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Research article

Linkage analysis of economic consumption, pollutant emissions and concentrations based on a city-level multi-regional input–output (MRIO) model and atmospheric transport

Yuan Wang [a], Xinming Li [a], Yun Sun [a], Lanxin Zhang [a], Zhi Qiao [a,*], Zengkai Zhang [b,**], Heran Zheng [c], Jing Meng [d], Yaling Lu [a,e], Yue Li [a]

[a] School of Environmental Science and Engineering, Tianjin University, Tianjin, China
[b] College of Management and Economics, Tianjin University, Tianjin, China
[c] School of International Development, University of East Anglia, Norwich, NR4 7TJ, UK
[d] The Bartlett School of Construction and Project Management, University College London, London, UK
[e] State Environmental Protection Key Laboratory of Environmental Planning and Policy Simulation, Chinese Academy for Environmental Planning, Beijing, China

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ABSTRACT

China is experiencing serious atmospheric pollution, which also exhibits significant spatial heterogeneity. The Chinese government has implemented targeted pollution control measures at the city level, emphasizing coordination among cities to prevent and control air pollution in key regions such as Beijing–Tianjin–Hebei (BTH) urban agglomeration. This study combined an inter-city multi-regional input–output (MRIO) model with an air quality dispersion model consisting of a weather research and forecasting (WRF) model and the CALPUFF model (WRF/CALPUFF) to study the inter-city economic consumption, pollutant emission and concentration among 13 cities in BTH urban agglomeration. NO_x is chosen as an example. The combined effects of economic linkage and atmospheric transport show that NO_x concentrations in cities in the BTH urban agglomeration are attributable to three consumption sources: a local contribution from the target city's own local economic consumption (average, 25%), and non-local consumption contributions, including other cities in the BTH urban agglomeration (average, 36%) and regions outside of BTH (average, 39%). Compared with the contributions to NO_x concentrations calculated using only the MRIO model or atmospheric transport stimulation model, the results of this paper quantify that the consumption outside of a city could provide a greater impact on the city's air quality due to the combined effects of economic linkage and atmospheric transport. To avoid negative impacts of emission reduction targets on economic consumption, governmental regional pollution control policies should consider the combined effects of economic linkage and atmospheric transport.

1. Introduction

The rapid development of China's heavy industry and the intensive use of energy have caused severe air pollution and negative public health impacts in China over the past few decades, which has become a significant environmental problem in China (Zhang et al., 2019). The latest Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution emphasizes collaborative efforts across administrative boundaries for emissions control and pollution prevention [Ministry of Ecology and Environmental Protection of China (MEPC), 2018]. Such collaborative pollution prevention efforts require an understanding of pollution at the regional scale, including the interaction among regions or even cities.

Currently, two types of research are being conducted to explore interactions of air pollution from different sources at the regional level. The first is transboundary atmospheric transport research, which focuses on how local air quality is affected by atmospheric transport of pollution from non-local sources (Chang et al., 2018; Hua et al., 2016; Huang et al., 2015; Li et al., 2015; Kwok et al., 2013; Zheng et al., 2018). This type of research is based on both air quality simulation modeling and measurements of air pollutants to determine their interactions among regions. The second type of research emphasizes the transfer of virtual

* Corresponding author.
** Corresponding author.
E-mail addresses: qiaozhi@tju.edu.cn (Z. Qiao), zengkaizhang@tju.edu.cn (Z. Zhang).

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emissions through trade (Weber and Matthews, 2007; Yong et al., 2017; Zhao et al., 2015; Jiang et al., 2016; Jiang and Guan, 2017; Mi et al., 2017; Xu et al., 2009). The contribution from non-local final demand to local emissions is a key problem resulting from the production of goods (and their associated emissions) in one region for consumption in another region. Many previous studies have focused on examining the embodied environmental impacts of trade by input-output (IO) model, such as wastewater (Zheng et al., 2020), municipal solid waste (Li et al., 2019). But unlike other wastes, air pollutants emissions will affect other areas along with the wind. Therefore, the integration of the economic model with the atmospheric transport of pollution model is necessary.

Recently, a third type of research has attempted to combine the multi-regional input-output (MRIO) model with the atmospheric transport of pollution model, to determine the concentrations of pollutants produced by emissions driven by consumption. These studies have focused on the coupling of atmospheric transport and trade at the country or provincial scales, such as China and the United States (Lin et al., 2014), among countries worldwide (Zhang et al., 2017) and among multiple Chinese provinces (Li et al., 2016; Lu et al., 2019; Zhao et al., 2017). Many studies have considered the impact of atmospheric pollutant transmission and economic consumption, but most of them are between various countries and provinces. From intercity perspective, the combined effects of atmospheric pollutant transport and economic linkages are seldom considered, mainly due to the lack of appropriate city-level data. Zheng et al. (2019) compiled a city-level MRIO table for Hebei Province of China to determine a city-level energy footprint; this table is also useful for studying consumption-driven air quality at the city scale, which could in turn yield accurate scientific data for studies of the interactions of air pollutants at the city level from the perspective of economic consumption.

The purpose of this study is to examine air pollution interactions among cities using the city-level MRIO model and an air quality simulation model [a weather research and forecasting (WRF) model coupled with the CALPUFF model (WRF/CALPUFF)]. Although there are a lot of research about CALPUFF modeling (Abdul-Wahab et al., 2011; Dresser and Huizer, 2011; Wu et al., 2018; Shubbar et al., 2019), few studies have considered the combination of this model and MRIO model to reveal the contribution on air quality driven by economic consumption. This paper attempts to combine the above two models to reveal the natural and economic linkages of air pollution among cities. The air quality simulation model is used to simulate the diffusion process of pollutants and further calculate the concentration of pollutants in each region. In addition, this study also focuses on the relationship between the pollutants and economic flows among these regions. Therefore, the MRIO model is introduced to estimate the hidden environmental impact of trade. By combining and comparing the results of these models, we can find the difference of pollutant emission and economic consumption on pollutant concentration.

In this paper, the Beijing–Tianjin–Hebei urban agglomeration (BTH) is chosen as the study area. Because this region is the most polluted areas in China, containing 5 of the 10 cities with the worst air quality in the country; 49.5% of days did not satisfy the national air quality standard in 2018 (MEPC, 2019). The BTH region has become a hotspot for air pollution research in China, including studies of emissions attributable to the supply chain by MRIO model (Zhao et al., 2016; Wang et al., 2017a; Chen and Chen, 2016; Zhang et al., 2016; Zheng et al., 2016). However, these studies regarded Hebei as a whole province, and did not analyze 11 cities in Hebei Province. Obviously, the research between cities can further reveal the emissions of economic linkage attributed to the supply chains in BTH region. There are also some researches on physical and chemical atmospheric transport of pollutants among cities in this area (Wang et al., 2017b; Chang et al., 2019). However, few studies have reported the combined effects of atmospheric transport and economic linkage on air pollution in the BTH region.

In sum, this study considers pollutant concentrations, emissions, and economic consumption to understand atmospheric pollution at the city level. The results of this study could facilitate optimization of emission reduction targets for different cities, to minimize the impact of emission reduction on the economy and living standards.

2. Study area and data sources

The study area was the Beijing–Tianjin–Hebei urban agglomeration (Fig. 1), one of three major urban agglomerations in China. BTH includes Beijing, Tianjin, and 11 cities in Hebei Province.

NO_x is chosen as a typical air pollutant to explore economic and atmospheric linkages of air pollution among cities. The control of NO_x is one of key steps in reducing $PM_{2.5}$ and O_3 levels (Sillman et al., 1990). Although there are many sources of emissions in the BTH urban agglomeration, including industry, residential areas and transportation, among these, industrial pollution sources account for 70–90% of the total emissions (MEPC, 2013). Limited by statistical data, it only has relatively accurate data of industrial emissions (including the Electricity & heat sector and Transportation & storage sector) at present. The provincial NO_x emissions data are obtained from the 2012 National Environmental Statistical Yearbook. The city-level NOx emissions data are derived from the official environmental statistics emission database. NO_x emissions are aggregated from 12,929 industrial enterprises in BTH into 22 industry sectors. More details on 13 cities of BTH region with the 22 industrial sectors and those industrial enterprises distributions are provided in the Supplemental Information (Tables S1 and S2 and Fig. S1). Because the national MRIO table lacks detailed city-level data, the 2012 city-level MRIO table in Zheng et al. (2019) is used, which describes intermediate trade flow among 13 BTH cities and 30 provinces. This city-level MRIO table is constructed with consideration of the flow of domestic intermediate products, re-exports and inter-city trade flow.

3. Methods

3.1. MRIO analysis

In the 1930s, Leontief proposed an IO method for economic analysis that captured the relations between sectors and industries (Leontief, 1970). There are three types of IO model: single-region input–output (SRIO), bilateral trade input–output (BTIO), and MRIO model. These models differ in terms of their system boundaries and research objectives (Sato, 2013). The MRIO model can characterize economic flows between regions, economic sectors and final demand. Through a combination of regional and sectoral emission inventories, MRIO can effectively uncover the pollutant emissions in other regions caused by the consumption of a given region (Wiedmann et al., 2011). These features make MRIO a popular method to quantify trade activities and their national or regional environmental impacts (Li et al., 2016; Wang et al., 2017a; Zhao et al., 2017; Lu et al., 2019; Zhang et al., 2017). Recently, the MRIO model has been widely used to quantify emissions transfer attributable to trade, because it considers economic output at both the regional and sectorial level, as well as the output of one region as consumed in another region (Davis and Caldeira, 2010; Lenzen et al., 2012; Wiedmann et al., 2015). The MRIO table is an effective tool for MRIO analysis that intuitively presents IO monetary flow data in terms of regions and industries.

The current study generally uses two parts of the MRIO table: intermediate IO, of 22 sectors among 13 cities located in BTH, and the connections between BTH and 27 other provinces in China. Regarding the latter, we focus on the "final consumption" in these regions.

The MRIO model is constructed based on the connections in the MRIO table. The balance of trade flow for the entire research system is described by the following equation (Leontief, 1970):

$$Q = AQ + Y \tag{1}$$

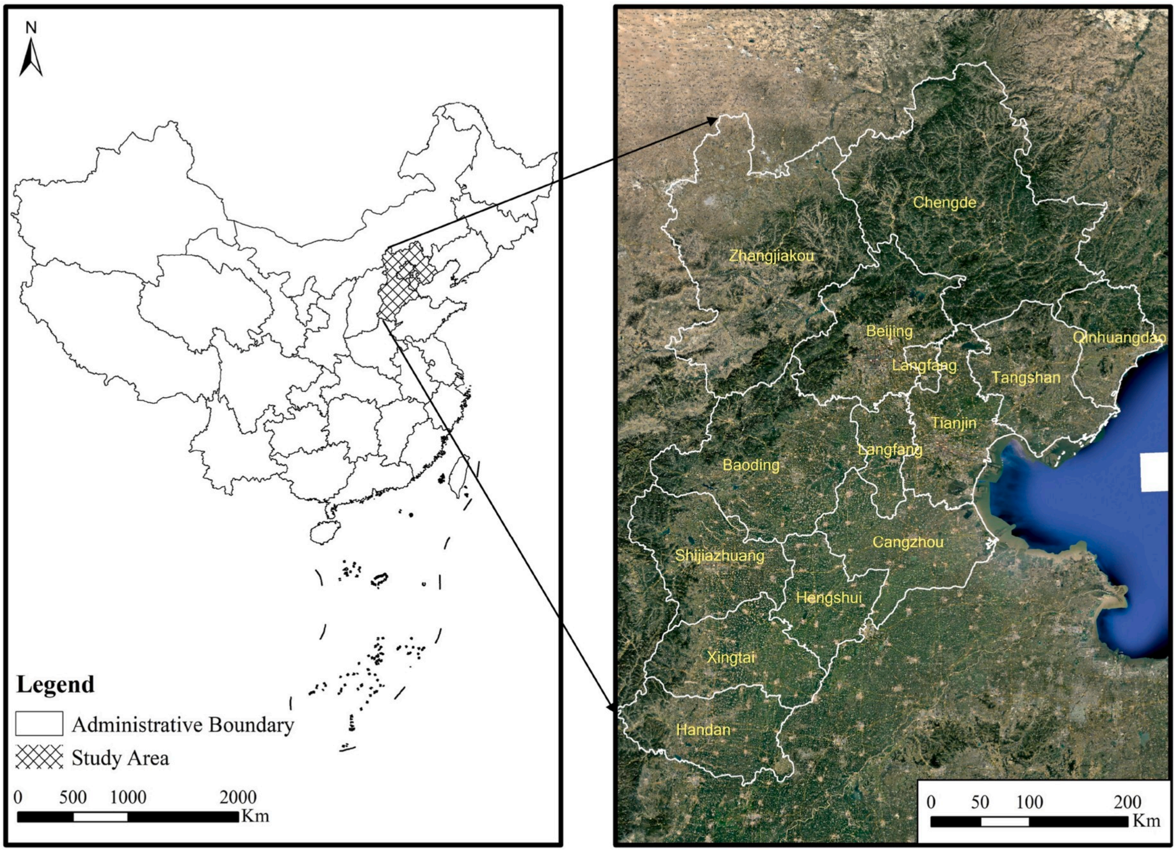

Fig. 1. Location of the Beijing–Tianjin–Hebei (BTH) urban agglomeration. City abbreviations are BJ, Beijing; TJ, Tianjin; SJZ, Shijiazhuang; TS, Tangshan; QHD, Qinhuangdao; HD, Handan; XT, Xingtai; BD, Baoding; ZJK, Zhangjiakou; CD, Chengde; LF, Langfang; HS, Hengshui.

where Q is the total output of the system; A is the direct consumption coefficient matrix, whose elements a_{ij}^{rs} ($a_{ij}^{rs} = x_{ij}^{rs}/q_j^s$) indicate the amount of intermediate economic input from sector i in region r that produces a unit output for sector j in region s; and Y is a vector representing the final demand, including investment, final consumption (i.e., household and government consumption) and net export.

If Y is known, then Q can be calculated using the following equation (Leontief, 1970)

$$Q = (I - A)^{-1} Y \tag{2}$$

and consumption-based NO_x emissions can be obtained as follows:

$$E = EI\ (I - A)^{-1}\ Y_c \tag{3}$$

where EI is a vector whose elements are defined as the amount of direct NO_x emissions per unit total output, $(I - A)^{-1}$ is the Leontief inverse matrix, and Y_c is the final consumption (Li et al., 2016).

Net NO_x emission flux is calculated as follows:

$$\mathrm{netE}^{r\to s} = \mathrm{E}^{rs} - \mathrm{E}^{sr} \tag{4}$$

where $netE^{r\to s}$ is the net NO_x emission from region r to region s. When $netE^{r\to s} > 0$, regions s and r are the receptor and source, respectively, and vice versa (Wang et al., 2017a).

3.2. WRF/CALPUFF model

WRF/CALPUFF model is used to simulate NO_x concentrations in the BTH urban agglomeration. This model is used widely in air quality simulations (Abdul-Wahab et al., 2011; Dresser and Huizer, 2011; Wu et al., 2018), and has been applied and validated for use in BTH (Wang et al., 2019). The coupling of WRF and CALPUFF is to simulate the diffusion process of NO_x and spatial distribution of NO_x concentration. The objective of WRF is to generate the real meteorological field in the simulation area by using the NCEP/NCAR reanalysis data. The output of WRF is further used as the initial meteorological field for CALPUFF model. The simulated diffusion process of NO_x in CALPUFF model is completed in this meteorological field generated by WRF. Finally, the spatial distribution of NO_x concentration is generated according to the set time interval and spatial accuracy.

The data for 2012 January is extracted to represent pollutant diffusion in winter because winter is the most polluted season (Wang et al., 2014). All parameter settings and accuracy verification data used in this paper are reported previously (Wang et al., 2019). The detail parameters setting in WRF/CALPUFF model is provided in Supporting Information (Tables S3 and S4).

3.3. Combined MRIO and WRF/CALPUFF model analysis

The MRIO and WRF/CALPUFF models are combined through the following steps. For a given city (taking Tianjin as an example), first the MRIO model is used to separate the annual emissions of every cities driven by consumption of Tianjin. And then the annual emission data is averaged into hourly emissions. Next, the hourly emissions are input to the WRF/CALPUFF model to simulate daily average atmospheric pollutant concentrations in each BTH city. A conceptual diagram of the MRIO + WRF/CALPUFF model is shown in Fig. 2, illustrating the relationships among consumption, emissions, and pollutant concentration.

3.4. Inter-city contributions from a consumption perspective

The contribution of consumption-based emissions from other regions

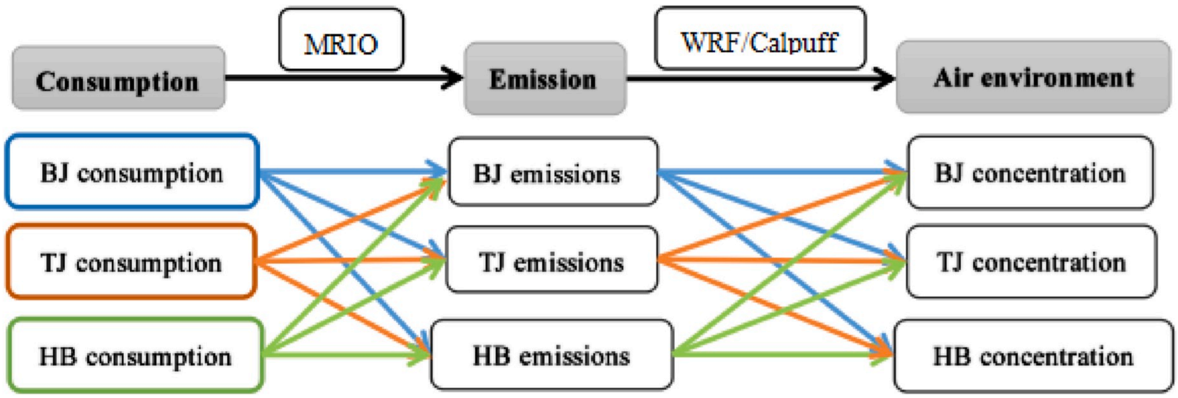

Fig. 2. Interactions among economic consumption, NOx emissions and concentrations in the BTH urban agglomeration. City or province abbreviations are BJ, Beijing; TJ, Tianjin; HB, Hebei.

to a given local region is expressed as follows:

$$P^{rs} = E^{rs} / E^{s} \tag{5}$$

where P^{rs} is the inter-region consumption contribution, referring to the share of emissions in region s originating from consumption in region r; E^{rs} is the emissions in region s originating from consumption in region r; and E^{s} is the direct emissions (production-based) in region s.

After simulating NO_x concentrations, the contribution of NO_x concentration is calculated as follows:

$$R^{rs} = C^{rs} / C^{s} \tag{6}$$

where R^{rs} is the contribution to NO_x concentration from interregional consumption, C^{rs} is the NO_x concentration in region s due to consumption in region r, and C^{s} is the NO_x concentration in region s.

4. Results

4.1. Inter-city/province NO_x emissions virtual transfer only by MRIO model

The consumption-based emissions are virtual emissions driven by the consumption of local and imported goods, which are derived from final consumption output calculated by equation (3). The total production-based emissions amount was 1628.06 Gg in BTH, of which originating from BTH in-region consumption accounted for 773.12 Gg (47.49%). BTH out-region consumption, from the other 29 provinces of China and abroad, accounted for 854.94 Gg of emissions. From a production perspective, Tianjin ranked highest, with a total emissions amount of 375.48 Gg, followed by Tangshan (271.63 Gg) and Shijiazhuang (197.27 Gg). From a consumption perspective, Tianjin and Beijing were the two highest ranking cities in terms of consumption-based emissions, due to their huge populations; their consumption-based emission data were very similar, at 384.82 and 382.98 Gg, respectively. However, Tianjin's proportion of local consumption based on local production reached nearly 50%, whereas that of Beijing was only about 20% (Fig. 3a, Table S5).

In total, 8 of the 13 BTH cities were consumption-based emissions receptors; the other 5 cities were consumption-based sources. However, if these cities are analyzed in detail, some new finding can be found. For most cities, production-based emissions nearly matched consumption-based emissions (Fig. 3b). Take Tianjin and Shijiazhang as examples, the consumption- and production-based emission amounts of these two cities were relatively large due to their large populations and thriving heavy industry sectors. Tianjin is a municipality under the direct control of the Central Government and Shijiazhuang is the capital city of Hebei

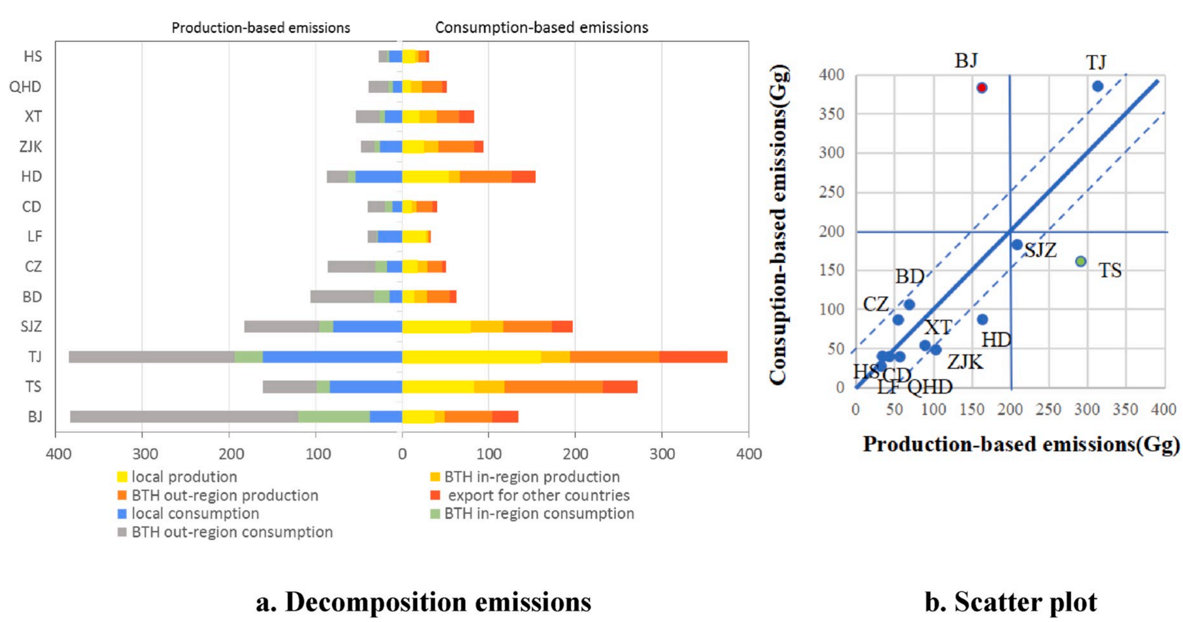

Fig. 3. Comparison of production- and consumption-based NO_x emissions.

Province; both cities are consumption- and production-oriented. Only Beijing is a typical consumption-oriented city due to its special economic and political status. In contrast, Tangshan is a typical production-oriented city. Because Tangshan is heavily industrialized and provides other regions with high-emission industrial products (e.g., iron and steel products) (National Bureau of Statistics of China, 2019), and its production-based emissions were much larger than its consumption-based emissions (Fig. 3b), with the production-based NO_x emissions reaching nearly 300 Gg.

The consumption-driven virtual NO_x emissions transfer matrix between BTH and other provinces was calculated using Equation (6) (Table S6). The main net NO_x emission flows of BTH cities and surrounding provinces are shown in Fig. 4a. Net receptor cities, especially Tangshan, were mainly characterized by heavy industry. Tangshan's industrial activities and associated emissions were influenced by consumption in other regions, particularly in southeast coastal developed provinces such as Jiangsu, Zhejiang, and Guangdong. Conversely, Beijing was a major net consumption-driven emission source. As shown in Fig. 4, the major flows were from Beijing to other provinces, including Inner Mongolia, Henan, Heilongjiang, Shaanxi, Shanxi, Liaoning and Shandong. At the same time, some cities in Hebei Province, such as Baoding, Xingtai and Canghou, have transferred virtual emissions to the Central and East China.

Within the BTH region, the major net emission flow was from Beijing to other cities in the BTH urban agglomeration, such as Tianjin (16 Gg), Tangshan (14.5 Gg), Baoding (9 Gg) and Shijiazhuang (8 Gg) (Fig. 4b). To satisfy the consumption requirements of Beijing, these cities emit large amounts of pollutants. Beijing is the largest consumption-driven source city in BTH, based on virtual emissions.

4.2. Inter-city linkages under the combined effects of economic linkage and atmospheric transport

By combining the MRIO and WRF/CALPUFF models, the matrix of pollutant concentrations induced by consumption is simulated by using Equation (5) (Fig. 5, Table S9). The contribution to atmospheric environment quality of a city can be divided into local city itself contribution and non-local contribution (Li et al., 2016). In this study, the non-local includes "BTH in-region consumption" (consumption in the other 12 cities within BTH) and "BTH out-region consumption" (consumption in other provinces of China).

As Fig. 5 shown, the NO_x concentrations of most cities are mainly affected by non-local consumption. According to the combined effect, the 13 cities in BTH region can be divided into three categories.

(1) The I category

Tianjin and Shijiazhuang belong to this category. These two cities have the largest contribution on their local NOx concentration among the 13 cities. The reason is the results of the previous 4.1 section. The two cities have large populations and thriving heavy industry sectors to induce both large consumption- and production-based emission.

(2) The II category

These cities are mainly affected by the inner cities of BTH region, such as Hengshui, Langfang, Cangzhou and Baoding. It is worth noting that most of these cities are in the center of Hebei Province. Hengshui was mainly characterized by in-region consumption (61%), of which Tianjin accounted for 20% and Shijiazhuang 12%. For Baoding, the in-region consumption was 52%, of which Tianjin accounted for 12%, Shijiazhuang 10% and Beijing 9%. Tianjin's consumption was also responsible for 37% and 28% of the NO_x in Langfang and Cangzhou, respectively (Fig. 5). The first column of Fig. 5 indicate that Tianjin's consumption has not only a great impact on the air quality of the local environment, but also on the air quality of other cities in the BTH urban agglomeration. Therefore, Tianjin is an important source city to affect the central Hebei Province.

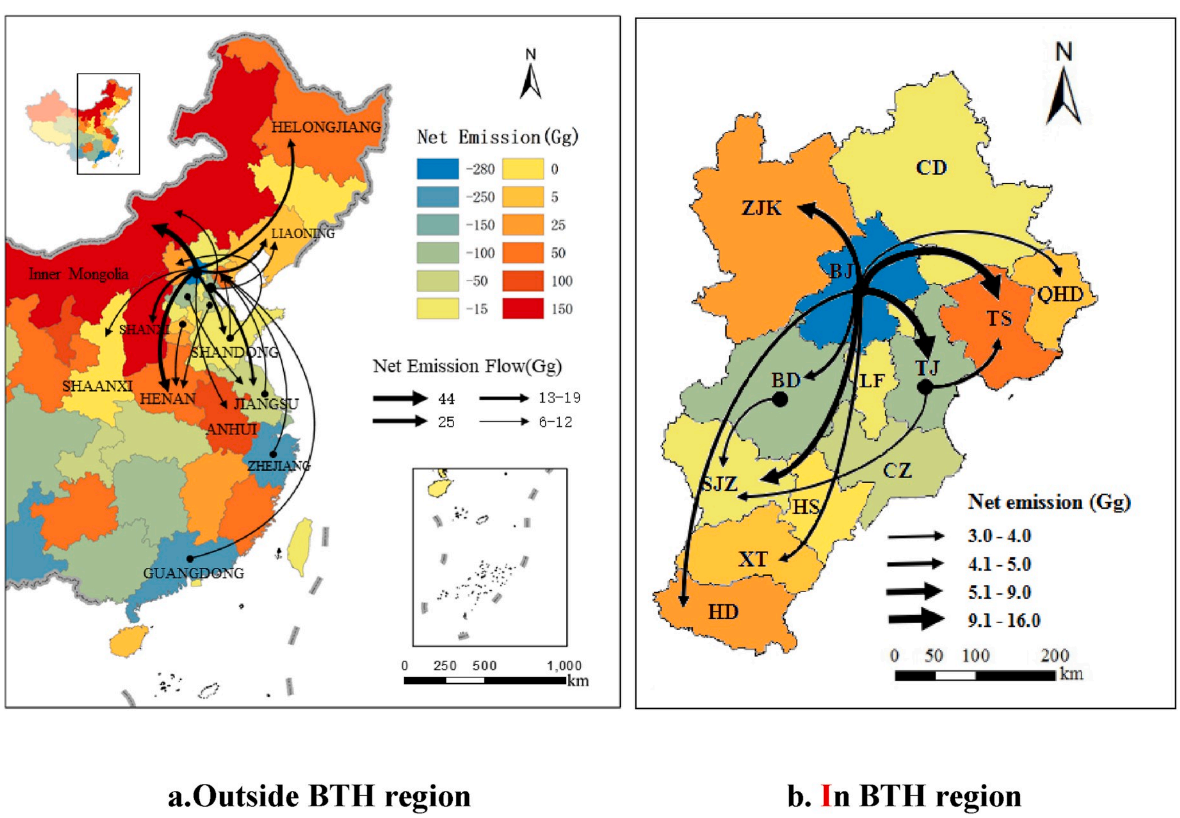

Fig. 4. Consumption-driven virtual NO_x emission transfer flows. Only flows of > 3 Gg between BTH cities and other provinces are shown.

Comsuption-based source (columns); Comsuption-based receptor (rows)

	TJ	SJZ	HS	CZ	LF	BD	XT	BJ	TS	CD	ZJK	QHD	HD	In-region	Out-region	
TJ	47	1	0	1	2	1	0	7	6	0	0	0	0	18	35	I
SJZ	4	36	1	2	4	3	2	5	2	1	1	1	2	28	36	
HS	20	12	30	6	3	2	3	6	3	1	0	0	5	61	9	II
CZ	28	5	3	20	7	2	1	5	5	1	1	1	2	61	19	
LF	37	1	0	4	30	1	1	7	6	0	1	0	1	59	11	
BD	12	10	1	2	8	13	1	9	4	1	1	1	2	52	35	
XT	6	17	3	2	1	2	15	5	2	1	1	1	9	50	35	
BJ	13	1	0	1	3	1	0	21	3	0	2	0	0	24	55	III
TS	9	1	0	1	1	1	0	5	28	0	0	1	1	20	52	
CD	6	1	0	1	1	1	0	7	10	14	3	0	1	31	55	
ZJK	2	2	0	0	0	1	0	9	2	1	23	0	1	18	59	
QHD	8	2	0	1	0	2	1	6	13	1	1	12	1	36	52	
HD	3	5	1	1	0	1	4	3	1	0	0	0	30	19	51	

Fig. 5. NO_x concentration contributions of the BTH cities. Each cell in the grid shows the contribution of a source city's economic consumption to the NO_x concentration in the receptor city. The unit of numbers in each grid is %. Darker colors indicate greater contributions. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(3) The III category

The third category is opposite to the second category, including Beijing, Tangshan, Chengde, Zhangjiakou, Qinhuangdao, Handan. It is worth noting that most cities locate near the border of BTH urban agglomeration, except Beijing and Tangshan. The major contributor to their urban air quality is the consumption from BTH out-region due to the close distance from the surrounding provinces. For Beijing and Tangshan, as the above research shows, the two cities have the closest economic ties with the region outside BTH. The former is a typical

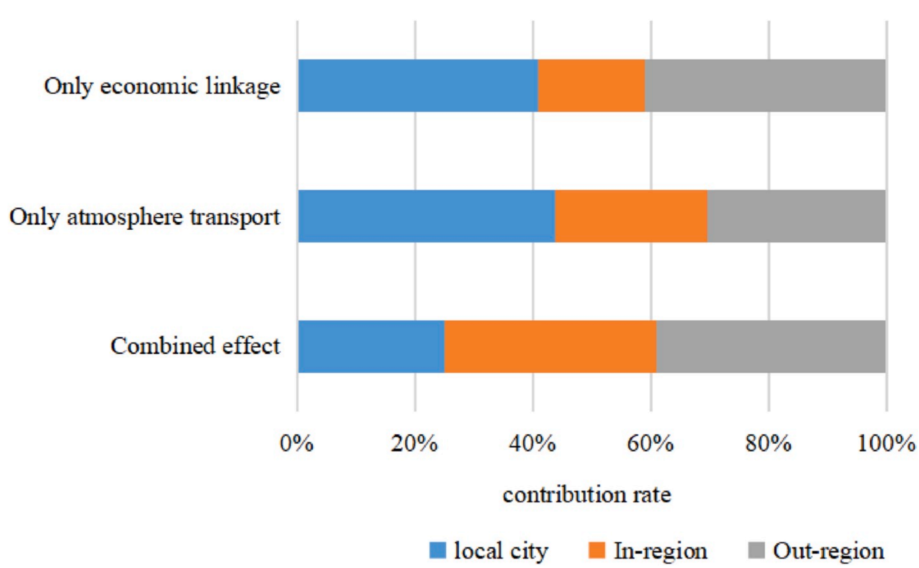

Fig. 6. Comparation of the three kinds of contribution analysis. The first kind of contribution analysis is considered only economic linkage based on MRIO model, the second kind of contribution analysis is considered only atmosphere transport based on air quality model according to the reference(Wang et al., 2017b), the third kind of contribution analysis is considered the combined effect of economic linkage and atmosphere transport.

consumption-oriented city, the latter is a production-oriented city. As a result, like other border cities, they are more affected by outside.

4.3. Comparison of the results

The average value of the three kinds of linkages contribution analysis is compared (Fig. 6). The first contribution analysis result is only from the economic linkage perspective (determined by MRIO only). This result is from our research. The result shows that the main contribution is from the local city and BTH out-region about 40% respectively. The contribution of BTH in-region cities is smallest (average 20%).

The second kind of contribution analysis is only from the atmosphere transport perspective. This kind contribution analysis result is based on the research results of the application of CAMx-PSAT air quality model by Wang et al. (2017b). Their results show that the major contributor to urban air quality is emissions of local cities, about 40% on average. It happens to be similar to the first result of only considering economic relation. The other research also shows similar results. For example, Li et al. (2015) used CAMx-PSAT to quantify the contribution of $PM_{2.5}$ concentration in the BTH region in 2006 and 2013. Their results show local emissions make the largest contribution (40%–60%) for all receptors. Chang et al. (2019) used WRF–CMAQ modeling system to simulate the air quality in the BTH region. Their results show annual averaged local contribution ranges from 32% to 63% for the 13 cities in the BTH region. However, the contribution of BTH in-region is bigger than that of the first result, about close to 30%. This phenomenon shows that the contribution of BTH in-region will increase if atmospheric transport is considered due to the close physical distance between cities in BTH region.

The third kind of contribution analysis is the results of combined effect of economic linkages and atmosphere transport. This result shows that local contributed less than 30% in most cities. For all cities, more than 50% of the NO_x concentration induced by other area contribution. These findings indicate that other area is an important contributor in the BTH urban agglomeration at the city level. BTH out-regions were responsible for 39% of the NO_x concentration. BTH in-region consumption and city's own consumption made contributions 36% and 25% on average, respectively. This result indicates that the contribution from local city decreased when combined effect was considered.

Therefore, the unique characteristic captured in this paper is when the MRIO and air quality models are combined, the relative contribution of local urban decreases and the non-local contribution from the surrounding cities and other area becomes more important.

To further explain the atmospheric transport mechanism, the impact of economic consumption of Tianjin on the pollutant concentration in Cangzhou is assessed as an example. As shown in Fig. 7, consumption in Tianjin led to production in Cangzhou (associated with 1.15 Gg NO_x emissions; 2.6% of all Cangzhou emissions), as well as in Tianjin (160.52 Gg NO_x emissions) and other regions (31.85 Gg NO_x emissions among the other 11 BTH cities). The contribution of emission in Cangzhou driven by consumption of Tianjin was only 0.88 μg m^{-3}. However, Tianjin's consumption also led to emissions in Tianjin itself (contribution of 18.07 μg m^{-3} to the NO_x concentration in Cangzhou through atmospheric transport). Similarly, consumption in Tianjin led to emissions in the remaining 11 cities, contributing 0.38 μg m^{-3} to the NO_x concentration in Cangzhou. Cumulatively, these three sources contributed 28% of the NO_x concentration in Cangzhou. This is the real linkages between Tianjin and Cangzhou about air pollution.

5. Conclusion and policy implications

In this paper, take the BTH region as example, when the combined effect of economic linkages and atmospheric transport is considered, the result shows the non-local contribution is greater than that only considering atmospheric transport or only considering economic correlation.

These atmospheric and economic relationships should be taken into account in air pollution control policies. It suggests that governments should exercise cautious when formulating industrial emission reduction targets and policies, because emissions reduction in one city may affect both the air quality and economic consumption in other cities. Thus, air pollution policies should consider both economic and atmospheric relations among cities to reduce the negative impacts of emission reductions on living standards and the economy. From a perspective of regional collaboration, Beijing and Tianjin, as two metropolises of consumption and production, are suggested to give support to other cities in Hebei Province in terms of air pollution control technology and funds. Hebei Province should avoid receiving the polluted enterprises from Beijing or Tianjin. The government should seize the two-source control means of new source environmental access and old source backward production capacity elimination to speed up industrial upgrading. Moreover, it is suggested to establish the emergency emission reduction scheme for heavy pollution in winter and the intercity air pollution joint prevention and control plans from the perspective of differentiation and economic influence. Furthermore, the establishment of investigation mechanism of long-distance transmission of fixed sources, the performance evaluation mechanism and financial mechanism are suggested to guarantee these plans.

Equalizing the spatial and temporal resolution of economic and atmospheric data is difficult; improving the accuracy of this process would improve the quality of research in this area. The limitation of this paper is the lack of more detailed input data for the atmospheric transport simulation. Because the basic scientific research on the mechanism of chemical transformation of air pollutants in BTH area is not mature enough, this study lacks the atmospheric chemistry simulation. But this article focuses on the relationship between economy and environment. The method in this paper represents an improvement of the application of input-output model in air pollution research. Future studies can apply the methods proposed in this study to explore a wider range of air pollutants, and their sources, to provide a scientific basis to optimize emissions reduction targets at the city level and formulate rational air pollution control policies.

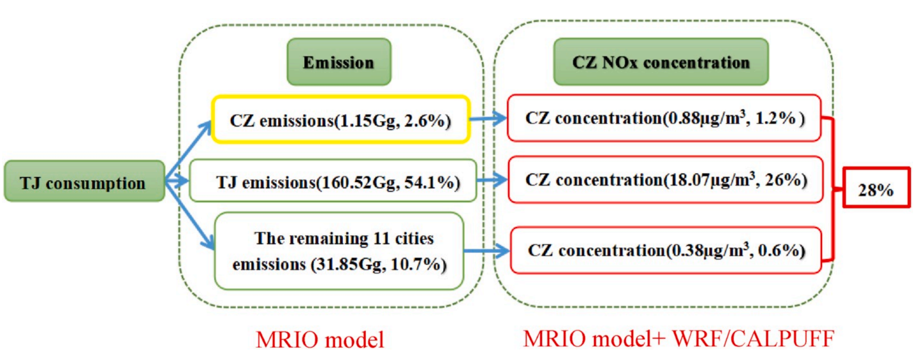

Fig. 7. The impact of economic consumption in Tianjin (TJ) on the NO_x concentration in Cangzhou (CZ). Yellow box indicates the contribution of consumption in Tianjin on the emissions in Cangzhou, i.e., Tianjin consumption→Cangzhou NO_x emissions (2.6%) determined using only the MRIO model. Red boxes indicate the contribution of consumption in Tianjin to the pollutant concentration in Cangzhou, i.e., Tianjin consumption→Cangzhou NO_x concentration (28%), as calculated using the MRIO and WRF/CALPUFF models. For data on the other cities, see the Supporting Information (Fig. S2). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Author statement

Y. Wang, Z. Qiao and Z. Zhang designed the study and performed the analysis. X. Li and Y. Sun drew the figures. H. Zheng and J. Meng provided a city-level MRIO table. Y. Sun compiled sectoral air pollutant emission inventories. All authors participated in the writing of the manuscript. Y. Wang and Z. Qiao contributed equally to this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.110819.

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