&= \sum_i \sum_j \sum_k E_i^r L_{ij}^{rr} M_j^{rs} V^{rs}
\end{aligned} \quad (6)$$

where c_i^{kr} is the emissions for total output in sector *i* in region *r*; m_i^r represents the total output in sector *i* in region *r*; E_i^r indicates the emissions produced for a unit of output in sector *i* in region *r*; L_{ij}^{rr} indicates the total inputs from sector *i* to produce one unit of output in sector *j* in region *r*; M_j^{rs} is the share of the export of products in sector *j* from region *r* to region *s* in the total exports from region *r* to region *s*; V^{rs} is the total export volume from region *r* to region *s*.

Thus, the change in the emission transfers between two points in time (indicated by the subscripts 0 and 1) can be expressed as $\Delta\mathbf{T}_a^{rs}=\mathbf{T}_1^{rs}-\mathbf{T}_0^{rs}$. However, a major problem of structural decomposition techniques is that the decomposition is not unique. When the number of factors is m, the number of all possible equivalent decompositions is equal to $m!$. In order to resolve the non-uniqueness decomposition problem of SDAs, we apply an established methods using the average of the termed polar decompositions as an approximation of the average of all $m!$ equivalent decomposition forms[57]. The two polar decompositions ($\Delta\mathbf{T}_a^{rs}$ and $\Delta\mathbf{T}_b^{rs}$) are as follows:

$$\begin{aligned}\Delta\mathbf{T}_a^{rs} &= \sum_i\sum_j\sum_k(\Delta E_i^r)\ L_{ij1}^{rr}M_{j1}^{rs}V_1^{rs}+\sum_i\sum_j\sum_k E_{i0}^r(\Delta L_{ij}^{rr})M_{j1}^{rs}V_1^{rs}\\ &+\sum_i\sum_j\sum_k E_{i0}^r L_{ij0}^{rr}(\Delta M_j^{rs})V_1^{rs}+\sum_i\sum_j\sum_k E_{i0}^r L_{ij0}^{rr}M_{j0}^{rs}(\Delta V^{rs})\\ &=\Delta\mathbf{E}_a+\Delta\mathbf{L}_a+\Delta\mathbf{M}_a+\Delta\mathbf{V}_a\end{aligned} \tag{7}$$

$$\begin{aligned}\Delta\mathbf{T}_b^{rs} &= \sum_i\sum_j\sum_k(\Delta E_i^r)\ L_{ij0}^{rr}M_{j0}^{rs}V_0^{rs}+\sum_i\sum_j\sum_k E_{i1}^r(\Delta L_{ij}^{rr})M_{j0}^{rs}V_0^{rs}\\ &+\sum_i\sum_j\sum_k E_{i1}^r L_{ij1}^{rr}(\Delta M_j^{rs})V_0^{rs}+\sum_i\sum_j\sum_k E_{i1}^r L_{ij1}^{rr}M_{j1}^{rs}(\Delta V^{rs})\\ &=\Delta\mathbf{E}_b+\Delta\mathbf{L}_b+\Delta\mathbf{M}_b+\Delta\mathbf{V}_b\end{aligned} \tag{8}$$

The average of the polar decomposition is expressed as follows:

$$\begin{aligned}\Delta\mathbf{T}^{rs} &= \frac{1}{2}[\Delta\mathbf{T}_a^{rs}+\Delta\mathbf{T}_b^{rs}]\\ &=\frac{1}{2}(\Delta\mathbf{E}_a+\Delta\mathbf{E}_b)+\frac{1}{2}(\Delta\mathbf{L}_a+\Delta\mathbf{L}_b)+\frac{1}{2}(\Delta\mathbf{M}_a+\Delta\mathbf{M}_b)+\frac{1}{2}(\Delta\mathbf{V}_a+\Delta\mathbf{V}_b)\\ &=\Delta\mathbf{E}+\Delta\mathbf{L}+\Delta\mathbf{M}+\Delta\mathbf{V}\end{aligned} \tag{9}$$

where $\Delta \mathbf{T}^{rs}$ is the growth in embodied emissions transfers between two points in time, which in this study corresponds to 2010-2012, 2012-2014, 2014-2016 and 2016-2018. $\Delta \mathbf{E}$, $\Delta \mathbf{L}$, $\Delta \mathbf{M}$ and $\Delta \mathbf{V}$ refer to the emission intensity effect, production structure effect, trade structure effect and trade volume effect, respectively.

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Author contributions

J.M. designed the study. J.H. and J. M. performed the analysis and prepared the manuscript. J.H, J.M., Y.G., C.D. and J.X. interpreted the data. D.G. coordinated and supervised the project. All authors participated in writing the manuscript.

Declaration of Interests

The authors declare no competing interests.

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Figures titles and legends

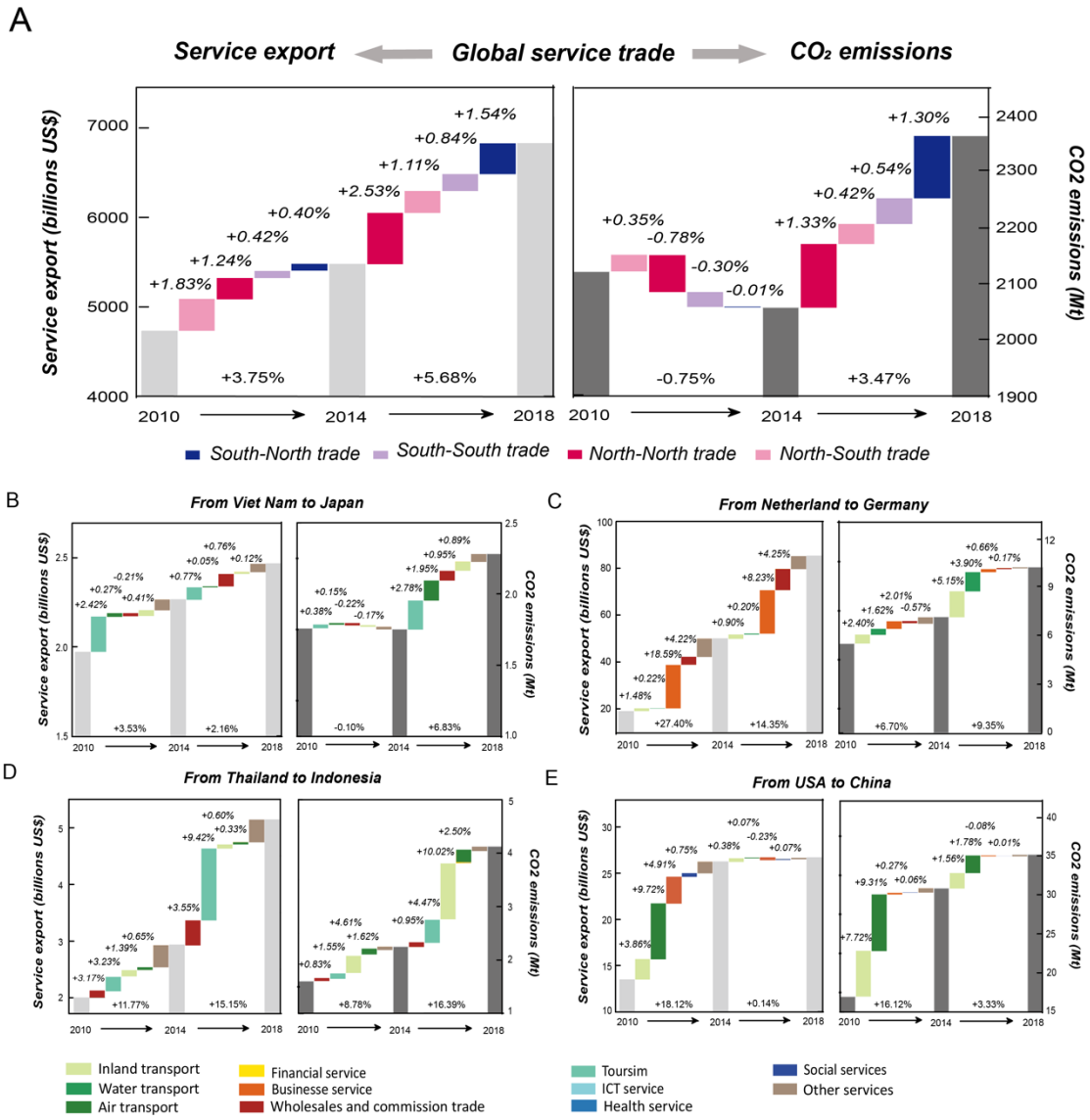

Figure 1. The evolution of services trade pattern and the emissions embodied in services trade from 2010 to 2018. Figure 1A presents the global services trade during 2010-2018. The left side (light grey bars) represents the amount of services trade in billion dollars in constant price of 2010. The right side (dark grey bars) represents the CO2 emissions embodied in global services trade measured by million tons. Blue bars are the trade flows from the global South to North, purple bars are from global South to South; red bars are from the global North to North, pink bars are from global North to South. Figure

1B-E represents services trade (left side in billion US$) and emission flows (right side in Mt) for selected countries. Color bars between grey bars represent sectoral contributions to increases of services trade. The percentage figures are average annual growth rate during 2010-2018.

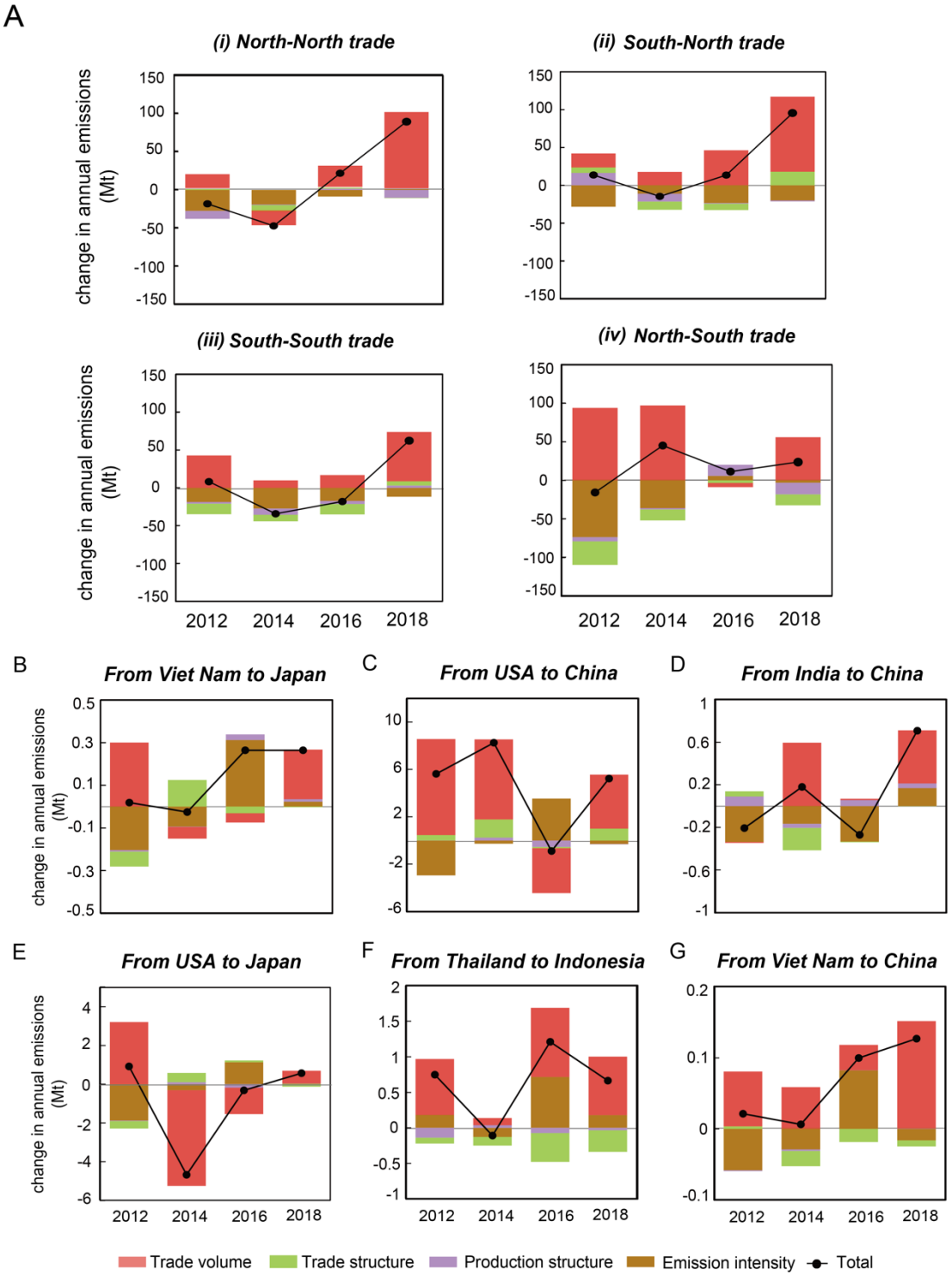

Figure 2. Time-series structural decomposition of changes in emissions embodied in trade compared to the previous year, over 2010-2018. Figure 2A represents the decomposition results of changes in emissions embodied in global services trade: (i) from developed regions (North) to developed regions (North); (ii) from South to North; (iii) from South to South; (iv) and from North to South. Bars show the contributions of four indicators: carbon intensity (CO_2 emissions/output), production structure, trade

structure, and trade volume. (See Method). Figure 2B-2G represents the decomposition of emissions change embodied in selected services flow between different countries.

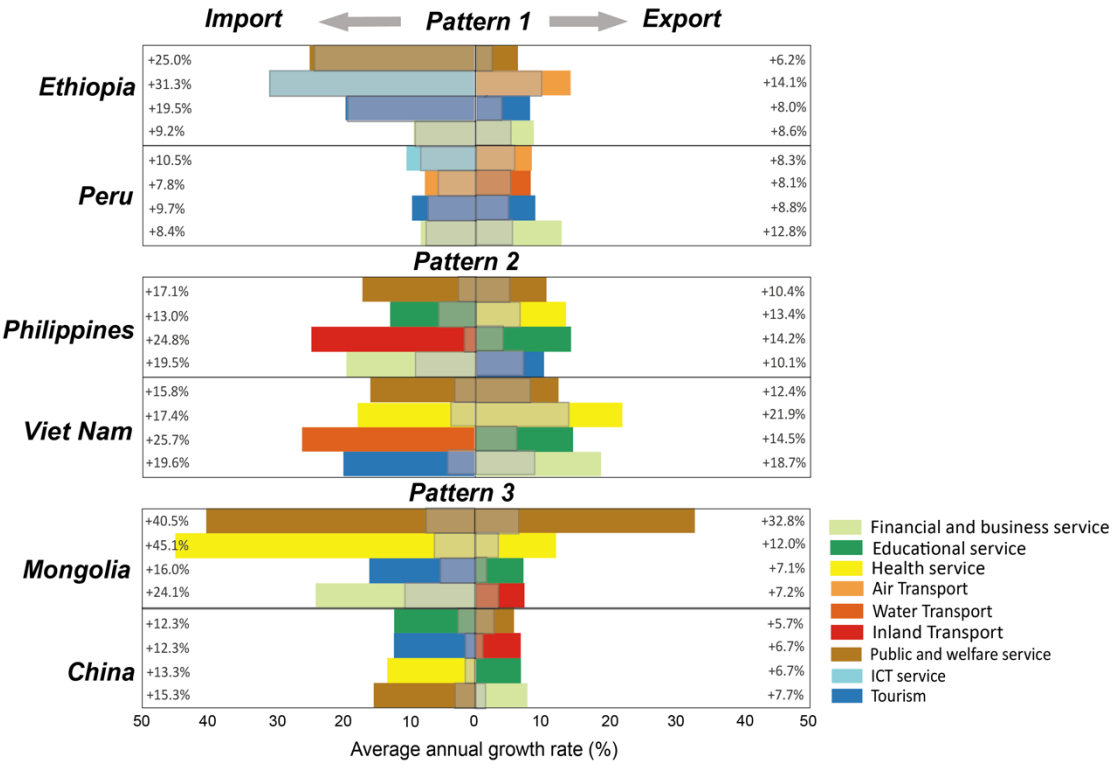

Figure 3. The composition of services export (on the right) and services import (on the left) in selected developing countries. Three modes of services trade across the global south are analyzed. Pattern 1: bilateral trade with the North; Pattern 2: mainly importing from the South whereas exporting to the North; Pattern 3: bilateral trade among countries of the global South. For countries in each pattern we showed the four services sectors with the largest average annual growth rate in imports and exports. Colors indicate the different services sectors with the largest average annual growth rate. The bars show the annual average contribution of each sector in 2010-2018. The gray shaded part of bars shows the share of the services trade volume these sectors trade with the global North.