Atmos. Chem. Phys. Discuss., 12, 7985–8007, 2012
www.atmos-chem-phys-discuss.net/12/7985/2012/
doi:10.5194/acpd-12-7985-2012

Atmospheric Chemistry and Physics Discussions

The carbon emissions of Chinese cities

H. Wang[1,2], J. Bi[1,2], R. Zhang[1], and M. Liu[1]

[1]State Key Laboratory of Pollution Control and Resource Reuse, School of the Environment, Nanjing University, Nanjing 210046, China
[2]Institute for Climate and Global Change Research, Nanjing University, Nanjing 210046, China

Received: 2 February 2012 – Accepted: 7 March 2012 – Published: 21 March 2012

Correspondence to: H. Wang (wanghk@nju.edu.cn)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

As increasing urbanization has become a national policy priority for economic growth in China, cities have become important players in efforts to reduce carbon emissions. However, their efforts have been hampered by the lack of specific and comparable carbon emission inventories. Comprehensive carbon emission inventories, which present both a relatively current snapshot and also show how emissions have changed over the past several years, of twelve Chinese cities were developed using bottom-up approach. Carbon emissions in most of Chinese cities rose along with economic growth from 2004 to 2008. Yet per capita carbon emissions varied between the highest and lowest emitting cities by a factor of nearly 7. Average per capita carbon emissions varied across sectors, including industrial energy consumption (64.3 %), industrial processes (10.2 %), transportation (10.6 %), household energy consumption (8.0 %), commercial energy consumption (4.3 %) and waste processing (2.5 %). The levels of per capita carbon emissions in China's cities were higher than we anticipated before comparing them with the average of global cities. This is mainly due to the major contribution of industry sector encompassing industrial energy consumption and industrial processes to the total carbon emissions of Chinese cities.

1 Introduction

As global climate changes become more apparent, efforts to control and reduce greenhouse gas (GHG) emissions have become a focus of attention worldwide in recent years. But the outcome of COP 15 in Copenhagen in December 2009 has made it clear that differences in the circumstances and interests of various countries will make it difficult to agree on common GHG reduction targets and strategies at the international level.

Nonetheless, bottom-up approaches to this problem are emerging in many countries (Gurney et al., 2009), and cities are taking on important roles in global efforts

ACPD

12, 7985–8007, 2012

to address climate change (Hillman and Ramaswami, 2010; Koehn, 2008). As cities contribute over 67 % of the global GHG emissions from fossil fuel use (Satterthwaite, 2008), developing benchmarks and more comprehensive carbon emission inventories at the spatial scale of a city becomes necessary in the context of global efforts to mitigate climate change (Gertz, 2009; Ramaswami et al., 2008). Creating carbon emissions inventories and improving our understanding of how and why cities differ in terms of emissions are essential to success in this realm (Kennedy et al., 2008). To make progress, however, a common and comparable carbon accounting system is needed.

Previous efforts have employed some accounting systems, such as the one developed by the International Council for Local Environmental Initiatives (ICLEI, 2008). But most studies have calculated GHG emissions for a specific city or a particular year, and they have not compared the components of GHG inventories using a consistent methodology. Life-cycle and demand-centered methodologies, which are thought to be able to assign emissions to political jurisdictions more accurately (Ramaswami et al., 2008; Larsen and Hertwich, 2009; Schulz, 2010), however, the lack of data on comprehensive consumptions at the city-scale and especially for cities in developing countries (Hillman and Ramaswami, 2010) constitutes a severe problem for studies of this kind. Moreover, different understandings of the definition and boundary of life-cycle (Matthews et al., 2008) make GHG emission data for cities difficult to be compared, and the risks of double-counting in a spatial and temporal sense also exist. Therefore, a comprehensive carbon accounting approach, which is comparable to ICLEI's, was proposed according to the data availability of Chinese cities in our previous study (Bi et al., 2011).

China has announced the 2020 target to reduce emission intensity by 40–45 % over 2005 levels. However, urbanization has been considered a national policy priority in efforts to spur economic and industrial growth in China, and the government aims to increase the urbanization rate from 40 % in 2005 to 60 % by 2030 (UN, 2007). As rising incomes make urban dwellers' lifestyles more energy intensive, and as the new urban migrants demand greater per capita energy than their rural counterparts (Dhakal, 2009), great pressures will be placed on controlling energy consumption and GHG emissions. Although there are several studies of GHG emissions for the cities in China, they are usually based on calculations of aggregated city energy consumption using top-down approaches (Dhakal, 2009; Li et al., 2010; Lin et al., 2010). They could give us basic proxies of the total GHG emissions; however, they are usually not able to present enough information for the local governments to define operable measures to reduce carbon emissions compared with bottom-up results. Furthermore, this also makes it difficult for the researchers to analyze the differences of carbon emissions at the city-scale between Chinese and other global cities. Bottom-up carbon emissions inventories of Chinese cities based on comparable accounting approaches are urgently needed.

The paper aims to analyze the GHG emission characteristics of Chinese mega cities. At first, we develop comprehensive and comparable carbon emissions inventories of twelve Chinese cities based on bottom-up approaches. Then, the driving factors of GHG emissions in those cities are analyzed. At last, the GHG emissions inventories between the cities in China and other countries will also be compared to discuss their differences. This is the first systematical accounting of GHG emissions at the city-scale based on a bottom-up methodology in China where the emissions are compared with global cities. The results can also serve as benchmarks in discussions of the effectiveness of strategies designed to reduce carbon emissions.

2 Methodology

2.1 Chinese cities

In order to represent various sizes and development characteristics, twelve Chinese cities- Beijing, Shanghai, Tianjin, Chongqing, Guangzhou, Hangzhou, Nanjing, Zhengzhou, Shenyang, Wuhan, Wuxi and Lanzhou- were analyzed in this study. These cities are situated in different geographical regions of China, which are indicated in

ACPD
12, 7985–8007, 2012

Fig. 1. Basic information about these cities and ten global cities comparing in this study are illustrated in Table S1.

In China, major environmental policies are usually made at the national government level, and then implemented by local governments, such as provinces and cities. The cities are not the same as urban areas; they are actually political administrative units which usually include urban, town and rural populations.

2.2 Components of a carbon emissions inventory

In this study, carbon emissions, expressed in carbon dioxide equivalents (CO_{2e}), are determined for six sectors of a city's GHG inventories, which are respectively industrial energy consumption, transportation, household energy consumption, commercial energy consumption, industrial processes and waste. The first 4 include emissions related to energy consumption, while the last two involve process and waste related emissions. Due to the high uncertainties and typically small contributions of agriculture, forest and other land use (AFOLU) to the total carbon emissions of cities (Kennedy et al., 2010), these emissions have not been included in this study. The specific methods used in calculating carbon emissions from each sector have already been discussed in our published paper (Bi et al., 2011); only the most salient details are given here. The carbon accounting scope of this study is illustrated in Table S2.

2.2.1 Energy consumption

This sector includes primary and secondary energy consumption relating to industrial, transportation, residential and commercial activities. In this study, GHG emissions from energy consumption are calculated by multiplying energy consumption of subsectors (like coal and oil for energy types) and corresponding emission factors, which could be summarized as Eq. (1). The methodologies for each specific sector are discussed in

ACPD
12, 7985–8007, 2012

our published paper (Bi et al., 2011).

$$\mathrm{GHG} = \sum_{i,j} [C_{i,j} \cdot \mathrm{EF}_j] \tag{1}$$

where, i represents subsectors in a typical sector (e.g. the transportation sector can be divided into passenger cars, heavy duty trucks, buses, etc); j represents energy types (e.g. coal, oil, electricity, etc); GHG is the sector's total CO_{2e} emissions, ton; $C_{i,j}$ is energy consumption per sub-sector (the units correspond to various energy type, such as tons for coal, m^3 for the natural gas, kWh for the electricity, etc); EF_j is the CO_{2e} emission factors for specific energy types.

2.2.2 Industrial processes

Carbon emissions from industrial processes mainly refer to those emitted from the chemical or physical transformation of materials during industrial production processes, such as cement manufacturing and limestone consumption. Emissions associated with combustion to produce energy for industrial use were excluded in this sector. The CO_{2e} emissions from this sector were calculated according to the outputs of various products. Because of constraints relating to the availability of information regarding industrial process at the city level, we focused on the carbon emissions from three major industrial processes (mineral, chemical, and metal productions).

2.2.3 Waste

We applied IPCC's (2006) First Order Decay approach to account for carbon emissions from landfill waste. This approach, however, requires ideally at least 20 or more years of landfill data and good estimates of decay coefficients. The data of industrial solid waste were obtained through the city statistical yearbooks, and municipal solid waste productions were estimated based on the populations of cities. Because there are few

ACPD
12, 7985–8007, 2012

studies with GHG emissions from landfills in Chinese cities, we applied the IPCC's recommended parameters for developing countries.

2.3 Overall carbon emissions

In this study, the ICLEI (2008) metrics were applied as much as possible to maximize the comparability of our results with the global cities. The comparisons of the carbon accounting scopes between ICLEI and this study are shown in Table S2. A city's overall carbon emissions include emissions from fossil fuel combustion and industrial processes occurring within the city boundaries, electricity use and waste disposal for the cities. Although some cities export their solid waste beyond their boundaries, the emissions from landfill methane are still included here.

In order to enable comparisons across cities and to assess the consistency of GHG emissions across spatial scales, we normalized the total GHG emissions for the 12 Chinese cities on a per capita basis and compared them with the emissions of other global cities. Per capita carbon emissions were also divided into non-industry and industry related emissions to reflect the impacts of living consumptions and industrial productions on the carbon emissions of Chinese cities.

2.4 Data sources

The data of industrial energy consumptions, industrial productions, vehicle populations, GDP and populations were collected from the statistical yearbook of each city. Detailed references were provided in our supporting information. Carbon emissions factors of each fossil fuel used in Eq. (1) were calculated using IPCC (2006) recommended method. Vehicle miles traveled (VMT) and fuel economies were acquired from our previous studies (Wang et al., 2010a, 2011) and The First Census of Pollution Source in China.

In China, many cities have power plants located within their geographical boundaries to generate and sell electricity to the national power grids. We included carbon emis-

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD

12, 7985–8007, 2012

The carbon emissions of Chinese cities

H. Wang et al.

sions from these plants in the industrial energy consumption sector. However, electricity consumption-related carbon emissions were also calculated for other sectors. Therefore, we accounted for the carbon emissions of electricity use from the consumption perspective to avoid double counting. It means that the emissions from power plants were excluded when we summed the emissions from various sectors to compute total carbon emissions for the cities.

It is very important to determine carbon emission intensities or emission factors of the electricity supply mix. There are six large national power grids in China, named for the regions they serve: Northeast China, North China, Central China, East China, Northwest China, and South China. These grids are not strictly independent, as one grid may buy power from another grid if needed. In this study, we applied the electricity generation fuel mixes for these six power grids from 2004 to 2008 (19) to calculate the carbon emission factors in different years and the power exchange between the grids have also been considered. Coal and hydro are the two major energy sources for power generation in China, and the split between them varies by region. Coal-based power dominates in the Northeast and North China generation mixes with a proportion reaching as high as 95–98 %. Although coal remains dominant, the Northwest, Central, and South mixes consist of 22 % or more of hydro power. The South and East China grids also include 5 % of nuclear power (Huo et al., 2010). The carbon emission factors from 2004 to 2008 for the cities included in this study are presented in Table S3.

3 Results and discussion

3.1 Profiles of carbon emissions

China consists of eight economic regions (Chen et al., 2009), including the North East (Heilongjiang, Liaoning and Jilin), the North Coast (Beijing, Tianjin, Hebei and Shangdong), the East Coast (Shanghai, Jiangsu and Zhejiang), the South Coast (Guangdong, Hainan and Fujian), the Middle Yangtze River (Anhui, Hubei, Hunan and Jiangxi),

ACPD
12, 7985–8007, 2012

the Middle Yellow River (Henan, Shanxi, Inner Mongolia, Shaanxi), the South West (Sichuan, Guizhou, Yunnan, Chongqing and Guangxi) and the North West (Gansu, Ningxia, Qinghai, Tibet and Xinjiang). The 12 cities included in this study are distributed in these 8 economic regions as shown in Fig. 1.

Except for Beijing, the total carbon emissions for the other 11 cities show increasing growth tendencies during the five years from 2004 to 2008. However, the growth rate in 2008 is not as high as experienced previously, and carbon emissions even decreased for some cities. This is related to the global recession of 2008–2009. The economy of Wuxi (in East Coastal region), for example, is heavily dependent on exports, and thus its carbon emissions declined nearly 5 % in from 2007 to 2008. By contrast, the emissions of mid-west city like Chongqing, which has a low export oriented economy, increased nearly 9 % from 2007 to 2008. Although the total carbon emissions of most Chinese cities have increased during the past five years, the carbon emission intensity of each city discussed in this study has decreased (Table S4). And the average reduction percentage is 25.86 %, which cover a range from 3.13 % (Chongqing) to 63.64 % (Beijing) for different cities.

As China's capital city, Beijing's carbon emissions decreased in recent years, mainly due to the measures associated with the 2008 Olympic Games. To ensure good air quality for the Olympic, Beijing's municipal government adopted an "Air Quality Guarantee Plan for the 29th Olympic Games" (Wang et al., 2010b). Starting in 2000, many energy intensive or heavy polluting industrial facilities (e.g., oil refineries and steel plants) were relocated; numerous coal-fired boilers and domestic stoves were modified to use natural gas, and older vehicles were replaced with newer, cleaner vehicles. Beijing also implemented other temporary measures during the period of Games, such as odd-even number permit policies for private cars driven on Beijing's road (i.e. vehicles with a license plate ending in an odd number were allowed only on odd-number days while even numbers were allowed only on even-number days) (Zhou et al., 2010b) as well as production controls for some energy-intensive industries. For example, Capital Iron and Steel General Corporation and Beijing Yanshan Petro-Chemical Corporation were

ACPD
12, 7985–8007, 2012

required to reduce their operations by 30–50 %. Overall, Beijing's carbon emissions in 2008 were 19.32 % below emissions in 2004 with an annual decrease rate of 5.22 %.

3.2 Carbon emission inventories

Figure 2a covers carbon emissions from the six sectors for each of the twelve cities normalized on a per capita basis. Overall, carbon emissions cover a broad range – from 3.72 to 22.54 tons CO_{2e} per person – attributable to the differences in economy developments, living standards, energy structures and geographic locations as shown in Fig. 1 and Table S1.

Average contributions from individual sectors to the total per capita carbon emissions and the ranges observed for each sector are displayed in Fig. 2b. Carbon emissions from industry energy consumption represent the largest source, which contribute 64.34 % to total per capita CO_{2e} emissions, and also exhibit the greatest variation across cities. Building, which includes household and commercial sectors, is the second largest source with a contribution of 12.33 % of the total carbon emissions. The third largest contributor is the transportation at 10.58 %, followed by industry process sector at 10.23 %. Waste sector contribute only 2.51 % of the total per capita carbon emissions on average.

Because carbon emissions inventories reflect the use of bottom-up methodologies, the large variation in carbon emissions associated with industry energy consumption sector could be disaggregated into various subsectors. Figure 3 shows that the contributions of subsectors to total carbon emissions differ among cities according to their specific industrial structures. As shown in Fig. 3a, power and heat production and supply, ferrous metal smelting and rolling processing, and chemical products manufacturing are the three largest subsectors contributing over 60 % of the total carbon emissions for the industry energy consumption sector in Wuxi. By contrast, the three largest subsectors in Tianjin are ferrous metal smelting and rolling processing, chemicals and chemical products manufacturing, and petroleum, coking and nuclear fuel processing, respectively. These three subsectors contribute 56 ∼ 66 % of the total carbon emissions

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD

12, 7985–8007, 2012

from the industry energy consumption sector. Such data are useful for local governments to identify the key emission sources in their cities so as to take corresponding measures to reduce the carbon emissions. The top 10 subsectors of carbon emissions in the industry energy consumption sector for the 12 Chinese cities are presented in Table S5.

3.3 Preliminary analysis of influencing factors on carbon emissions

The total carbon emissions of Chinese cities were found to correspond closely to gross domestic products (GDP). The linear regression between these two parameters is statistically significant (t_{stat} = 7.11, sig. < 0.001) and has an R^2 of 0.47 (Table 1). Further regressions were conducted to analyze whether the population impacted city's carbon emissions. As shown in Table 1, population was also included in a regression and produced a better linear fit (R^2 = 0.53). In the improved model, city population was statistically significant (t_{stat} = 2.74, sig. = 0.008), however, still secondary to GDP (t_{stat} = 5.54, sig. < 0.001). Per unit area carbon emissions were also found to be strongly correlated with population densities in China's cities (t_{stat} = 15.38, sig. < 0.001; R^2 = 0.80). As the per capita carbon emissions of most Chinese cities have shown growth trends during the past five years (Table S6), these imply that China's carbon emissions will inevitably increase in the near future with more and more people crowding into big cities and rapid development of economy.

The carbon emission intensities (per GDP carbon emissions) of Chinese cities were found to decrease with the economy development (Table 1). The linear regression of log (per GDP carbon emission) and log (GDP) shows statistically significant (t_{stat} = −11.59, sig. < 0.001) with good fit (R^2 = 0.70). Combining with Table S4, it indicates that there have already been some efforts of Chinese cities to reduce their carbon emission intensities to achieve the central government's objective declared at COP 15 in Copenhagen of reducing carbon emissions per unit of GDP by 40–45 %. However, as we discussed above, these kinds of efforts were counteracted by the rapid economy development and urban population growth, and the total emissions have kept increas-

ACPD
12, 7985–8007, 2012

ing during the past five years. To achieve the absolute carbon emission reductions, China will have to adopt stronger measures to save energy and reduce emissions.

There is little correlation between per capita carbon emissions and per capita GDP (t_{stat} = 0.13, sig. = 0.89; R^2 = 0.001), which seems to conflict with the environmental Kuznets curve argument. While China is presently undergoing rapid economic growth, the development is extremely unbalanced with the energy structures and technology levels differing greatly in various regions. This may explain why per capita carbon emissions (or energy consumption) do not correspond with per capita GDP in China's cities.

Other factors, such as city's climate (e.g. geographical location influences heating/cooling energy consumption in cities), industrial structure, energy structure and energy prices, might also play a big role in accounting for total GHG emissions (Kennedy et al., 2009; Zhao et al., 2010a). To develop a better understanding on the factors determining the emission trends in China a quantitative decomposition analysis should be provided (Dhakal, 2009; Minx et al., 2011). As this paper is based on a project focus on developing carbon emissions inventories of all the major cities in China (nearly 100 cities), such kind of analysis will be further processed in our future studies.

3.4 Comparisons with other mega cities

To provide context, we compared carbon emission levels in Chinese cities with data on 10 global cities in Kennedy's analysis (2009), which has similar accounting structure with ours. As Table 2 illustrates, eight of the twelve Chinese cities' per capita carbon emissions are over 8.0 t-CO_{2e}, which are comparable or even higher than that of the other global cities'. Carbon emissions in six Chinese cities exceed the average value of global cities. Several factors account for this phenomenon:

(1) The definition of a city in China differs from that in the United States as we discussed earlier. The Chinese definition is broader, encompassing more than the area of global cities (Table S1). As a result, many rapidly developing and highly energy intensive industries are included within cities in China. As industrial sectors, including industry energy consumption and industry processes account for nearly 75 % of the

ACPD
12, 7985–8007, 2012

total carbon emissions in China's cities, it is easy to understand the higher per capita carbon emission in these cities. However, according to IEA (2007), average per capita carbon emissions from energy use in China and the United States are respectively 6 and 25 t-CO_{2e}. This means that cities' per capita carbon emissions are higher than the national average in China, while the reverse is true of United States.

(2) Calculations for seven of the ten global cities did not include emissions from industry processes in computing total carbon emissions. But industry process is the third largest sector in China, contributing 1.54–23.85 % of total carbon emissions in China's cities. Eight of the 12 Chinese cities would have lower per capita carbon emissions than the average level for the global cities if we omit the contribution of industry processes.

(3) The results of this study clearly show that carbon emissions in China's cities are higher than we anticipated. But it is important to note that the 12 cities included in our assessment are among the most developed cities in each province of China. As we discussed before, a city's carbon emissions are highly correlated with GDP. Inclusion of a wider selection of cities in China would reduce the level of average emissions. However, it also revealed the fact that the average per capita carbon emissions of China is small, but in the case of developed cities, such as some cities in this study, their carbon emissions could be well above other cities in the developed world.

As China is a major exporter, the per capita carbon emission is probably not the best way of comparing cities with each other for the industrial emissions are the major contributor and vary widely among various cities. In order to objectively evaluate the carbon emission levels, we divide the per capita carbon emissions into per capita industrial and per capita non-industry emissions. As illustrated in Table 2, the average per capita industrial emission is 7.99 t-CO_{2e} for Chinese cities, which is three times the global cities'. However, the average per capita non-industry emission is only 37 % of the global cities'. This illustrates that the carbon emissions of Chinese cities are mainly caused by the industry production and the carbon emissions from citizen's everyday life are far below the average of global countries'.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD
12, 7985–8007, 2012

The carbon emissions of Chinese cities

H. Wang et al.

China's vehicle population (not including motorcycles) has increased nearly 3 times during the past decade; however, the vehicle ownership is only 50 per 1000 persons, which is only 40 % of the world average and just 5 % of the level in the United States. For this reason, most cities in China have a much lower per capita carbon emissions resulting from ground transport compared with the global cities, except for several developed cities (e.g., Beijing and Guangzhou). This explains why ground transportation generates only 10 % of total carbon emissions in China's cities, well below the 17–40 % of emissions in global cities. This is also supported by the fact that the vehicles only consumed 6–7 % of the total energy in China, while in the developed countries vehicles consumed 20–30 % of total energy (He et al., 2005).

3.5 Uncertainty and implications

A carbon emissions inventory for a city has inherent uncertainties because it simplifies complex real-world processes. The uncertainties may be from many different aspects, some of which are common to all carbon emissions inventories such as the errors in emission factors caused by real-world emission variability. In this study, the main uncertainties in the carbon emission inventory for Chinese cities may come from the following areas: (1) there is the uncertainty associated with the estimations of carbon emission factors for various types of energies/products. For example, the IPCC default emission factors were applied to the industrial processes and solid waste sectors. (2) Some activity data, such as municipal solid waste generation, are rarely collected and reported in China's local statistics, and are difficult to obtain directly. This was calculated from the rate of waste generation at the national average level, which may be different from the actual situation in specific cities. (3) Another uncertainty of this study was associated with the integrity of carbon accounting. Restricted by data availability, this study only calculated the carbon emissions from key industrial processes, which included mining, chemical and metal production. This would underestimate the carbon emissions from industrial processes. Quantitative analyses of these types of uncertainties will be conducted in our future studies when more basic information on carbon emissions in Chinese cities is available.

As industry sectors are the major contributors to the total carbon emissions and economy for the cities in China, more work is needed to understand the city's current and future carbon emissions and significantly improve energy and material consumption efficiencies. With the rapid urbanization, developing benchmarks of GHG emissions caused by city activities will definitely have a large impact on climate action plans for China and worldwide. However, we have not attempted to include carbon emissions from cross-boundary activities like air travel or embodied energy consumption of products produced or consumed in cities (e.g. food, water, fuel). These are also major contributors to emissions in developed countries (Hillman and Ramaswami, 2010; Kennedy et al., 2009). But we note that China is a major producer of products and commodities consumed abroad. Adopting a life cycle or consumption perspective would significantly affect comparisons between China's cites and global cities with regard to carbon emissions. This topic will merit attention in future research.

Supplementary material related to this article is available online at: http://www.atmos-chem-phys-discuss.net/12/7985/2012/acpd-12-7985-2012-supplement.pdf.

Acknowledgements. This work was supported by China National Program on Key Basic Research Project (973 Program, Project No. 2010CB950704) and China National Nature Science Foundation (Project No. 51008155). The contents of this paper are solely the responsibility of the authors and do not necessarily represent official views of the sponsors.

References

Bi, J., Zhang, R., Wang, H., Liu, M., and Wu, Y.: The benchmarks of carbon emissions and policy implications for China's cities: case of Nanjing, Energ. Policy, 39, 4785–4794, 2011.

Chen, Y., Yang, Z., Fang, S., Hu, Z., Matin, M., and Sujit, B.: A patent based evaluation of technological innovation capability in eight economic regions in PR China, World Patent Information, 31, 104–110, 2009.
Dhakal, S.: Urban energy use and carbon emissions from China and policy implications, Energ. Policy, 37, 4208–4219, 2009.
Gertz, M.: New research aims to create accurate account of a city's carbon burden, Environ. Sci. Technol., 43, 8006–8007, 2009.
Gurney, K. R., Mendoza, D. L., Zhou, Y., Fischer, M. L., Miller, C. C., Geethakumar, S., and de la Rue du Can, S.: High resolution fossil fuel combustion CO_2 emission fluxes for the United States, Environ. Sci. Technol., 43, 5535–5541, 2009.
He, K., Huo, H., Zhang, Q., He, D., An, F., Wang, M., and Walsh, M.: Oil consumption and CO_2 emissions in China's road transport: current status, future trends, and policy implications, Energ. Policy, 33, 1499–1507, 2005.
Hillman, T. and Ramaswami, A.: Greenhouse gas emission footprints and energy use benchmarks for eight U. S. cities, Environ. Sci. Technol., 44, 1902–1910, 2010.
Huo, H., Zhang, Q., Wang, M., Streets, D., and He, K.: Environmental implication of electric vehicles in China, Environ. Sci. Technol., 44, 4856–4861, 2010.
ICLEI: Cities for Climate Protection, Toronto, Canada, International Council of Local Environmental Initiatives, http://www.iclei.org/index.php?id=800, last access: 22 December 2010, 2008.
IEA (International Energy Agency): CO_2 Emissions from Fuel Combustion 1971–2005 Organization for Economic Cooperation and Development, Paris, 2007.
IPCC (Intergovernmental Panel on Climate Change): 2006 IPCC Guidelines for National Greenhouse Gas Inventories; Prepared by the National Greenhouse Gas Inventories Programme, edited by: Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K., IGES, Japan, 2006.
Kennedy, C., Steinberger, J., Casson, B., Hansen, Y., Hillman, T., Havránek, M., Pataki, D., Phdungsilp, A., Ramaswami, A., and Mendez, G.: Greenhouse gas emissions from global cities, Environ. Sci. Technol., 43, 7297–7302, 2009.
Kennedy, C., Steinberger, J., Casson, B., Hansen, Y., Hillman, T., Havránek, M., Pataki, D., Phdungsilp, A., Ramaswami, A., and Mendez, G.: Methodology for inventorying greenhouse gas emissions from global cities, Energ. Policy, 38, 4828–4837, 2010.

ACPD
12, 7985–8007, 2012

Koehn, P. H.: Underneath Kyoto: emerging subnational government initiatives and incipient issue-bundling opportunities in China and the United States, Global Environ. Polit., 8, 53–57, 2008.
Larsen, H. and Hertwich, E.: The case for consumption-based accounting of greenhouse gas emissions to promote local climate action, Environ. Sci. Policy, 12, 791–798, 2009.
Li, L., Chen, C., Xie, S., Huang, C., Cheng, Z., Wang, H., Wang, Y., Huang, H., Lu, J., and Dhakal, S.: Energy demand and carbon emissions under different development scenarios for Shanghai, China, Energ. Policy, 38, 4797–4807, 2010.
Lin, J., Cao, B., Cui, S., Wang, W., and Bai, X.: Evaluating the effectiveness of urban energy conservation and GHG mitigation measures: the case of Xiamen city, China, Energ. Policy, 38, 5123–5132, 2010.
Matthews, H. S., Hendrickson, C. T., and Weber, C. L.: The importance of carbon footprint estimation boundaries, Environ. Sci. Technol., 42, 5839–5842, 2008.
Minx, J. C., Baiocchi, G., Peter, G. P., Weber, C. L., Guan, B., and Hubacek, K.: A "Carbonizing Dragon": China's fast growing CO_2 emissions revisited, Environ. Sci. Technol., 45, 9144–9153, 2011.
Ramaswami, A., Hillman, T., Janson, B., Reiner, M., and Thomas, G.: A demand-centered, hybrid life cycle methodology for city-scale greenhouse gas emissions, Environ. Sci. Technol., 42, 6455–6461, 2008.
Satterthwaite, D.: Cities' contribution to global warming: notes on the allocation of greenhouse gas emissions, Environ. Urban., 20, 539–549, 2008.
Schulz, N.: Delving into the carbon footprints of Singapore-comparing direct and indirect greenhouse gas emissions of a small and open economic system, Energ. Policy., 38, 4848–4855, 2010.
SSBC (State Statistical Bureau of China): Electricity Yearbook of China 2009, China Statistics Press, Beijing, China, 2009.
UN: World urbanization prospects: the 2007 revision, United Nations Population, Population Division of the Department of Economic and Social Affairs, http://esa.un.org, last access: 10 November 2010, 2007.
Wang H., Fu L., Zhou, Y., Du, X., and Ge, W.: Trends in vehicular emissions in China's mega cities from 1995 to 2005, Environ. Pollut., 158, 394–400, 2010a.
Wang, H., Fu, L., and Bi, J.: CO_2 and pollutant emissions from passenger car in China, Energ. Policy, 39, 3005–3011, 2011.

ACPD
12, 7985–8007, 2012

Wang, S., Zhao, M., Xing, J., Wu, Y., Zhou, Y., Lei, Y., He, K., Fu, L., and Hao, J.: Quantifying the air pollutants emission reduction during the 2008 Olympic Games in Beijing, Environ. Sci. Technol., 44, 2490–2496, 2010b.

Zhao M., Tan L., Zhang W., Ji M., Liu Y., and Yu L.: Decomposing the influencing factors of industrial carbon emissions in Shanghai using the LMDI method, Energy, 35, 2505–2510, 2010.

Zhou, Y., Wu, Y., Yang, L., Fu, L., He, K., Wang, S., Hao, J., Chen, J., and Li, C.: The impact of transportation control measures on emission reductions during the 2008 Olympic Games in Beijing, China, Atmos. Environ., 44, 285–293, 2010.

ACPD

12, 7985–8007, 2012

Table 1. Linear regression analysis for the carbon emissions of 12 Chinese cities.

Variable	coefficient	t_{stat}	sig.	95 % CI
Total carbon emission (thousand tons) (R^2 = 0.47)				
constant	49162.77	8.09	0.000	36991.00 to 61334.54
GDP (million US$)	0.67	7.11	0.000	0.48 to 0.86
Total carbon emission (thousand ton) (R^2 = 0.53)				
constant	41984.70	6.63	0.000	29305.75 to 54663.65
GDP (million US$)	0.55	5.61	0.000	0.36 to 0.75
city population (thousand people)	1.25	2.74	0.008	0.34 to 2.17
Carbon emission density (ton km^{-2}) (R^2 = 0.80)				
constant	602.01	0.91	0.369	−728.86 to 1932.87
city population density (people km^{-2})	8.97	15.38	0.000	7.80 to 10.14
Log per GDP carbon emission (R^2 = 0.70)				
constant	15.29	22.72	0.000	13.94 to 16.63
Log GDP	−0.73	−11.59	0.000	−0.85 to −0.60

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD
12, 7985–8007, 2012

The carbon emissions of Chinese cities

H. Wang et al.

Table 2. Summary of the per capita carbon emissions from 12 Chinese cities in 2005 and other 10 global cities (t-CO_{2e}/capita)[a].

City	Electricity Use	Heating and industrial fuel use	Ground Transportation	Industry Process	Waste	Summary		
						Industry related[c]	Non Industry	Total
Bangkok	2.77	2.49	2.27	unknown	1.23	2.63	6.13	8.76
Barcelona	0.67	0.85	0.77	unknown	0.24	0.76	1.77	2.53
Cape Town	3.38	1.15	1.44	unknown	1.78	2.33	5.43	7.75
Denver	9.10	4.12	6.31	unknown	0.59	6.04	14.08	20.12
Geneva	0.35	3.45	1.85	unknown	0.38	1.81	4.22	6.03
London	2.50	2.58	1.22	unknown	0.21	1.95	4.56	6.51
Los Angeles	2.46	1.37	4.92	0.22	0.49	2.84	6.62	9.46
New York	3.01	3.13	1.53	unknown	0.35	2.41	5.61	8.02
Prague	3.31	3.20	1.44	0.43	0.11	2.55	5.94	8.49
Toronto	2.47	3.30	4.05	0.57	0.33	3.22	7.50	10.72
Beijing	3.40	3.01	1.46	0.61	0.14	5.12	3.50	8.62
Tianjin	3.53	3.85	0.90	0.42	0.16	6.83	2.03	8.87
Shanghai	4.82	3.77	0.95	0.83	0.19	7.44	3.13	10.57
Hangzhou	3.42	3.71	1.03	1.05	0.66	7.61	2.26	9.87
Nanjing	3.34	1.99	0.64	1.62	0.12	5.31	2.40	7.71
Wuxi	7.00	6.23	1.13	1.72	0.38	12.78	3.67	16.45
Guangzhou	3.27	1.87	1.57	0.98	0.17	4.47	3.39	7.86
Zhengzhou	3.10	3.39	0.81	1.44	0.50	6.32	2.92	9.24
Wuhan	1.16	11.16	0.77	0.60	0.16	12.59	1.25	13.84
Chongqing	0.76	1.22	0.35	0.43	0.13	2.03	0.85	2.88
Lanzhou	3.51	15.13	0.3[b]	2.26	0.13	20.71	0.32	21.04
Shenyang	1.93	3.44	1.01	0.12	0.17	4.62	2.06	6.68

[a] The carbon emissions data of bold marked cities are from this study and the data of other 10 global cities are from Kennedy's study (2009).
[b] Because no information about vehicle population were found for Lanzhou city, the analogy analysis between Zhengzhou and Lanzhou was applied to calculate the carbon emissions.
[c] For lack of information, the industries are assumed to contribute 30 %, which is similar to the proportion of average US level (www.state.gov/documents/organization/139999.pdf), of the total per capita carbon emissions of 10 global cities.

ACPD
12, 7985–8007, 2012

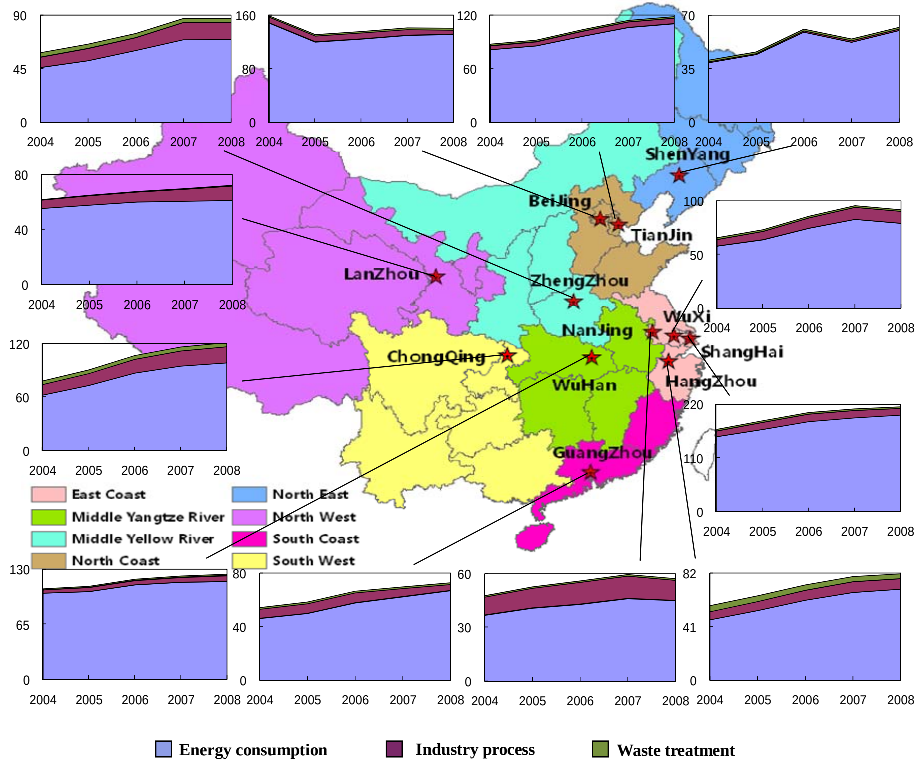


Fig. 1. Carbon emissions of the 12 cities in China from 2004 to 2008, million tons.

ACPD
12, 7985–8007, 2012

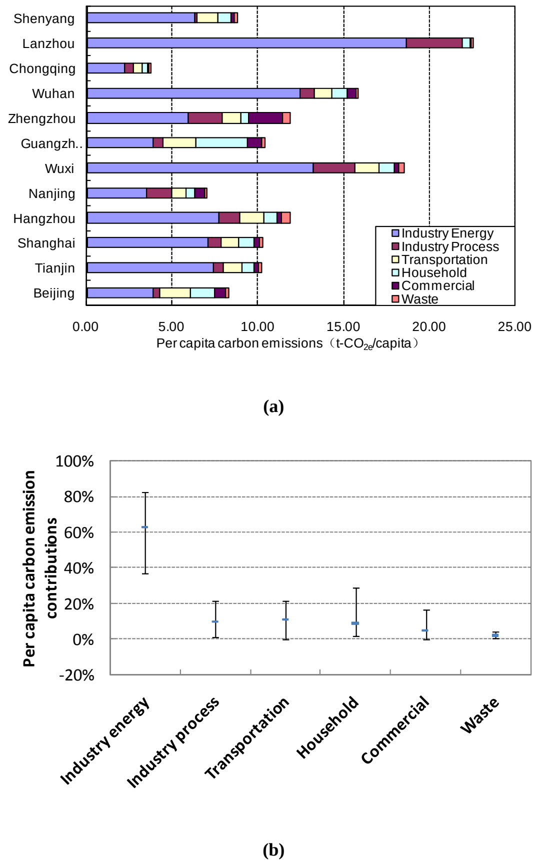
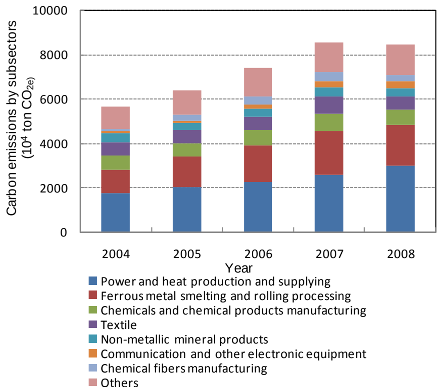
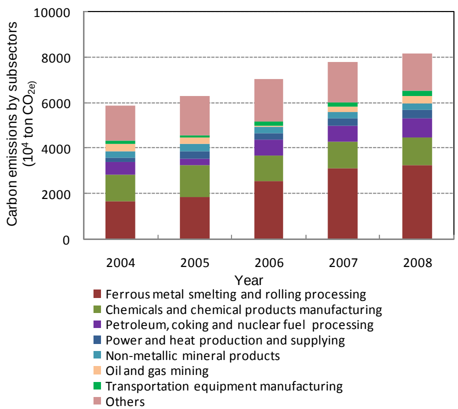


Fig. 2. Per capita carbon emissions (ton CO_{2e}) by sector for all 12 China's cities in 2008: **(a)** Individual city data of per capita carbon emissions; **(b)** Sector contribution rates (mean and range values) across the 12 cities.

ACPD
12, 7985–8007, 2012



(a)



(b)

Fig. 3. Detailed contributions of various subsectors to the industrial consumption sector in the cities **(a)** Wuxi; **(b)** Tianjin.

ACPD
12, 7985–8007, 2012