An emissions-socioeconomic inventory of Chinese cities

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Abstract

As the centre of human activity and being under the threat of climate change, cities are considered to be major components in the implementation of climate change mitigation and CO_2 emission reduction strategies. Inventories of cities' emissions serve as the foundation for the analysis of emissions characteristics and policymaking. China is the world's top energy consumer and CO_2 emitter, and it is facing great potential harm from climate change. Consequently, China is taking increasing responsibility in the fight against global climate change. Many energy/emissions control policies have been implemented in China, most of which are designed at the national level. However, cities are at different stages of industrialization and have distinct development pathways; they need specific control policies designed based on their current emissions characteristics. This study is the first to construct emissions inventories for 182 Chinese cities. The inventories are constructed using 17 fossil fuels and 47 socioeconomic sectors. These city-level emissions inventories have a scope and format consistent with China's national/provincial inventories. Some socioeconomic data of the cities, such as GDP, population, industrial structures, are included in the datasets as well. The dataset provides transparent, accurate, complete, comparable, and verifiable data support for further city-level emissions studies and low-carbon/sustainable development policy design. The dataset also offers insights for other countries by providing an emissions accounting method with limited data.

Background & Summary

Cities are considered to be major components in the implementation of climate change mitigation and CO_2 emission reduction strategies [1]. Although a mention of "city" is lacking in the Paris Agreement or the Sustainable Development Goals, as all submissions focused on the national level, climate change actions should be taken at the city level [2].

Cities are the basic units for human activity[3] and the main consumers of energy and emitters of CO_2 throughout the world [4,5]. The 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% [6]. In China, urban energy use accounts for 85% of total emissions, which is higher than its share in the USA (80%) or Europe (69%) [7,8]. The high energy demand and high CO_2 emissions of cities not only increase climate change concerns and environmental pressure but also increase residents' health problems through air pollution [9]. Both coastal and interior cities are facing danger from extreme weather, geological hazards, urban waterlogging, etc. Thus, cities are motivated to fight against climate change.

Although climate policies are usually designed at the national level, they are implemented at the city level. Without support from local city governments, national policies cannot be effectively executed. Considering that cities have different natural resource endowments and development pathways, each should have specific emission reduction actions that are designed based on that city's unique emission characteristics. In China, this is particularly true. There are over 330 cities in China, and they are at different stages of industrialization, with distinct development pathways. Therefore, cities are the key components in climate change policymaking, and many low-carbon projects and actions have been taken at the city level, such as the Local Governments for Sustainability (ICLEI) and the C40 Cities Climate Leadership Group (C40).

Understanding the emissions characteristics of cities is the foundation of any further city-level climate change actions. Compared to studies focused on national and provincial emissions accounts, far fewer have focused on city-level emissions, and those that do have methods limitations and geographical restrictions.

First, previous studies on city-level emissions have severe methodological weaknesses and limitations. Most previous city-level greenhouse gas emissions inventories were calculated using a bottom-up approach, i.e., by using energy consumption data from surveys of several sectors [10-12]. The sectors were set differently between studies, making the cities' CO_2 emissions inconsistent and not comparable across studies, as well as inconsistent with the national and regional emission inventories. In addition, some studies used spatial and geographical analysis [13,14], night-time light imagery [15,16], or economic models [17,18] to account for city emissions. These models can only estimate the overall CO_2 emissions of a city. They cannot exactly determine the contributions of emission sources (i.e., energy types or socioeconomic sectors).

Second, most of the previous studies on city-level emissions focused on megacities from developed countries with consistent and transparent data sources, especially US cities [19-23]. Currently, city-level emissions are being studied from a more international perspective by analysing more global cities, especially cities from developing countries [24-30]. Restricted by data availability, the CO_2 emissions from Chinese cities are far behind in their documentation. Sugar, et al. [31] reported emissions for Beijing, Tianjin, and Shanghai in 2006 and compared the three cities' emissions with those of ten other global cities. Wang, et al. [10] discussed the CO_2 emissions from 12 Chinese megacities, most of which are provincial capital cities. Dhakal [8] examined the energy consumption and CO_2 emissions of all Chinese provincial cities. Zhou, et al. [32] and Xu, et al. [33] account for the CO_2 emissions of specific city clusters, such as the Guangdong Bay cities and cities in the central plain. Ramaswami, et al. [34] in the cited study and a follow-up study developed a comprehensive emission database including the scope 1 and scope 2 CO_2 emissions of 233 prefecture-level and 637 county-level cities in China [35].

Thus, the previous assessments of city-level emissions either focused on total emissions (or combined emissions for several sectors) or on megacities with consistent and systematic energy statistics. Previous analyses of the bottom-up sector-based emissions of cities are inconsistent with national and regional emission inventories, making multi-scale emission studies unavailable. Additionally, such general emission data cannot support detailed city-level emission analysis and related emission reduction policy making.

The dataset in this study provides detailed emissions inventories for 182 Chinese cities. The inventories are constructed for 17 types of fossil fuel and 47 socioeconomic sectors that are consistent with the System of National Accounts. Additional socioeconomic indexes for the cities are included in the dataset. The dataset has been re-used in our latest study [1] and will facilitate further city-level emissions studies and low-carbon/sustainable development policy design.

Methods

City boundaries and emission scopes

This dataset provides the emissions and socioeconomic inventories of 182 Chinese cities; these cities cover 82% (33,880 billion yuan) of the country's GDP (41,303 billion yuan), 64% (860 million) of the population (1,341 million), and 35% (3.4 million km^2) of the land area (9.6 million km^2) in 2010 [36]. Most of the studied cities are located east of the Heihe-Tengchong line, where 96% of China's population lives on 43% of the land. The 182 cities are selected based on data availability.

The term 'city' here refers to administrative prefecture-level city rather than to a built-up city. Accordingly, the CO_2 emissions calculated in this dataset are Intergovernmental Panel on Climate Change (IPCC) administrative territorial CO_2 emissions, referring to emissions "taking place within national (including administered) territories and offshore areas over which the country has jurisdiction (page overview.5)" [37]. We exclude the emissions induced by international aviation and shipping [38]. Unlike production- or consumption-based emissions [17], the administrative territorial scope quantifies the direct emissions induced by human activities within a regional boundary. That is, territorial emissions provide the data baseline for emission-related studies and regional carbon control.

The emission inventories include two components: CO_2 emitted from fossil fuel combustion (energy-related emissions) and CO_2 emitted from industrial production (process-related emissions). Process-related emissions refers to CO_2 emitted from industrial raw materials during chemical reactions, such as CO_2 escaping during calcium carbonate ($CaCO_3$) calcination in cement production.

The cities' emissions inventories are uniform with China's national and provincial emission inventories in scope, format, and data sources [39], making them comparable.

Emissions calculation and inventory construction

The energy-related emissions are calculated based on 17 fuels (shown in Table 1) and 47 socioeconomic sectors (shown in Table 2). The 17 types of fossil fuels are selected based on China's official energy statistical system [36]. There are 29 energy types used in the system: 26 are fossil fuels, one is electricity, one is heat, and one is other energy. As our study only accounts for the direct emissions from fossil fuel burning within one city boundary (the IPCC administrative territorial scope), the inventories exclude the indirect emissions induced by electricity and heat use. The CO_2 emissions related to electricity and heat generation, therefore, are calculated based on fuel inputs and allocated to the power plants. We also assume that there is no, or little, CO_2 emitted from other energy uses. Some of the fossil fuels share similar carbon content and have very low consumption volumes; we merge them in the emission accounts [39]. The 47 socioeconomic sectors are set according to the System of National Accounts [40].

Energy-related CO_2 emissions are calculated based on the mass balance theory [41]; see Equation 1.

$$CE_{ij} = AD_{ij} \times NCV_i \times CC_i \times O_{ij} \qquad \textit{Equation 1}$$

where CE_{ij} represents the CO_2 emissions induced by the combustion of fuel i in sector j, AD_{ij} (activity data) represents fossil fuel combustion by fuel and sector. The emission factor ($ton\ CO_2/ton$) is composed of a specific heat value factor- NCV_i (J/ton) multiplied by the carbon content per unit heat value- CC_i ($ton\ CO_2/J$) and oxygenation efficiency- O_{ij} (quantified as percentage). Specifically, NCV_i refers to the heat value produced per physical unit of fossil fuel i combusted, CC_i is the carbon content emitted per unit heat value when combusting per physical unit of fossil fuel i, while O_{ij} stands for the oxidation ratio of the fossil fuel combusted.

The emission factors (NCV_i, CC_i, and O_{ij}) have been published by international institutions, including the IPCC and the United Nations (UN; governmental agencies in China such as the National Bureau of Statistics of China (NBS) and the National Development and Reform Commission of China (NDRC) [42]; and previous studies such as the Multi-resolution Emission Inventory for China (MEIC) [43], Liu, et al. [44]. Liu, et al. [44] re-evaluated the carbon content of raw coal samples from 4,243 state-owned Chinese coal mines and found that the emission factors for Chinese coal are, on average, 40% lower than the default values recommended by the IPCC. After comparing Liu, et al. [44] emissions factors with eight different sources, our previous study finds that Liu, et al. [44] emission factors are relatively lower than others (shown in Table 3). The seven sets of emission factors are collected from IPCC, NBS, NDRC, NC1994, NC2005, MEIC, UN-China, and UN-average. Generally, coal-related fuels have a larger range than oil- and gas-related fuels. Liu, et al. [44]'s re-evaluated emission factors have already been widely used by many studies and institutions to calculate China's emission inventory, including China's third official emission inventory 2012 [45]. Thus, this study uses the above-mentioned updated emission factors. Table 1 gives the net caloric value (NCV_i) and carbon content (CC_i). Table 4 shows the sector-specific oxygenation efficiency (O_{ij}), which considers sector discrepancies in technical level [39].

The process-related CO_2 emissions (CE_t) are calculated in Equation 2 [41]. We include seven industrial processes, including cement production (for approximately 70% of the total process-related emissions in China [45,46]), lime production (the 2nd largest emissions source [47]), ammonia production, soda ash production, ferrochromium production, silicon metal production, and unclassified ferro-production. The process-related emissions are allocated to the corresponding sectors in the emission inventory. Cement and lime-related emissions are allocated to the sector "Non-metal Mineral Products"; ammonia and soda ash-related emissions are allocated to the sector "Raw Chemical Materials and Chemical Products";

Ferrochromium, silicon metal, and unclassified ferro-related emissions are allocated to the sector “Smelting and Pressing of Ferrous Metals”.

$$CE_t = AD_t \times EF_t \quad \textit{Equation 2}$$

AD_t and EF_t in the equation refer to industrial production (activity data) and emission factors, respectively. The emission factors of industrial processes are collected from IPCC [41] and NDRC [42], as shown in Table 5.

The cities' CO_2 emissions matrices (namely, inventories) are created as 19 columns and 48 rows. Seventeen fossil fuel-related emissions, process-related emissions and total emissions are represented by 19 columns, while 47 rows correspond to the 47 socioeconomic sectors. Each element of the matrices is identified as the CO_2 emissions from fossil fuel combustion/industrial production in the corresponding sector. An inventory of Beijing is given in Table 6 as an example.

These methods on emission inventory construction are expanded version of descriptions in our related work [39]. MATLAB R2014a is used to construct the cities' emission inventories. We provided the MATLAD code in the Supplementary Information. We also provided the activity data of the cities for additional data transparency and verifiability (see "China city-level Energy inventory, 2010", Data Citation 1). Researchers will be able to use the MATLAB code and energy inventories to recalculate the emission inventories for the cities or replicate to other cities.

Activity data collection

Fossil fuel combustion, i.e., the activity data for energy-related emission accounts, includes two parts: the energy inputs for electricity/heat generation and the total final consumption. Other inputs for energy transformation, such as coal cleaning or petroleum refineries, transfer the carbon element from one fuel to another. These processes emit little CO_2. Following our previous emissions inventories constructed for China and its provinces [39], fossil fuel combustion can be collected from a region's energy balance table (EBT) and final energy consumption can be captured by the industrial sector ($Energy_{ij}$). The EBT provides each fossil fuel's transformation and final consumption in farming, industry, construction, three service sectors, and households (rural and urban). As the entire industry sector consists of 40 sub-sectors, $Energy_{ij}$ presents the sectoral consumption of fossil fuel for the industry sector.

Generally, the EBT and $Energy_{ij}$ can be found in a city's statistical yearbook. However, due to the poor data quality of city-level statistics, not all cities' yearbooks publish the EBT or $Energy_{ij}$. We developed a series of methods in our previous study to estimate missing data [48]:

1) EBT: Very few cities have EBT in their statistical yearbooks. We scale down the corresponding provincial EBT to obtain the city table. We use each sector's GDP to estimate farming, construction, and three service sectors, assuming that the city has the same farming/construction/service energy intensity as its province. We also use the urban/rural population to estimate the urban/rural household energy estimation on the premise that the city has the same per capita residential energy consumption

as its province. The GDP and population data are collected from statistical yearbooks for the cities and their corresponding provinces.

2) $Energy_{ij}$: Some cities only provide $Energy_{ij}$ from enterprises of above-designated-size (ADS). ADS enterprises are defined as enterprises with prime operating revenue over 20 or 5 million yuan for different cities. ADS enterprises account for 50% to 90% (roughly) of one city's total industrial output. We use the ADS industrial output ratio (calculated as the whole-industry output divided by the ADS enterprises' output) to scale up ADS $Energy_{ij}$ and obtain sectoral fossil fuel consumption at the whole-industry scale.

As for cement production, the cities' statistical yearbooks provide total cement production or production from ADS enterprises. We then scaled up the ADS cement production by the ADS industrial output ratio to obtain the total cement production.

The raw activity data are collected through a "crowd-sourcing" working mode implemented in the Applied Energy Summer School 2017 and 2018. Over 100 students joined the summer school and participated in data collection. The summer school will be held annually in the future, and more researchers will contribute to and update city-level data collection.

These methods on city-level data estimation and collection are expanded version of descriptions in our related work [48].

Socioeconomic indexes

This study collects several socioeconomic indexes for the 182 cities from the "China City Statistical Yearbook" [49], including:

1) population, in 10 thousand;
2) employed population, in 10 thousand;
3) employed population in sectors (primary industry; mining; manufacturing, electric power, gas and water production and supply; construction; transport, storage and post; information transmission, computer services and software industry; wholesale and retail trade; hotel and catering services; financial intermediation; real estate; leasing and business services; scientific research, technical services and geological exploration; water, environmental and public facilities management; resident services and other services; education; health, social security and social welfare; culture, sports and entertainment; public administration and social organization), in 10 thousand;
4) area, in square kilometres;
5) built up area, in square kilometres;
6) gross domestic product (GDP), in 10 thousand yuan;
7) primary industry, secondary industry, and tertiary industry's share in GDP, in %;
8) industrial output, in 10 thousand yuan.

The socioeconomic indexes (as shown in Table 7 and "China city-level socioeconomic inventory, 2010", Data Citation 1) can be used to explore the drivers and characteristics of cities' emissions.

Data Records

A total of 365 data records (emissions-socioeconomic inventories) are contained in the datasets. Of these,

- 182 are emissions inventories for cities (2010) ["China city-level emissions inventory, 2010", Data Citation 1];
- 182 are energy inventories for cities (2010) ["China city-level energy inventory, 2010", Data Citation 1];
- 1 is a socioeconomic inventory for cities (2010) ["China city-level socioeconomic inventory, 2010", Data Citation 1];

The cities' CO_2 emissions inventories are constructed at an IPCC territorial administrative scope, including both energy-related emissions (from fossil fuel combustion) and process-related emissions (from cement production). The socioeconomic inventory presents GDP, population, employed population (with structure), GDP (with structure), and area of the 182 cities.

Technical Validation

Uncertainties

CO_2 emissions inventories gather the contributions of economic activity to total CO_2 emissions for a given time period and area. Inventories are critical to many environmental decision-making processes and scientific goals. Policymaking and scientific research require reliable inventories to ensure the effectiveness of the policy process. In both types of applications, it is important to understand the uncertainty in emissions inventories. Additionally, uncertainty analysis can improve the accuracy of emissions accounts. Regarding the city-level CO_2 emissions inventories in this article, the literature shows that uncertainty regarding the process-related emissions in cement production is low. The inventories' uncertainty mainly depends on energy-related emissions part [44,50]. The contributing sources of uncertainty for energy-related emissions accounting are associated with emission factors, activity data and other estimation parameters *(Volume 1, Chapter 3, Page 6)*" [41]. The uncertainty induced by emissions factors and energy activity data are both quantified for the cities' emission inventories.

1) Uncertainties in activity data and emission factors

China's energy data are of relatively poor quality compared with those of developed countries, especially city-level data. The literature also shows that the uncertainties range widely from sector to sector. The coefficient of variation (CV; the standard deviation divided by the mean) is used to quantify the uncertainty. According to a field survey led by previous studies, the fossil fuel consumed in China's power generation sector has the lowest CV (5%) [51,52], compared with primary industry (30%) [53], other manufacturing sectors (10%), construction (10%) [41,54], transportation sector (16%) [55], and residential energy use (20%) [41]. The sources of uncertainties could lie in the opaqueness in China's statistical systems, especially on the "*statistical approach on data collection, reporting and validation (Page 673)*" [56] and the dependence of China's statistics departments on other government departments. Such uncertainties result in a large gap between China's national fossil fuel consumption data and the aggregated provincial data. To cover the gap, China has adjusted its energy data three times since 2004, resulting in a gap between the latest national fossil fuel consumption data and provincial aggregated data of 5% [57]. The gap between city-level aggregated energy consumption and the national overall data could be even larger.

Previous studies have debated China's emission factors [58-61]. The range of emission factors across different sources is as high as 40%. This study collects emission factors from Liu, et al. [44], which measured them based on a broad investigation of China's fuel quality. Based on the statistical analysis of surveyed fuel quality, the CVs of coal-, oil-, and gas-related fuels are estimated as 3%, 1%, and 2%, respectively.

2) Monte Carlo simulations

Monte Carlo methods are used to simulate the uncertainties resulting from both fossil fuel combustion and emissions factors to estimate the overall uncertainty of the emissions [41]. Monte Carlo simulations select random values for the emission factor and activity data (fossil fuel consumption) from within their individual normal probability (density) functions and calculate the corresponding emission values (chapter 6 IPCC [41]). To perform Monte Carlo simulations, we first set up probability density functions for each input variable (emission factor and activity data). Both variables are assumed to follow a normal distribution [44]. Then, we randomly sample both the activity data and the emission factors 20,000 times and obtain 20,000 CO_2 emission estimations. The uncertainties are obtained at a 97.5% confidence level and are calculated as the 97.5% confidence intervals of the estimates.

This article finds that the average uncertainties in the cities' total CO_2 emissions range from -3.65% to 3.67% at a 97.5% confidence level (±47.5% confidence interval around the estimate). Hegang in Heilongjiang has the highest uncertainties in emissions of (-5.83%, 5.86%), while Huizhou in Guangxi has the lowest value of (-0.91%, 0.91%).

Limitations and future work

The cities' emission inventories have some limitations that could lead to more uncertainty. Although these uncertainties may not be large enough to quantify, they are an indispensable component of the emission inventories' uncertainties. First, this study only takes the energy-related and process-related emissions from seven industrial production processes into account in the emission accounts, and emissions emitted by other sources is missing, such as "agriculture", "land-use change and forestry", "waste", and other industrial processes. Thus, the analysis incomplete. In the future, we will expand the emission scope to achieve more complete inventories for cities. Second, the cities' emission factors for fossil fuels and industrial processes are substituted by national average emission factors during the process of accounting for cities' CO_2 emissions, resulting in inaccuracy. We hope that specific city-level emissions factors could be updated in the future to increase the accuracy of our results. If not, in our future research, we could employ provincial emission factors to obtain a more accurate emission inventory for the provinces. Third, due to the poor data quality for the cities, the EBTs of most cities are a downscaled version of the provincial table, assuming that the cities have the same sectoral energy intensity and per capita residential energy consumption with their provinces. Such assumptions bring additional uncertainties to cities' emission inventories. In the future, a consistent time-series emission inventory dataset for Chinese cities will be completed. We will integrate the bottom-up estimations (calculated based on survey data from enterprises) [14] and satellite observations to achieve more emission accounts for these cities. More specifically, the high-resolution bottom-up emissions and satellite images can confirm some of the cities' emission sources (i.e. some super-emitting points). The night-light data will also be used to verify our top-down emissions inventories [16,62].

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Author Contributions

Y.S. led the project, calculated and assembled the data, and prepared the manuscript. D.G. designed the research. J.L. collected the raw data and participated in the database construction. Z.L. and S.S. revised the manuscript.

Competing Interests

The authors declare no competing financial interests.

Table Captions

Table 1 Fossil fuels in the city-level emissions inventories and emissions factors
Table 2 Sectors' definition of the emission inventories
Table 3 Fuel's emission factors from other sources
Table 4 Oxygenation efficiency of fossil fuels combusted in sectors
Table 5 7 industrial processes and emissions factors
Table 6 Emissions inventory of Beijing in 2010
Table 7 Emissions-socioeconomic indexes of the cities

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Data Citations

1. Shan, Y., Liu, J., Liu, Z., & Guan, D. *Figshare* https://doi.org/10.6084/m9.figshare.c.4237544.v1 (2018).