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CO_2 emissions inventory of Chinese cities

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Abstract

China is the world's largest energy consumer and CO_2 emitter. Cities contribute 85% of the total CO_2 emissions in China and thus are considered the key areas for implementing policies designed for climate change adaption and CO_2 emission mitigation. However, understanding the CO_2 emission status of Chinese cities remains a challenge, mainly owing to the lack of systematic statistics and poor data quality. This study presents a method for constructing a CO_2 emissions inventory for Chinese cities in terms of the definition provided by the IPCC territorial emission accounting approach. We apply this method to compile CO_2 emissions inventories for 20 Chinese cities. Each inventory covers 47 socioeconomic sectors, 20 energy types and 9 primary industry products. We find that cities are large emissions sources because of their intensive industrial activities, such as electricity generation, production for cement and other construction materials. Additionally, coal and its related products are the primary energy source to power Chinese cities, providing an average of 70% of the total CO_2 emissions. Understanding the emissions sources in Chinese cities using a concrete and consistent methodology is the basis for implementing any climate policy and goal.

Keywords: Energy balance table, CO_2 emissions inventory, Chinese cities

1. Introduction

Cities are the main consumers of energy and emitters of CO_2 throughout the world. The International Energy Agency (IEA) estimates that CO_2 emissions from energy use in cities will grow by 1.8% per year between 2006 and 2030, with the share of global CO_2 emissions rising from 71% to 76% (International Energy Agency (IEA), 2009). As a result of urbanization, the world's urban population grew from 220 million in 1990 (13% of the world's population) to 3530 million in 2011 (52% of the world's population) (Kennedy et al., 2015). Therefore, cities are major components in the implementation of climate change adaption and CO_2 emission mitigation policies. Understanding the emission status of cities is considered a fundamental step for proposing mitigation actions.

With rapid economic development, lifestyle change and consumption growth (Hubacek et al., 2011), China is now the world's largest consumer of primary energy and emitter of greenhouse gas emissions (Guan et al., 2009a). China produces 25% of global CO_2 emissions (U.S. Energy Information Administration (EIA), 2010) and consumes 20.3% of global primary energy (British Petroleum (BP), 2011). Among CO_2 emission sources, 85% of China's emissions are contributed by energy usage in cities, which is much higher than that of the USA (80%) or Europe (69%) (Dhakal, 2010;Dhakal, 2009). Complete energy balance tables and CO_2 emission inventories are available for Chinese megacities, including Beijing, Tianjin, Shanghai, and Chongqing. Another 300+ cities of various sizes and development stages lack consistent and systematic energy statistics. An effective understanding of the energy consumption and emission status of cities is required to practically mitigate climate change (Su et al., 2012;Yuan et al., 2008;Zhang and Cheng, 2009;Jiang et al., 2010;Richerzhagen and Scholz, 2008;WWF China, 2012;National Development and Reform Commission (NDRC), 2012).

In this study, we develop a concrete and consistent methodology for constructing CO_2 emissions inventories for Chinese cities for fossil energy combustion and industrial processes. We collect and compile energy and emission balance table at city administration boundary level, aiming at providing unified and comparable energy and emission statistics for Chinese cities. We identify the main contributors to CO_2 emissions in a selection of 20 Chinese cities.

2. Selective Review To Emission Inventory

2.1. City-level emission inventory

The CO_2 emission inventory has captured both public and academic attention in recent years. Most of the previous emissions inventories were developed at the national level (Peters et al., 2007;Guan et al., 2008;Guan et al., 2009b;Guan et al., 2014;Guan et al., 2012;Liu et al., 2013;Peters et al., 2012;Davis and Caldeira, 2010;Menyah and Wolde-Rufael, 2010) and sectoral level (Shan et al., 2015;Liu et al., 2012a;Sheinbaum et al., 2010;Shao et al., 2011) and for specific fossil fuel combustion emission sources (Pan et al., 2013;Shan et al., 2014). Emission inventories for cities are limited (Ramaswami et al., 2008;Hillman and Ramaswami, 2010;Dodman, 2009;Hoornweg et al., 2011;Satterthwaite, 2008;Kennedy et al., 2011;Brondfield et al., 2012).

Most city-level GHG emissions inventories are calculated using a bottom-up approach currently, i.e., by using energy data from certain sectors. The sectors set are different from study to study. For example, Wang et al. (2012) calculated carbon emissions for six sectors of a city's GHG inventories, including industrial energy consumption, transportation, household energy consumption, commercial energy consumption, industrial processes and waste. Kennedy et al. (2010) compiled a carbon emissions inventory that covers electricity, heating and industrial fuels, ground transportation fuels, aviation and marine transportation, industrial processes and product use, and waste. Their subsequent research focuses on the balance of geophysical factors (climate, access to resources, and gateway status) and technical factors (power generation, urban design, and waste processing), and analyse their influence on the GHGs attributable to the ten cities (Kennedy et al., 2009). In accordance with this method, Kennedy et al. (2014) complied the greenhouse gas inventories of 22 global cities, including three Chinese cities: Beijing, Tianjin, and Shanghai. The research shows how the differences in city characteristics, such as climates, incomes, levels of industrial activity, urban forms and existing carbon intensity of electricity supplies, lead to wide variations in emissions reducing strategies. Furthermore, Kennedy et al. (2015) quantified the energy and material flows through the world's 27 megacities, including four Chinese cities: Beijing, Shanghai, Guangzhou, and Shenzhen. The megacities are chosen by populations greater than 10 million people as of 2010. Creutzig et al. (2015) built a energy/emission dataset including 274 cities, and present the aggregate potential for urban climate change mitigation.

Compared with global research, CO_2 emission inventory research on Chinese cities has not been well documented. Dhakal (2009) focused on 35 provincial capital cities in China, and compiled energy usage and emissions inventories. The results show that urban regions is the primary energy consumer and CO_2 emitter in China. Liu et al. (2012b) complied the scope 1 and 2 emission inventories of four Chinese municipalities from 1995 to 2009. Sugar et al. (2012) compiled the 2006 emission inventories of

Chinese municipalities and compared the results with 10 other global mega cities. Wang et al. (2012) complied emission inventories for 12 Chinese megacities based on bottom-up approaches. Most of the cities are chosen from provincial capital cities, such as Hangzhou and Nanjing.

Above all, there is no unified and consistent compilation method to for Chinese cities' CO_2 emission inventory, and most existing research has focused on a few specific megacities, such as municipality cities (Zhou et al., 2010a;Gielen and Changhong, 2001) (Beijing, Shanghai, Tianjin, Chongqing) and few provincial capital cities (Xi et al., 2011), which have consistent and systematic energy statistics.

2.2. Challenges in emissions inventory construction for Chinese cities.

There are some challenges for the compilation of greenhouse gas inventories at the city level for China. First, it is difficult to define a city's boundary for greenhouse gas emissions accounting because energy and material flows among cities may bring a large quantity of cross-boundary greenhouse gas emissions (Liang and Zhang, 2011;Wolman, 1965). Commercial activities are much more frequent among cities, compared with inter-provinces / nations. This leads to a great challenge in defining a city's boundary and calculating its emissions. Second, data for energy consumption and industry products at the city level are incomparable and very limited (Liu et al., 2012b). For most cities in China, there are no concrete and consistent energy consumption data. Data used in previous studies are from various sources – including data from city statistical documents and remote sensing images, data from direct interviews with local governmental officials, and published reports and literature (Xi et al., 2011). Those data require systematic reviews for consistency and accuracy.

3. Methodology

Figure 1 shows the overall methodology framework designed for the construction of emissions inventories for Chinese cities in this study.

3.1. Scope and boundary for energy statistics and emissions accounting

In accordance with the guidelines from the Intergovernmental Panel on Climate Change (IPCC) regarding the allocation of GHG emissions, we consider the administrative territorial scope for each city's energy statistics and CO_2 emissions in this study. Administrative territorial emissions refers to the emissions that occur within administered territories and offshore areas over which one region has jurisdiction, (Intergovernmental Panel on Climate Change (IPCC), 2006) including emissions produced by socioeconomic sectors and residence activities directly within the region boundary (Kennedy et al.,

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Atmospheric Chemistry and Physics Discussions

2010;Kennedy et al., 2011). In this paper, we define the administrative territorial emissions for the city level in Table 1.

The CO_2 emissions inventory compiled by this method consists of two parts (see Figure 1). The first part is emissions from fossil fuel consumption, and the second part is emissions from industrial processes.

First, we calculate the emissions from fossil fuel combustion within the city boundary. The emissions are calculated for 20 energy types and 47 socioeconomic sectors. The 47 socioeconomic sectors are defined according to the Chinese National Administration for Quality Supervision and Inspection and Quarantine (NAQSIQ) (P.R. China National Administration for Quality Supervision and Inspection and Quarantine, 2011), which include all possible socioeconomic activities conducted in a Chinese city's administrative boundary (shown in SI Table S1). We include 20 energy types in this paper that are widely used in the Chinese energy system (see SI Table S5) (Department of Energy Statistics of National Bureau of Statistics of the People's Republic of China, 1986-2013). We exclude emissions from imported electricity and heat consumption from outside the city boundary owing to the lack of data on the energy mix in the generation of imported electricity.

In the second part of the emissions inventory, we calculate emissions from 9 industrial production processes (see SI Table S6). The industrial process emissions are CO_2 emitted as a result of chemical reactions in the production process, not as a result of the energy used by industry. Emissions from industrial processes are factored into the corresponding industrial sectors in the final emissions inventory.

By including the emissions from industrial processes, the emissions inventory designed in this paper includes all administrative boundary territorial CO_2 emissions from 47 sectors, 20 energy types and 9 main industrial products.

3.2. Data requirement

3.2.1. Basic energy balance table (EBT_{sj})

The basic energy balance table is an aggregate summary of energy production, transformation and consumption in one area. The table shows the primary and secondary energy flows among sectors within any administrative region (Qiu, 1995). The table is usually compiled by the Bureau of Statistics of an administrative region. Table 2 shows the energy balance table items in the Chinese energy

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system (Department of Energy Statistics of National Bureau of Statistics of the People's Republic of China, 1986-2013).

The table is constructed in four parts: "Primary energy supply" provides the information of energy supply, such as production and import; "Input and output of transformation" refers to the primary energy input and secondary energy output in energy transformation process; "Loss" covers all the energy loss during the utilization; "Final consumption" covers all energy supplied to the final consumer for all energy uses. Especially, "Non-energy use" in the final consumption refers to energy consumed without burning, such as used as chemical material. Generally speaking, the energy burning consumption equals to "Final consumption" + "Transformation - thermal power / heating supply" – "Loss" – "Non-energy use". The fossil fuel related CO_2 emissions are calculated based on the energy burning consumption.

3.2.2.Extended energy balance table at city-level

The basic energy balance table counts industry as one entire component of all consumption components ($s = 21$). However, industry is the major energy consumption component and contributes the majority of greenhouse gas emissions. In addition, industry is also the primary area for applying low carbon technologies (Liu et al., 2013). Therefore, we disaggregate the final energy consumption of industry into 40 sub-sectors to develop an extended energy balance table. The extended energy balance table provides a more detailed illustration of energy utilization for both industry and the entire city.

We expand the industry sector according to the industry classification provided by NAQSIQ (Xu, 2005). We divide industry into 40 final sub-sectors ($i \in [2,41]$) and make the final consumption portion of the extended energy balance table consist of 47 socioeconomic sectors ($i \in [1,47]$) (shown in SI Table S1).

3.2.3.Industrial product production

In this paper, we calculate the industrial process CO_2 emissions based on industrial product production.

From the discussion above, we need a basic Energy Balance Table (EBT_{sj}), the sectoral energy consumption of industry by energy types (AD_{ij}), and the production of industrial products (AD_t) to compile the extended energy balance table and CO_2 emissions inventory for cities (see Figure 2). The subscript $s \in [1,31]$ represents items in energy balance table (see Table 2), $i \in [2,41]$ represents 40 industry sectors (see SI Table S1), $j \in [1,20]$ represents 20 energy types (see SI Table S2), and $t \in$

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-176, 2016
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[1,9] represents 9 main industrial products (see SI Table S6). Generally, the data for cities can be collected from city level statistical yearbooks. However, for many Chinese cities, data are not fully available. In terms of data availability, we develop a method to cover the data gaps under different scenario (see Sect. 3.3, 3.4, and 3.5).

3.3. Basic energy balance table collection and compilation

3.3.1. Case α: city with basic energy balance table

Some cities compile an energy balance table in their statistical yearbooks; these include Jixi, Hohhot, Changsha, Weifang, Tangshan and Guangzhou. We use the table directly to compile the extended energy balance table.

3.3.2. Case β: city without basic energy balance table

For cities such as Hefei, Xiamen, Nanning, Zhoushan, Chengdu, Yichang, Xi'an, and Shenzhen, there is no basic energy balance table in their statistical yearbooks. In these cases, we deduce the city's basic energy balance table (EBT_{sj}) from its corresponding provincial energy balance table (EBT_{sj-p}). First, we define a city-province percentage p in Eq. (1), which can be calculated using different indexes, such as industrial outputs and population. The equation reflects the percentage relation between a city and its province.

$$p = \frac{Index_{city}}{Index_{province}} \times 100\% \qquad \text{Eq. (1)}$$

With the city-province percentage, p, we scale down the provincial energy balance table to the city level (see Eq. (2)). In the following calculation of a city's emissions, the data on energy transformation, loss, and final consumption ($s \in [9, 29]$) will be used. Therefore, we focus solely on these three components in this study.

$$EBT_{sj} = EBT_{sj-p} \times p, s \in [9, 29], j \in [1, 20] \qquad \text{Eq. (2)}$$

By using different indexes, p can indicate the different percentage types of emissions in one city based on the entire province. We use different city-province percentages, p, to deduce the relevant items for the energy balance table in this paper. For 'Input & Output of Transformation' ($s \in [9, 17]$) and 'Loss' ($s = 18$), we use the industrial output as the index because energy transformation departments belong to industrial sectors. For 'Final consumption', we use the corresponding outputs of each sector

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-176, 2016
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as the indexes ($s \in [19, 26]$). For 'Residential consumption', we use population as the index ($s \in [27, 29]$). The industrial output and population can be collected from city's statistical yearbook.

Thus, we deduce a city's basic energy balance table from its corresponding provincial table.

3.3.3. Case γ: city without energy balance table, but with "Transformation usage of energy types"

Some cities do not have a basic energy balance table in their statistical yearbooks, but have compiled a table of "Transformation usage of energy types (T_j)"; these include Handan, Nanping, Dandong, Baicheng, Zunyi, and Huangshi.

The transformation table presents the energy used in the "Input & Output of Transformation" section and can be used to make our deduced basic energy balance table more accurate. We modify $EBT_{sj}, s \in [9, 17], j \in [1, 20]$ according to the table.

3.4. Industrial sector energy consumption collection and deduction

3.4.1. Case A: city with sectoral energy consumption of industry (AD_{ij})

For some cities such as Jixi and Shenzhen, the sectoral energy consumption of industry is provided in the statistical yearbook. We use the data to directly compile the extended energy balance table.

3.4.2. Case B: city with sectoral energy consumption of industry enterprises above designated size (AD_{ij-ADS}) and total energy consumption of industry (AD_j)

For cities such as Hohhot, Changsha, Tangshan, and Guangzhou we can only collect sectoral energy consumption of industrial enterprises above designated size ($\mathrm{AD_{ij-ADS}}$) and total energy consumption of industry ($\mathrm{AD_j}$) in the statistical yearbook. The enterprise above designated size refers to the enterprise with annual main business turnover above 5 million Yuan. In this case, we expand AD_{ij-ADS} by AD_j to obtain AD_{ij} in Eq. (3).

$$AD_{ij} = \frac{AD_{ij-ADS}}{\sum_i AD_{ij-ADS}} \times AD_j, i \in [2, 41], j \in [1, 20] \qquad \text{Eq. (3)}$$

In particular, the total energy consumption of industry (AD_j) can be obtained from an independent table or from the city's original energy balance table.

3.4.3. Case C: city with sectoral energy consumption of industry above designated size (AD_{ij-ADS}) only

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-176, 2016
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Atmospheric Chemistry and Physics
Open Access
EGU
Discussions

These cities are the most common types in terms of data collection for Chinese cities. Most cities are classified into this case; these include Handan, Nanping, Hefei, Xiamen, Nanning, Zhoushan, Chengdu, Dandong, and Xi'an. To calculate the sectoral energy consumption of industry (AD_{ij}) in these cities, we expand AD_{ij-ADS} to AD_{ij} by industry to the industry of ADS (above the designated size) multiplier m (refer to Eq. (4)).

$$AD_{ij} = AD_{ij-ADS} \times \frac{O_{industry}}{O_{ADS}}, i \in [2, 41], j \in [1, 20] \qquad \text{Eq. (4)}$$

$O_{industry}/O_{ADS}$, which is the ADS multiplier (m) in this paper, refers to the multiple of industrial output to that of the industry above the designated size.

Note that the total energy consumption of industry calculated in this manner can be different from that deduced in the basic energy balance table. We use the consumption calculated by the ADS multiplier as the correct consumption data, and modify the relevant data in the basic energy balance table. Because the consumption calculated by the ADS multiplier is compiled by sectors, it is assumed to be more accurate.

3.4.4.Case D: city with total energy consumption of industry above designated size (AD_{j-ADS}) only

For cities such as Weifang, Baicheng, Yichang, Zunyi, and Huangshi, we can collect only the total energy consumption of industry above the designated size (AD_{j-ADS}) from the statistical yearbooks. In this case, we first scale up AD_{j-ADS} to AD_j by the ADS multiplier m and then divide AD_j into each sector by the sectoral comprehensive energy consumption of the industry above the designated size (AD^*_{i-ADS}) (refer to Eq. (5)). If one city does not have AD^*_{i-ADS}, we use the sectoral industry output instead.

$$AD_{ij} = AD_{j-ADS} \times \frac{O_{industry}}{O_{ADS}} \times \frac{AD^*_{i-ADS}}{\sum AD^*_{i-ADS}}, i \in [2, 41], j \in [1, 20] \qquad \text{Eq. (5)}$$

With these three cases, we collect and deduce the sectoral energy consumption of industry for one city. By replacing the total energy consumption of industry in the basic energy balance table (EBT_{21j}) with the sub-sectoral detail, we obtain the extended energy balance table.

3.5. Data collection and deduction for the production of industrial products

Data collection for the production of industrial products is much easier and universal. Every city has the "Production of industrial products" table in its statistical yearbook. A portion of the production is derived from industrial enterprises above the designated size. If we expand the production above the designated size (AD_{t-ADS}) by the city's ASD multiplier m defined above, we can obtain the total production of each industrial product (AD_t), shown in Eq. (6), in which the subscript $t \in [1, 9]$ represents the different industrial products (refer to SI Table S6).

$$AD_t = AD_{t-ADS} \times m, t \in [1,9] \quad \text{Eq. (6)}$$

3.6. Construction of a city level CO_2 emission inventory

We adopt the IPCC sectoral approach(Intergovernmental Panel on Climate Change (IPCC), 2006) to calculate the CO_2 emissions from fossil fuel combustion and industrial process (Peters et al., 2006) and applied by other scholars (United Nations Framework Convention on Climate Change (UNFCC);International Energy Agency (IEA);European Commission, 2014;Feng et al., 2013;Wiedmann et al., 2008;Liu et al., 2014;Zhou et al., 2010b;Lei et al., 2011;Zhao et al., 2013).

$$CE_{ij} = AD'_{ij} \times NCV_j \times EF_j \times O_{ij}, i \in [1,47], j \in [1,20] \quad \text{Eq. (7)}$$

We calculate the fossil fuel-related CO_2 emissions in Eq. (7). CE_{ij} represents the CO_2 emissions of different sectors and energy types; AD'_{ij} represents the adjusted energy consumption; NCV_j represents the net calorific value of different energy types; EF_j refers to the emission factors; and O_{ij} refers to the oxygenation efficiency of different sectors and energy types. Both the IPCC and NDRC provide default emission factors for fossil fuels (Intergovernmental Panel on Climate Change (IPCC), 2006;P. R. China National Development and Reform Commision (NDRC), 2011). However, based on measurements of 602 coal samples from the 100 largest coal-mining areas in China (Liu et al., 2015), the emission factors recommended by the IPCC and NDRC are frequently higher than the real emissions factors. In this study, we adopted the newly measured parameters (NCV_j, EF_j, and O_{ij}), which we assume to be more accurate than the IPCC and NDRC default values (see SI Table S5).

$$CE_t = AD_t \times EF_t, t \in [1,9] \quad \text{Eq. (8)}$$

We estimate the process CO_2 emissions in Eq. (8). CE_t represents the CO_2 emissions of industrial products, and EF_t represents the emission factors for each industrial product. The emission factors are collected from IPCC (Intergovernmental Panel on Climate Change (IPCC), 2006) and National

Development and Reform Commission in China (P. R. China National Development and Reform Commision (NDRC), 2011) as well, shown in SI Table S6. After the calculation, CO_2 emissions from the industrial process will be separated into the relevant manufacturing sectors in the final emission inventory.

4. CO_2 Emissions Inventory For 20 Case Cities

4.1. City choice

In this paper, we apply our method to 20 case cities and compile the CO_2 emissions inventory for 2010. These 20 cities, which cover all the possible situations for Chinese cities' emission inventory construction, are in different developmental stages. Figure 3 shows the locations of these 20 case cities.

All necessary activity data were collected from cities' 2011 statistical yearbooks. We present the calculation and results in SI Table S3-S8. These cities belong to different data collection cases, as discussed above.

4.2. Results

In 2010, total CO_2 emissions of the 20 cities varied widely from 6.13 to 104.33 million tonnes. Figure 3 shows the locations and total CO_2 emissions of the 20 case cities. Tangshan and Guangzhou belong to the highest emission class, with more than 100 million tonnes, followed by Handan, Hohhot, and Weifang, Xi'an, and Changsha which have between 50 and 100 million tonnes. All these seven cities have heavy-intensity industries, such as coal mining and manufacturing. The third emission class includes all cities with CO_2 emissions between 25 and 50 million tonnes, i.e., Jixi, Shenzhen, Hefei, Chengdu, Huangshi, and Zunyi. The remaining cities belong to the lowest emissions class; these include cities with less heavy-intensity manufacturing industry / more developed service industry (i.e., Yichang, Nanning, and Xiamen) and cities located in more remote areas with a smaller population and smaller gross domestic product (i.e., Dandong, Nanping, Baicheng, and Zhoushan) compared with the other three classes.

If we divide the total CO_2 emissions by the population, we obtain the CO_2 emissions per capita of the 20 case cities (shown in SI Table 2). We find that, among the 20 case cities, the CO_2 emissions per capita in Hohhot is the highest, with 29.67 tonnes, followed by Jixi (22.84 tonnes), Shenzhen (14.69 tonnes), and Tangshan (14.20 tonnes). The two cities with the lowest CO_2 emissions per capita are Nanping (2.38) and Chengdu (2.53 tonnes). The CO_2 emissions per capita are similar to the total CO_2

emissions of the 20 case cities. Cities with coal mines and heavy-intensity industry have high CO_2 emissions as well as high CO_2 emissions per capita, such as Jixi, Hohhot and Tangshan. Cities located in remote areas and in less developed stages have lower CO_2 emissions per capita as well as less CO_2 emission.

4.2.1.Emissions of different energy types and industrial process

Figure 4 shows the energy type distribution for the CO_2 emissions inventory in 2010. Raw coal is the largest primary source of emissions among the 20 energy types, with an average percentage of 69.55%. The high CO_2 emissions are induced by the large consumption and high carbon content of raw coal (Pan et al., 2013). Coal is the largest primary energy source in China. More than 65% of the total energy used in China comes from coal (U.S. Energy Information Administration (EIA)).

For example, Jixi is one of the coal bases in China and produced 20.46 million tonnes raw coal in 2010. Coal and its related products (cleaned coal, other washed coal, briquettes, and coke) become the primary energy types in Jixi. In 2010, 42.28 million tonnes of CO_2 emissions were produced by coal and combustion of coal products; this is of 97.84% of Jixi's total emissions. Similar to Jixi, Inner Mongolia province is also a main coal base in China. As the provincial capital city of Inner Mongolia, Hohhot uses coal and coal products as the main energy types as well. In 2010, Hohhot produced 6.01 million tonnes raw coal, 0.60 million tonnes coke, and generated 35.26 billion watt-hour electricity in fire power plant in 2010. Coal and coal products contributed 57.57 million tonnes of CO_2 emissions (84.34%) to Hohhot's total CO_2 emissions.

In addition to coal, diesel oil is another important source of CO_2 emissions, with an average percentage of 8.08%. Diesel oil is widely used most types of transportation, such as oversize vehicle and ship. Among the 20 cities, Shenzhen, Zhoushan, Guangzhou, and Xiamen have a much higher percentage of diesel use (32.34%, 22.64%, 14.79%, and 13.57% respectively) than the average percentage Diesel oil is widely used by truck and cargo shippers. These three cities are located in the south and on the southeast coast of China; they are important ports. The freight and transportation industry is more developed in these cities than others. Take Shenzhen as an example, there are 172 berths in Shenzhen harbour with 79 berths over 10 thousand tonnes class, the cargo handled at seaports are 220.98 million tonnes in 2010. The waterways and highway freight traffic in 2010 are 198.47 and 58.59 million tonnes, taking a percentage of 1.38% and 0.70% over the whole Chinese 300+ cities. Therefore, the diesel oil and Transportation sectors has a higher percentage of these cities' total CO_2 emissions compared with other cities (shown in Sect. 4.2.2).

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Atmospheric Chemistry and Physics Discussions
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Industrial processes also contribute much to a city's total CO_2 emissions. The total CO_2 emissions produced during the industrial process of the 20 case cities are 86.73 million tonnes, which is 10.57% of the total CO_2 emissions. For example, there are many manufacturing industries in Tangshan, particularly 'non-metal mineral products' and 'smelting and pressing of ferrous metals'. The production of cement, iron, and steel in 2010 are 37.32 Mt, 65.67 Mt and 68.32 million m^3. Therefore, the industrial process contributes greatly to Tangshan's total CO_2 emissions. The CO_2 emissions from Tangshan's industrial process in 2010 were 18.80 million tonnes (18.01%), which is much higher than the average level. Changsha (10.32 tonnes), Yichang (9.87 tonnes), and Huangshi (7.22 tonnes) are similar manufacturing cities.

4.2.2.Emissions of different sectors

We summarise the CO_2 emissions of 47 socioeconomic sectors into 9 key sectors in Figure 4 in order to present sectoral contribution clearly. Industry sectors are the primary resources that contribute to a city's CO_2 emissions. Approximately 78.37% of the total CO_2 emissions are contributed by industry sectors, on average. Among the 40 sub-industry sectors defined in this paper, the "Electricity generation" ($i = 39$) sector produces the most CO_2 emissions, generating 38.07% of the total CO_2 emissions, on average. This generation is caused by the huge quantities of electricity generated in coal-fired power plants.

The "non-metal mineral products" ($i = 27$) sector contributes a lot of CO_2 emissions to the total emissions as well, taking a percentage of 13.22% averagely. This sector includes all the CO_2 emissions during non-metal mineral production, such as cement and lime. Tangshan (20.41 Mt), Changsha (14.98 Mt), Nanning (9.63 Mt), Huangshi (9.52 Mt), and Chengdu (9.46 Mt) have high CO_2 emissions in the "non-metal mineral products" sector compared with other cities. As discussed above, the cement production of Tangshan in 2010 is 37.32 Mt. Changsha (20.70 Mt), Nanning (11.87 Mt), Huangshi (14.49 Mt), and Chengdu (10.39 Mt) also produced more cement in 2010.

"Coal Mining and Dressing" ($i = 2$) sector is the third largest industrial source of CO_2 emissions (7.73% averagely), especially for Jixi (75.43%). This finding is because Jixi is a major coal-producing area in China, as discussed above. Large quantities of fossil fuels are consumed in mines to produce and wash coal and produce coke.

In addition, there are many "Smelting and pressing of ferrous Metals" ($i = 28$) industries in Tangshan and Handan. Tangshan produced 65.67 Mt iron and 68.32 million m^3 steel, while Handan produced

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-176, 2016
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Published: 1 March 2016

33.22 Mt iron and 36.84 Mt steel in 2010. The large production brings the two cities large CO_2 emissions of these sector (26.64 Mt and 8.10 Mt respectively).

In addition to industry sectors, service sectors also greatly contribute to total CO_2 emissions. The "service sectors" in Figure 4 include two components: "transportation" ($i = 43$) and "wholesale services" ($i = 44$). CO_2 emissions from these two sectors generate an average of 14.50% of the emissions in the 20 cities. For Shenzhen, Guangzhou, Changsha, Zhoushan, and Xiamen, the CO_2 emissions that the service sectors contribute (34.34%, 28.39%, 27.38%, 26.10%, and 23.41%, respectively) are much higher than the average level. Among these five cities, Shenzhen, Guangzhou, and Zhoushan are located on the south / southeast coast of China. These cities are very important ports with high waterways and highway freight traffic, as discussed above. Xi'an and Changsha are inland transport junctions. The overall freight traffic of Xi'an and Changsha in 2010 are 343.23 and 229.47 Mt. The "transportation services" sectors of these five cities are well developed. In addition, Shenzhen is one of the most developed cities in China with a larger share of tertiary industries. The proportion of value added by Shenzhen's tertiary industry is 52.7%, which is much higher than the national average of 44.2%. Therefore, the CO_2 emissions of Shenzhen's service departments are higher than those of other cities.

Primary industry and residential energy usage generate a small percentage of cities' CO_2 emissions in China. Based on the 20 case cities, the average percentage of the total CO_2 emissions generated by the two departments is 1.16% (primary industry) and 4.73% (residential energy usage).

5. Conclusion

This paper develops a consistent methodology for constructing territorial CO_2 emissions inventories for Chinese cities. By applying this methodology to cities, researchers can calculate the CO_2 emissions of any Chinese cities. This knowledge will be helpful for understand energy utilization and identify key emission contributors and drivers given different socioeconomic settings and industrialisation phrase for different cities.

We applied this methodology to 20 representative cities and compiled the 2010 CO_2 emissions inventories for these 20 cities. The results show that, in 2010, the "Production and supply of electric power, steam and hot water", "Non-metal mineral products", and "Coal mining and dressing" sectors produced the most CO_2 emissions. Additionally, coal and its products are the primary energy source in Chinese cities, with an average of 69.55%.

Therefore, in order to reduce the CO_2 emissions in Chinese cities, we could take policy from two aspects. The first path is reducing the coal share in the energy mix and replacing by low-emission energy types, such as nature gas. As discussed above, coal combustion emits more CO_2 to produce the same unit of heat compared with other energy types. Replacing coal by clearer energy types, such as nature gas, will help emission control in both Chinese cities and the whole world. China has already take some efforts on coal consumption control at national level. According to the most up to data research at COP 21, the global carbon emissions decreased slightly by 2015 due to Chinese coal consumption decreasing, and renewable energy increasing globally (Le Quéré et al., 2015). The coal share in the energy mix decreased from 72.40% to 64.04% in the recent 10 years from 2005 to 2014, while the natural gas share doubled from 2.40% to 5.63%. Cities in China should also undertake efforts to reduce the coal share in their energy mixes. Beijing, as the capital city and the most developed city in China, has a more balanced energy mix compared with other cities. The coal and natural gas share in the energy mix is 20.41% and 21.13%, respectively, in 2014. Therefore, Beijing's CO_2 emissions has remained stable since 2007 and has seen a slight decrease in recent years (Shan et al., 2016;Guan et al., 2016).

The other way to control CO_2 emissions in Chinese cities is reforming the industrial structure with less heavy emission intensity manufacturing industries and more service sectors. Reviewing the emission intensity of the 20 case cities (see SI Table S3), we find that cities with more heavy manufacturing industries usually have a higher emission intensity, such as Jixi, Huangshi, Hohhot, Zunyi and Tangshan. On the contrary, more developed cities with more service sector activities have a smaller emission intensity, such as Shenzhen, Chengdu, Xiamen and Guangzhou. Through reforming the industrial structure, Chinese cities may not reduce CO_2 emissions at the expense of economic development, and achieve both environmental and social objectives.

The study still contains some limitations. For example, we scale down the provincial energy balance table by using a city-province percentage. By using the different city-province percentages, the deduced table for the city may not be balanced. However, this is restrained by the data at city level. The method developed in this study is based on the most comprehensive data we can ever find. Further research will be conducted to improve the accuracy of city's emission data.

The Supplement related to this article is available online at.

Author Contribution

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Y. Shan and D. Guan designed the research. Y. Shan, Jianghua Liu, and Z. Liu handled the data. Jingru Liu, H. Schroeder, Y. Chen, S. Shao, Z. Mi, and Q. Zhang contributed to the data analysis. Y. Shan prepared the manuscript with contributions from all co-authors.

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Published: 1 March 2016

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Table 1. Scope definition for city energy statistics

Spatial boundaries	Components
In-boundary energy consumption / fossil fuel combustion	Primary-industry use (farming, forestry, animal husbandry, fishery and water conservancy) Industrial use (40 sectors) Construction use Tertiary-industry use (2 sectors) Residential use (Urban and Rural) Other

Note: Due to the city administrative boundary spanning both urban and rural geographies in China, we divide the residential energy use into 2 categories: urban and rural.

Table 2. Basic Energy Balance Table

No. (s)	Item
1	Total Primary Energy Supply
2	Indigenous Production
3	Recovery of Energy
4	Import
5	Domestic Airplanes & Ships Refuelling Abroad
6	Export
7	Domestic Airplanes & Ships Refuelling in China
8	Stock Change
9	Input & Output of Transformation
10	Thermal Power
11	Heating Supply
12	Coal Washing
13	Coking
14	Petroleum Refineries
15	Gas Work
16	Natural Gas Liquefaction
17	Briquettes
18	Loss
19	Total Final Consumption
20	Farming, Forestry, Animal Husbandry, Fishery Conservancy
21	Industry
22	Non-Energy Use
23	Construction
24	Transport, Storage and Post
25	Wholesale, Retail Trade and Hotel, Restaurants
26	Other
27	Residential Consumption
28	Urban
29	Rural
30	Statistical Difference
31	Total Energy Consumption

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-176, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 1 March 2016

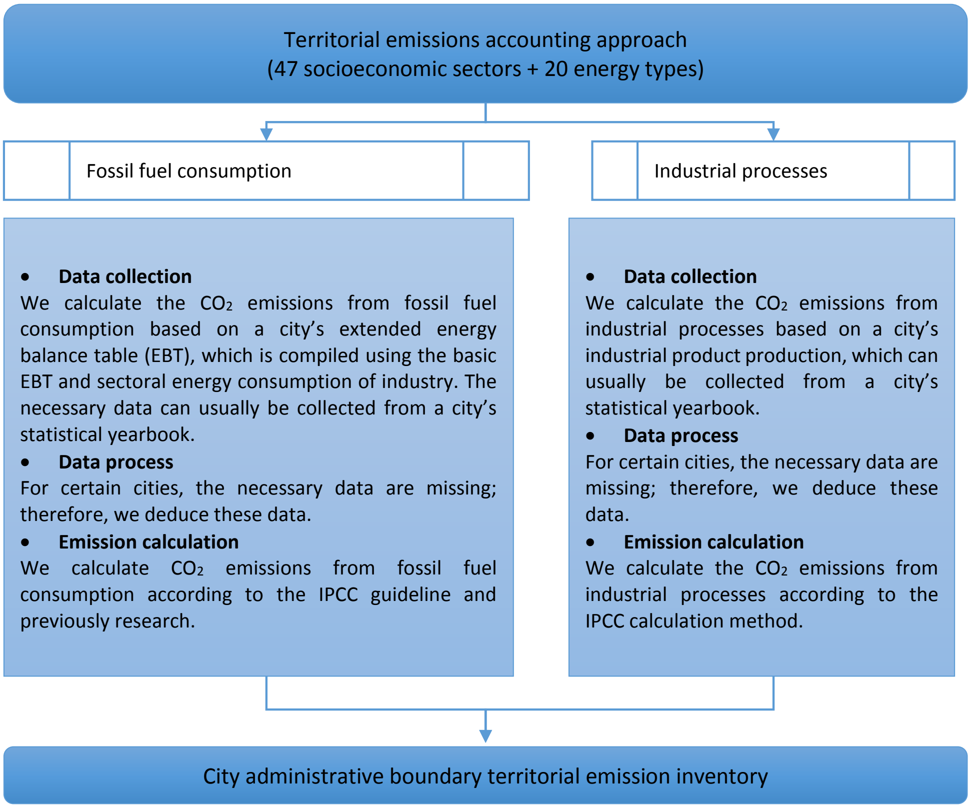

Figure 1. CO_2 emissions inventory construction framework for Chinese cities

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-176, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 1 March 2016

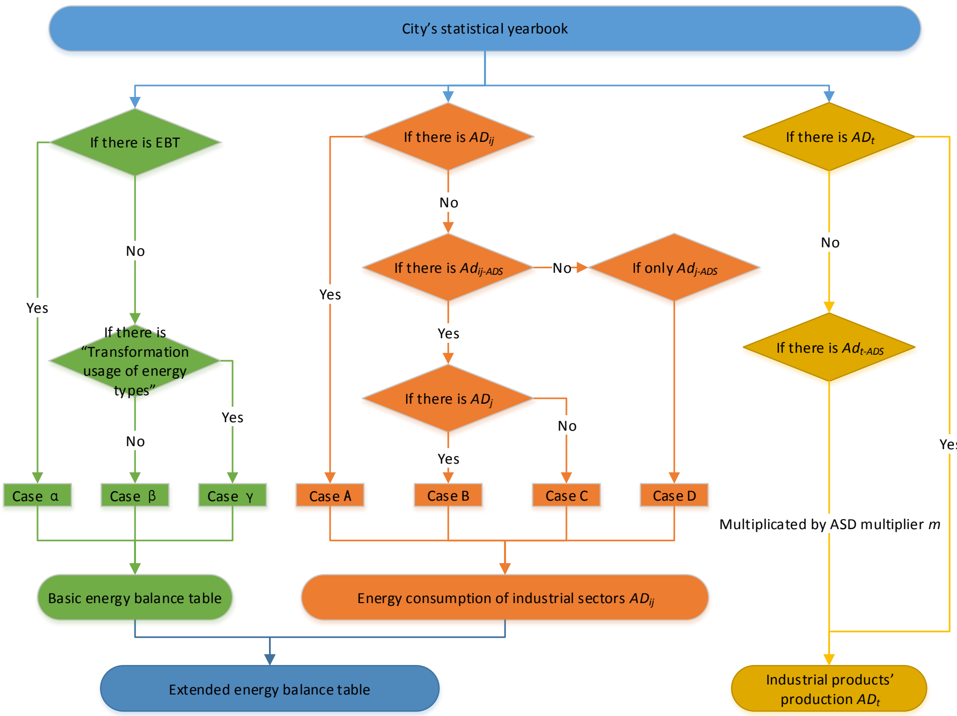

Figure 2. Data availability and estimation strategies at city level

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-176, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 1 March 2016

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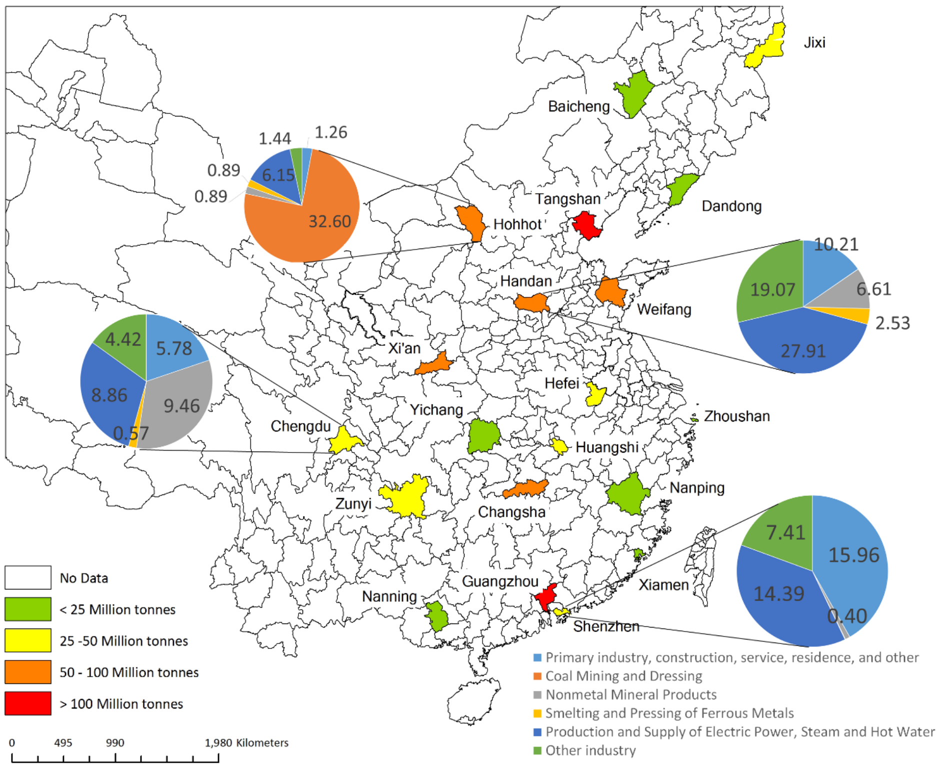

Figure 3. CO_2 emissions of the 20 case cities, 2010, tonnes

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-176, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 1 March 2016

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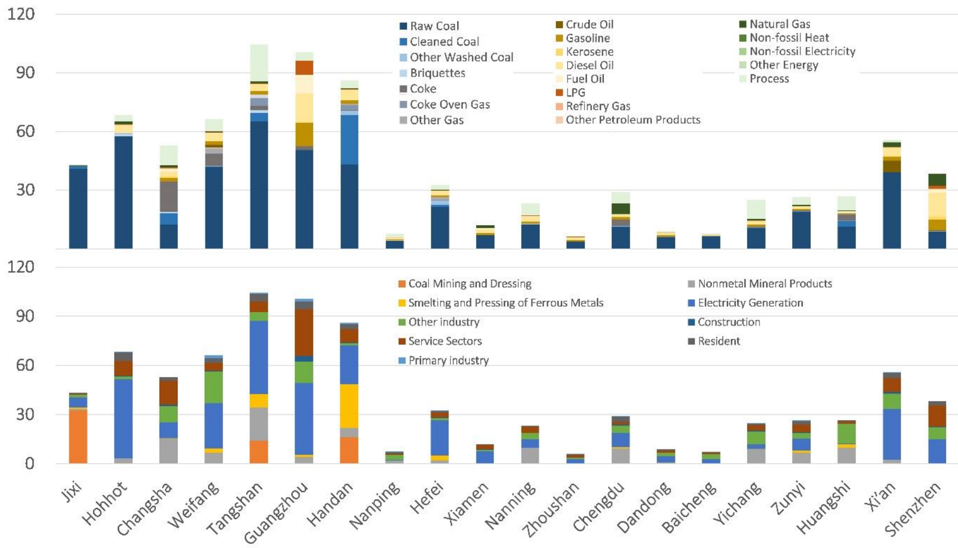

Figure 4. CO_2 emissions from 20 energy types and 9 sectors (million tonnes, 2010)