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A high-resolution emission inventory of primary pollutants for the Huabei region, China

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Abstract

Huabei is a part of eastern China located between 32° N and 42° N latitude. Administratively it is a region including Beijing and Tianjin Municipalities, Hebei and Shanxi Provinces, and Inner-Mongolia Autonomous Region. Over the past decades, the region has experienced dramatic changes in air quality and climate, and has become a major focus of environmental research in China. Here we present a new inventory of air pollutant emissions in Huabei for the year 2003 developed as part of the project Influence of Pollution on Aerosols and Cloud Microphysics in North China (IPAC-NC).

Our estimates are based on the data from the statistical yearbooks of state and provinces as well as local districts including major sectors and activities of power generation, industrial energy consumption, industrial processing, civil energy consumption, crop straw burning, oil and solvent evaporation, manure, and motor vehicles. The emission factors are selected from a variety of literature and those from local measurements in China are used whenever available. The estimated total emissions in the Huabei administrative region in 2003 are 4.73 Tg SO_2, 2.72 Tg NO_x (in equivalent NO_2), 1.77 Tg VOC, 24.14 Tg CO, 2.03 Tg NH_3, 4.57 Tg PM_{10}, 2.42 Tg $PM_{2.5}$, 0.21 Tg EC, and 0.46 Tg OC.

For model convenience, we consider a larger Huabei region with Shandong, Henan and Liaoning Provinces included in our inventory. The estimated total emissions in the larger Huabei region in 2003 are: 9.55 Tg SO_2, 5.27 Tg NO_x (in equivalent NO_2), 3.82 Tg VOC, 46.59 Tg CO, 5.36 Tg NH_3, 10.74 Tg PM_{10}, 5.62 Tg $PM_{2.5}$, 0.41 Tg EC, and 0.99 Tg OC. The estimated emission rates are projected into grid cells at a horizontal resolution of 0.1° latitude by 0.1° longitude. Our gridded emission inventory consists of area sources, which are classified into industrial, civil, traffic, and straw burning sectors, and large industrial point sources, which include 345 sets of power plants, iron and steel plants, cement plants, and chemical plants.

The estimated regional NO_2 emissions are about 2–3 % (administrative Huabei region) or 5 % (larger Huabei region) of the global anthropogenic NO_2 emissions. We

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compare our inventory (IPAC-NC) with a global emission inventory EDGAR-CIRCE and an Asian emission inventory INTEX-B. While the total emissions in Huabei are comparable with each other, large differences up to a factor of 2–3 for local emissions in the areas such as the Beijing and Tianjin megacities are found. We expect that our inventory will provide more practical spatial distributions of air pollutant emissions in the Huabei region of China and can be applied for air pollution and chemistry research on this region in the future.

1 Introduction

North China, or Huabei in Chinese (hereafter we use the latter), is a geographical region located in the northern part of eastern China, including several provinces and large municipalities, e.g. Beijing and Tianjin, both with populations greater than 10 million. Being influenced by both anthropogenic activities and natural desert, Huabei has become one of the most severely polluted regions in China as indicated by numerous studies including both ground measurements (e.g. Yan et al., 2008; Li et al., 2007; Lin et al., 2008, 2009; Meng et al., 2009; Pan et al., 2009; Sun et al., 2010; Tang et al., 2007) and satellite data analyses (e.g. Xu and Lin, 2010; Chen et al., 2009; Peng et al., 2007; Li et al., 2003a; Ma et al., 2006b; Richter et al., 2005; Shi et al., 2008; Tie et al., 2006; Zhang et al., 2007; Zhao et al., 2006). The project Influence of Pollution on Aerosols and Cloud Microphysics in North China (IPAC-NC) was implemented in order to assess the causes of such severe pollution and its potential impact on regional climate (Ma et al., 2010). As part of the IPAC-NC project, we have developed a high-resolution emission inventory of primary pollutants for the Huabei region of China. Our objective is to provide a reliable emission database that can be used to drive the regional meteorology-chemistry coupled model with fine-grid cells (e.g. at a horizontal resolution of 0.1° latitude by 0.1° longitude), to better understand chemical and physical processes involved in dramatic changes in air quality and climate over this part of China in the 2000s and find their linkages with energy consumption and technology innovation.

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The emission inventory and its accuracy are important for the ability of modelling studies to characterize the historical, present, and future states of the atmospheric environment (Russell and Dennis, 2000; Ma and van Aardenne, 2004). Global and Asian emission inventories naturally include the estimates for a specific region, e.g. Huabei, China. Global emission inventories, e.g. EDGAR (the Emission Database for Global Atmospheric Research) v32 (Olivier et al., 2002); EDGAR v3.2 Fast Track 2000 (Olivier et al., 2005; data available at http://www.mnp.nl/edgar/model/v32ft2000edgar), IPCC-AR4 (Dentener et al., 2005; data available at ftp://ftp-ccu.jrc.it/pub/dentener/IPCC-AR4/2000), and RETRO (Pulles et al., 2007; data available at http://retro.enes.org), generally have too low grid resolution (e.g. 1° latitude by 1° longitude) for urban/regional model simulations. Moreover, there are very large differences (often a factor of two) between the emissions for individual cities, even when the total global emissions are very similar (Butler et al., 2008). The use of an ensemble of inventories, increased attention to the geographical distribution of emissions, and better integration of local inventories into global emission inventories, has been recommended (Butler et al., 2008).

Several Asian emission inventories were developed for the support of different projects and associated field campaigns that focused on the impacts of Asian pollution outflow on West-Pacific and North America, e.g. TRACE-P (Transport and Chemical Evolution over the Pacific) campaign in 2001 (Jacob et al., 2003) and INTEX-B (Intercontinental Chemical Transport Experiment-B) campaign in 2006 (Singh et al., 2009). Almost all of these inventories, e.g. TRACE-P (Streets et al., 20003; data available at .http://www.cgrer.uiowa.edu/EMISSION_DATA/index_16.htm), REAS (Ohara et al., 2007), and INTEX-B (Zhang et al., 2009.; data available at http://mic.greenresource.cn/intex-b2006 or http://www.cgrer.uiowa.edu/EMISSION_DATA_new/index_16.htm) were initially estimated by province for China and by country for the rest of Asia. They are generally distributed at the same (1° latitude by 1° longitude for TRACE-P) or slightly finer (0.5° latitude by 0.5° longitude for REAS and INTEX-B) grid resolution, although it was declared that the data with much finer resolution (0.3° latitude by 0.3° longitude for

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TRACE-P and INTEX-B) might be accessed. While these emission inventories have widely been used and evaluated in model simulations (e.g. Carmichael et al., 2003), the comparisons of model results with measurements for the polluted regions inside China (e.g. Huabei) are relatively few. It was shown that the uncertainty in the emission estimates may result in 30–50 % differences in surface ozone concentrations in polluted areas of China (Ma and van Aardenne, 2004).

Regional pollution related to photochemical smog and haze-fog has been recognized as one of the severe environmental problems in China (Zhang et al., 2008; Ma et al., 2010). The most serious pollution regions are typically the Huabei region with the Beijing and Tianjin megacities included, the Yangtze River Delta region with the Shanghai megacity included, and the Pear River Delta region with the Guangzhou and Hong Kong megacities included. Such air pollution not only has adverse effects on human health and the ecosystems, but also has large impacts on weather and climate in urban and regional scales. Accurate and highly-resolved emission inventories are essential for understanding pollution formation and transport, planning abatement and control measures, and operating chemical weather forecasting in these regions. Wang et al. (2005b) developed a source-specific high-resolution emission inventory for the Shandong region of eastern China for the year 2000 and implemented it to a regional chemical transport model of 12 km × 12 km horizontal resolution. Bo et al. (2008) established a multiyear emission inventory of anthropogenic non-methane volatile organic compounds (NMVOC) in China for 1980–2005 with a high spatial resolution of 40 km × 40 km. Cao et al. (2006) presented a high-resolution emission inventory of elemental carbon (EC) and organic carbon (OC) aerosols in China for the year 2000 with 0.2° latitude × 0.2° longitude resolution. Recently, Zheng et al. (2009) developed a highly resolved temporal and spatial emission inventory for the Pearl River Delta region for the year 2006 and allocated it onto grid cells with a resolution of 3 km × 3 km.

In this paper, we present a high-resolution emission inventory of the major air pollutants developed for the Huabei region of China for the year 2003. Our inventory includes sulfur dioxide (SO_2), nitrogen oxides ($NO_x \equiv NO + NO_2$), VOC (abbreviated

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from NMVOC, Non-Methane Volatile Organic Compounds), carbon monoxide (CO), ammonia (NH_3), particulate matter of diameter smaller than or equal to 10 µm (PM_{10}), particulate matter of diameter smaller than or equal to 2.5 µm ($PM_{2.5}$), EC, and OC. In Sect. 2 we describe the methodology and data sources used in this study. In Sect. 3 we present our emission inventory by sectors, provinces and fine-grid cells (with a horizontal resolution of 0.1° latitude by 0.1° longitude). In Sect. 4 we estimate the uncertainties of our estimates in comparison with other emission inventories. A summary of our inventory is given in Sect. 5.

2 Methodology

2.1 General description

Huabei is a part of eastern China, located approximately between 32° N and 42° N latitude in a geographical sense. Administratively it is a region including Beijing and Tianjin Municipalities, Hebei and Shanxi Provinces, and Inner-Mongolia Autonomous Region. For model convenience, the statistical data for Shandong, Henan and Liaoning Provinces are also taken into account in our inventory although these provinces do not belong to Huabei currently in an administrative sense (Fig. 1). Table 1 gives a summary of social and economic index in Huabei, and Table 2 presents the energy use by fuel type in the region. Beijing, Tianjin, Hebei, Shandong, and Liaoning together compose the main industrial base of China, Shanxi is an important energy base, Henan is a large agricultural province, and Inner-Mongolia is one of dust storm sources in northern China.

We use a bottom-up approach to develop the emission inventory for the Huabei region, considering only anthropogenic emissions on an annual basis. The annual anthropogenic emission rate of the i-th chemical species in the j-th area, $Q_{i,j}$, is calculated as

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$$Q_{i,j} = \sum_{k=1}^{n} A_{j,k} F_{i,j,k} \quad (1)$$

where $A_{j,k}$ is the annual rate of the k-th activity or fuel use in the j-th area, $F_{i,j,k}$ is the emission factor of the k-th activity or fuel use for the i-th species in the j-th area, and n is the total number of activities or fuel types in the area. The chemical species or pollutants we consider are SO_2, NO_x, VOC, CO, NH_3, PM_{10}, $PM_{2.5}$, EC, and OC. Molar or total masses of each species or pollutant are calculated. As previous studies (e.g. van Aardenne et al., 1999; Zhang et al., 2009) we use the equivalent NO_2 masses to represent the amount of emitted NO_x, although NO_x from fossil fuel burning is generally released in the form of NO (>90 %). In this study we present the emissions in the Huabei region for the year 2003, which was the latest year for which Chinese statistical data could be obtained when the IPAC-NC project started. Although some new emission inventories have been available for the years after 2003, e.g. INTEX-B for 2006 (Zhang et al., 2009), we still believe that our emission inventory will be very useful for model work on historical trend and field experimental data analyses.

Compared to existing global or Asian emission inventories, an advantage of our emission inventory is that we collected the original data from the statistical yearbooks of local districts (which have an administrative level between province and county in China) instead of only provinces. The major sectors and activities included in our inventory are power generation, industrial energy consumption, industrial processing, civil energy consumption, crop straw burning, oil and solvent evaporation, manure, and motor vehicles. Another advantage of our emission inventory is that we performed an intensive literature research on the emission factors and tried to use the ones derived by local measurements in China whenever possible.

We investigated the annual product of large power plants, iron and steel plants, cement plants, fertilizer plants, coke plants, petrochemical plants, grains and oil plants, sulfuric acid plants, and paint plants in Huabei (345 in total), defined their geographical positions exactly by latitude and longitude, and estimated the emissions of SO_2, NO_x,

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VOC, CO, NH_3, PM_{10}, $PM_{2.5}$, EC, and OC from these plants as point sources. The total emissions in the districts or counties were deduced by the emissions from these point sources correspondingly, and the rest were mapped into the gridded cells using geographical information system (GIS) to get the emissions of area sources. A gridded emission inventory of Huabei with a 0.1° latitude × 0.1° longitude resolution was derived based on these point and area source emission rates.

2.2 Activity rates

We performed a detailed analysis of the statistical data of local districts in Huabei (e.g. China Statistic Bureau, 2004a; China Statistic Bureau, 2004b; China Electric Power Yearbook Editorial Board, 2004; China Steel Indsutrial Association, 2004; China Traffic Yearbook Editorial Board, 2004) The pollution sources are separated into various sectors including power generation, industrial energy consumption, industrial processing, civil energy consumption, crop straw burning, central heating, oil and solvent evaporation, major ammonia sources, major particle sources, cooking, and motor vehicles. The industrial energy sector is subdivided into different fuel types including coal, coke, gasoline, diesel oil, fuel oil, crude oil, liquefied petroleum gas (LPG), coal gas, and natural gas. The industrial processing sector refers to the emissions during the production of fertilizer, sulfuric acid, ammonia, cement, iron, steel, coke, paints, vegetable oil and crude oil excluding fuel burning. The emissions from these two industrial sectors (energy consumption and processing) are distributed according to the industrial production quantity of the counties.

The civil energy sector is also subdivided into different fuel types including civil coal, civil LPG, civil natural gas, and civil coal gas for benefit stove (BS). The emissions from the civil energy sector, central heating, oil and paint evaporation, and motor vehicles are distributed according to the population of the counties. The emissions from straw burning sector are distributed according to the agricultural production of the countries. Table 3 presents the annual crop straw masses burned for each province in Huabei in the year 2003.

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The major ammonia sources include animal, man, and fertilizer applications, which are estimated based on animal husbandry production, population, and sowing areas, respectively. While the emissions due to traffic blowing dust are estimated, particle sources from building construction and bare land are not taken into account in this study. Motor vehicles are subdivided into passenger vehicles (large, middle, small, and mini), goods vehicles (heavy, middle, light, and mini), motorcycles, and tractors. The emissions of motor vehicles are estimated as the product of numbers of vehicles in a county or district, annual distance traveled in km, and emission factor in $g\,km^{-1}$ of pollutant emitted. Table 4 provides the motor vehicle numbers by province in Huabei in the year 2003.

2.3 Emission factors

The emission factors are very important for the accuracy of an emission inventory. The emission inventories developed previously for China were mostly based on the emission factors measured abroad, which may not completely be suitable for the situation in China. Since some measurements of emission factors, especially in the Huabei region of China, have been performed (e.g. Jiang and Tang, 2002), we try to use these local emission factors in the calculations as much as possible. Tables 5–10 show the emission factors of various fuel composition and activities adopted in our inventory. Below we give a general description of the selection or estimation of the specific emission factors of our inventory.

2.3.1 Coal burning

Due to high coal burning efficiency (>90 %) for boilers in the power plants, the CO and EC emission factors for power generation are much lower than those for other coal burning activities (Table 5). Although the sulfur burning efficiency is high under such boiler condition, the SO_2 emission factor for power generation is also lower since low-sulfur-content coal and desulfurization technology have been widely used in the power

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plants. The coal burning efficiency in residential use is much lower than that (~80 %) for industrial boilers. As a result, the SO_2 and NO_x emission factors for coal burning are lower, and the CO and EC emission factors are much higher, in the civil sector than those in the industrial sector. The sulfur content of the coal used in the larger Beijing, Tianjin, and Tangshan areas (called Jing-Jin-Tang in Chinese) is lower (~0.6 % in average) than in the rest of Huabei (~0.92 %) (Bai, 1996; Jiang and Tang, 2002). Moreover, more advanced production technology was adopted in Jing-Jin-Tang than in the other areas. Therefore, lower SO_2 emission factors for coal burning are used for Jing-Jin-Tang and its nearby areas than the rest of Huabei in our inventory.

2.3.2 Industrial processes

In addition to fuel combustion, some pollutants are emitted during industrial processes (Table 6). The emission factors of SO_2, PM_{10}, and $PM_{2.5}$ for the steel processing are taken from local experimental results (Jiang and Tang, 2002). The CO emission factor for steel processing is determined using a CO emission factor reported by previous work (Wang et al., 2005a) weighted by the fraction of steelmaking processes (e.g. converter and electric furnace). The methods of coke making include the uncontrollable heap coking and the controllable mechanical coking, which have large effects on the amount of EC and OC emitted during the coke processing. The EC and OC emission factors for the coking process are estimated according to the work of Bond et al. (2004) with a mechanical coking method assumed.

2.3.3 Straw burning

Crop straw burning is an important way of obtaining energy for cooking and heating in the countryside of China. Since the residential stoves used for burning straw are small and the water content of straw burned is high, the burning temperatures and burning efficiency are generally low and the emission factors of major pollutants are large. With increasing crop yields and possibility of using other energy, open-air straw

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burning in the field has occurred more frequently in the developed areas of Huabei, e.g. Beijing and Tianjin. The NO_x and SO_2 emission factors for crop straw burning are taken from the work of Tian et al. (2002), with wheat straw, corn straw, rice straw, and oil straw being as herbal straw and cotton straw being as core wood. The CO and VOC emission factors are taken from the work of Fine et al. (2001), which are typically applicable to the traditional straw-burning stoves in China. The $PM_{2.5}$ emission factor is adopted according to the measurement work of Zhu et al. (2005). As no relevant literature for the PM_{10} emission factor was found, we assume that the value of the PM_{10} emission factor is twice as much as that of the $PM_{2.5}$ in this study. The EC and OC emission factors are given based on analyses of literature (Andreae and Merlet, 2001; Cao, 2005; Cooke et al., 1999; Jenkins et al., 1996; Reddy and Venkataraman, 2002; Streets et al., 2001) (Table 7).

2.3.4 Solvent and oil evaporation

The evaporation of paint solvents and petroleum products is an important source of VOC in the atmosphere. The VOC emission factors measured in the work of Jiang and Tang (2002) are adopted in this study (Table 6). Organic solvent is assumed to take up 50 % of the solvent-based paints, i.e. 500 g VOC can evaporate from 1 kg paints. The VOC emission factors for the evaporation of petroleum products are also used in our emission estimates (Table 8).

2.3.5 Fertilizer application

Ammonia is emitted into the atmosphere mainly from animals, fertilizer production, soil fertilization, and man. Several kinds of animals are considered in our estimates of NH_3 emissions, and the emission factors of typical animals are shown in Table 9. The NH_3 emission factor for soil fertilization is determined mainly by the amount of fertilizers, their types and application ways and soil characters according to the work of Sun and Wang (1997) (Table 6).

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2.3.6 Traffic

China began to implement the National I Standard (referring to Euro I Standard) for automobile exhaust emissions in 1999, National II Standard (referring to Euro II Standard) in 2003, and National III Standard (referring to Euro III Standard) in 2006. Beijing does better in air quality control, with National II Standard implemented in 2002 and National III Standard implemented in 2005. The SO_2 emission factors for traffic are determined by the product of the sulfur content of various fuel types and the fuel usage per kilometer. The ratio of the large passenger and heavy goods vehicles using gasoline to those using diesel fuel is 1:9, and the ratio of the middle passenger and heavy goods vehicles using gasoline to the ones using diesel fuel is 1:3. These statistical data are used in our calculations of the CO emission factors for the passenger and goods vehicles. Table 10 gives a list of the emission factors for motor vehicles used in our inventory. These parameters are determined mostly according to the local measurements as reported by literature (e.g. Jiang and Tang, 2002; Cao, 2005; Li et al., 2003b; Wang, 2002) and partly referring to the experimental results abroad (e.g. Reddy and Venkataraman, 2002).

3 Results

3.1 Emissions by province and sector

Tables 11 and 12 show the calculated anthropogenic emissions in the larger Huabei region in the year 2003 by sector (Table 11) and by province (Table 12), respectively. The percent contributions to the total emissions of different pollutants in the region are shown in Fig. 2 for each sector of the region, and in Fig. 3 for each sector of the provinces. Although our estimates are based on various sectors, we provide a gridded emission inventory only for four sectors, i.e. industrial, civil, traffic, and straw burning. The industrial sector includes the power generation, industrial energy, and industrial

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processing, and the civil sector includes the civil energy (including central heating), oil and solvents, and manure. Power generation is an important emission source, and was generally considered as a separate sector in previous inventories (e.g.,Zhang et al., 2009). In our inventory the industrial sector is further separated into the industrial area and point sub-sectors, with the most important emission sources (e.g. large power plants) provided specifically. Therefore, the power generation sector is not given as a sector in our gridded emission inventory. Straw burning for heating and cooking might be considered as a part of the residential sector in other inventories (Zhang et al., 2009). In this study straw burning is treated as one sector exclusively, mainly because it has unique emission factors and its activities occur in the countryside. This separation strategy may be useful for emission updates and model applications in the future.

3.1.1 SO_2

The total SO_2 emission is estimated to be 9.55 Tg in the larger Huabei region (4.73 Tg in the Huabei administrative region) in the year 2003. Coal burning makes a dominant contribution (~83 %) of the total SO_2 emission, with 12 % for power generation, 61 % for industrial energy, and 10 % for civil energy. In addition, the amount of SO_2 produced during industrial processing, e.g. the sintering and smelting of iron minerals during steel production, is also considerable, making ~15 % in the total SO_2 emission. Shandong is a developed province in economy with a huge amount of energy consumed, mostly from coal burning. Shanxi is a developed province in coal industry with many power generation and coking enterprises. Therefore, Shandong and Shanxi are larger SO_2 emission sources than the other administrative regions in larger Huabei. Nevertheless, Tianjin is the administrative region with the highest SO_2 emission strength (the emission rates per unit area) due to many power and steel plants there.

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3.1.2 NO_x

The total NO_x emission is estimated to be 5.27 Tg in the larger Huabei region (2.72 Tg in the Huabei administrative region) in the year 2003. The estimated regional NO_2 emissions are about 2–3 % (administrative Huabei region) or 5 % (larger Huabei region) of the global anthropogenic NO_2 emissions. Coal burning makes a major contribution (~50 %) to the total NO_x emissions, with up to 10 % for power generation, 35 % for industrial energy, and 5 % for civil energy. The industrial processing and traffic sectors contribute 14 % and 31 % of the total NO_x emissions in the larger Huabei region, respectively. Industrial activity (energy and processing together) makes an half of the total NO_x emission in the region. Straw burning has a relatively small contribution (~5 %) to the total NO_x emission in larger Huabei. Shandong and Hebei have higher NO_x emission sources than the other administrative regions in larger Huabei. There are many power, steel, coking, and petroleum plants as well as motor vehicles in Hebei Province. The emission strength of NO_x is very strong in Beijing and Tianjin mainly due to numerous automobiles accumulated in small areas.

3.1.3 VOC

The total anthropogenic VOC emission is estimated to be 3.82 Tg in the larger Huabei region (1.77 Tg in the Huabei administrative region) in the year 2003, with a predominant contribution (~96 %) from non-industrial activities. Traffic makes a major contribution (55 %) to the total VOC emission, and the contributions of other non-industrial activities are 23 % for evaporation of oil and paint solvents, and 18 % for straw burning. General industrial activities including power generation, industrial energy and industrial processing, make a small contribution (~3 %) to the total VOC emission in larger Huabei. The VOC emissions in Shandong are the largest because of many traffic, straw burning, and crude oil processing activities. The emission strength of VOC in Beijing and Tianjin is very strong mainly due to the high concentrated numerous of vehicles.

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3.1.4 CO

The total CO emission is estimated to be 46.59 Tg in the larger Huabei region (24.14 Tg in the Huabei administrative region) in the year 2003. The contributions are from industrial processing (38 %), traffic (22 %), straw burning (19 %), industrial energy (13 %) and civil energy (8 %), respectively. Large amounts of CO can be emitted during industrial processing in the coke, steel, and cement production. Industrial activities including industrial energy and industrial processing together make a dominant contribution (51 %) to the total CO emission in larger Huabei. The contribution of coal burning to the total CO emission is about 21 %. Hebei is the largest CO emission source in larger Huabei, followed by Shandong.

3.1.5 NH_3

The total NH_3 emission is estimated to be 5.36 Tg in the larger Huabei region (2.03 Tg in Huabei) in the year 2003. The contribution of manure to the total NH3 emission is predominant (~98 %), with 48 % from animals, 41 % from agricultural fertilizers, and 9 % from man, respectively. As both agricultural and animal husbandry activities are strong in Henan, Shandong and Hebei, these three provinces together are the main sources (56 %) of the total NH_3 emission in the larger Huabei region.

3.1.6 PM_{10} and $PM_{2.5}$

The total anthropogenic PM_{10} and $PM_{2.5}$ emissions are estimated to be 10.74 Tg and 5.62 Tg in the larger Huabei region (4.57 Tg and 2.42 Tg in the Huabei administrative region) in the year 2003, respectively. Note that the particle sources from building construction and natural dust are not taken into account in this study. The sources from straw burning are the strongest, contributing 80 % and 76 % of the total PM_{10} and $PM_{2.5}$ emissions, respectively. The traffic sector with traffic blowing dust included contributes 7 % of the total PM_{10} and 10 % of the total $PM_{2.5}$, and the industrial energy

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and processing together contributes 11 % of the total PM_{10} and 12 % of the total $PM_{2.5}$, respectively. Shandong is the largest PM_{10} and $PM_{2.5}$ emission source in the larger Huabei, and followed are Hebei and Henan. Tianjin is the second in respect to the emission strength followed by Shandong.

3.1.7 EC and OC

The total EC and OC emissions are estimated to be 0.41 Tg and 0.99 Tg in the larger Huabei region (0.21 Tg and 0.46 Tg in the Huabei administrative region) in the year 2003, respectively. The industrial sector contributes 38 % and 37 % of the total EC and OC emissions, respectively. The contributions from straw burning are 39 % and 45 %. The traffic sector contributes 15 % and 10 % respectively to EC and OC. Shandong is the largest EC and OC emission source in the larger Huabei followed by Hebei and Henan. The emission strength of EC and OC in Beijing and Tianjin are very high compared to other provinces.

3.2 Spatially gridded emissions

Figure 4 shows the spatial distributions of primary pollutant emissions in larger Huabei in 2003 at a 0.1° latitude × 0.1° longitude resolution. The polluted areas in Huabei are clearly visible with 1–2 order of magnitude higher emission rates in the central and southern Huabei (e.g. 1–10 $Gg\,yr^{-1}$ per grid for SO_2 and NO_x) than those in the northern Huabei (e.g. ~0.1 $Gg\,yr^{-1}$ per grid for SO_2 and NO_x). Three major emission source areas can be identified in the region: the first is the larger Beijing-Tianjin-Tangshan area in the northern parts of Hebei Province, the second is the larger Shijiazhuang-Handan-Taiyuan area in the south parts of Hebei Province and the central parts of Shanxi Province, and the third is the larger Zibo-Zaozhuang area in the central and southern parts of Shandong Province. The hot spots due to emissions in the Beijing and Tianjin megacities and other large industrial cities, e.g. Tangshan, Shijiazhuang and Taiyuan, are also clearly visible (e.g. larger than 10 $Gg\,yr^{-1}$ per grid for SO_2 or

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NO_x). Although the emission spatial distributions of different pollutants are very similar to each other in general, some difference can also be seen. For example, while SO_2 has peak emissions (larger than 20 Gg yr^{-1} per grid) in some industrial cities such as Taiyuan in Shanxi Province, VOC has peak emissions (larger than 10 Gg yr^{-1} per grid) in the Beijing and Tianjin megacities, indicating the variations of pollution source types in these different regions.

4 Discussions

4.1 Comparison with other inventories

Several global or Asian emission inventories for the period from 2000 to 2006 are available, e.g. EDGAR v3.2 Fast Track 2000 (Olivier et al., 2005), TRACE-P (Streets et al., 2003), and INTEX-B (Zhang et al., 2009.). However, these inventories do not provide an emission estimate for the year 2003 specifically. Here we compare our inventory with a global emission inventory for the year 2005, EDGAR-CIRCE, and an Asian emission inventory for the year 2006, INTEX-B. The INTEX-B emission inventory was developed by Zhang et al. (2009) initially for the support of the Intercontinental Chemical Transport Experiment-B campaign in 2006 (Singh et al., 2009). The gridded emissions of INTEX-B were estimated initially by province for China and by country for the rest of Asia with a 0.5° latitude × 0.5° longitude resolution (Zhang et al., 2009). The EDGAR-CIRCE emission inventory used in this study was prepared in the framework of the CIRCE Project (No. 036961) by the EDGAR group of the EC-Joint Research Center Ispra (Italy), Climate Change Unit (Doering et al., 2009a; Doering et al., 2009b). This dataset includes greenhouse gases, NO_x, CO, VOCs, NH_3, SO_2 from fossil fuel and bio fuel related emissions. Although emissions are present for the year 1990–2005, only the last year present monthly specification and has been evaluated with the model EMAC (Pozzer at al., 2011). The emission inventories of EDGAR v3.2 Fast Track (Olivier et al., 2005) and TRACE-P (Streets et al., 20003) are not selected in this

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study, because they were developed for the emissions in 2000 at a low grid resolution (1° latitude × 1° longitude). Satellite measurements indicated that pollutant emissions in China increased dramatically from 2000 to 2003 (Richter et al., 2005). Moreover, model studies showed that the TRACE-P inventory underestimates the tropospheric NO_2 column density in all the regions of China with respect to the satellite observations (Ma et al., 2006). The TRACE-P inventory was compared with the INTEX-B inventory and revised accordingly (Zhang et al., 2009).

Figure 5 presents the spatial distributions of major pollutant emissions in Huabei estimated by our 2003 inventory (denoted as IPAC-NC), the 2005 EDGAR-CIRCE inventory (denoted as EDGAR), and the 2006 INTEX-B inventory (denoted as INTEX-B). Note that with respect to Fig. 4 we select a smaller Huabei region including Beijing, Tianjin, Hebei, Shanxi, Shandong, and parts of Inner-Mongolia, Henan and Liaoning for the comparison. Although the IPAC-NC is generally in agreement with the EDGAR-CIRCE and INTEX-B in the emission distribution patterns, e.g. high emissions in the Huabei Plain and peak emissions in Jing-Jin-Tang, differences are present, as shown in Fig. 5. The EDGAR-CIRCE and INTEX-B inventories provide more homogeneously distributed emissions. They underestimate the emissions in two highly-polluted areas (the larger Shijiazhuang-Handan-Taiyuan area in Hebei and Shanxi Provinces and the larger Zibo-Zaozhuang area in Shandong Provinces) other than Jing-Jin-Tang and overestimate the emissions in the background areas located in the north and northwest of Huabei. Compared to the IPAC-NC inventory, EDGAR-CIRCE estimates more hot spots, i.e. higher emissions from small cities, due to the distribution of the emissions based on power plant presence and population density.

The total emissions in the smaller Huabei region estimated by the three inventories are shown in Fig. 6. For the purpose of comparison, the INTEX-B emissions are distributed into finer grid cells (0.1° latitude × 0.1° longitude), the same as those of the IPAC-NC and EDGAR-CIRCE inventories. The Huabei region in Fig. 6a refers to all the grid cells in Fig. 5 where the IPAC-NC data are available. For a consistency in comparisons, the EDGAR-CIRCE and INTEX-B emissions in the grid cells where the

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IPAC-NC has a default value are not taken into account. It can be seen that except for SO_2 the IPAC-NC and EDGAR-CIRCE inventories estimate nearly the same total emissions of major pollutants in the Huabei region. The total emissions estimated by the INTEX-B inventory are generally higher for most pollutants, by a factor of 2 for VOC and 3 for EC. The largest total emission rate of SO_2 is estimated by the EDAGR-CIRCE inventory. The Beijing region in Fig. 6b (the Tianjin region in Fig. 6c) refers to the 16 grid cells that have a distance of less than 0.2° from the city center, i.e. 39.92° N, 116.46° E (39.02° N, 117.02° E). The total area of these grid cells is smaller than the real area under the jurisdiction of the municipality, but it is representative for the normal size of a megacity. Larger differences are present between the inventories for the Beijing and Tianjin areas, in contrast to the Huabei region. For example, IPAC-NC estimates higher emissions of VOC by a factor of 2–3 than the other two inventories, and EDGAR-CIRCE estimates higher emissions of SO_2 by a factor of 2–4 than the other two inventories. These kinds of differences cannot be explained completely by the differences in economy and energy use, and could be caused most probably by different emission factors used in the estimates.

4.2 Uncertainty analysis

The uncertainties in emission inventories result from the uncertainties both in activity rates and emission factors. For the Chinese inventories, almost all the activity data are from the governmental yearbooks. These statistical data have relatively smaller error than the emission factors and are very reliable for the emission estimates at the national and provincial levels. However, distributing the activation rates from provincial levels to local areas and then onto much fine grid cells generally results in large bias due to usage of impractical methods, e.g. scaling by population. For this study we collected the original data from the statistical yearbooks of local districts and investigated the annual product of hundreds of large point sources from power plants, iron and steel plants, and other industrial plants in Huabei. Therefore, our inventory should be more concise and thus have an advantage in the spatial distributions of the emissions.

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Another advantage of our emission inventory is that we use the emission factors derived from local measurements in China. However, these measurements were sparse and confined to limited areas, and thus some emission factors from literature were still used in our estimates, making a great contribution to the uncertainties in the estimated emissions. For example, the SO_2 emission factors of coal burning used for the power plants in our inventory are 8.46 g Kg^{-1} for the larger Jing-Jin-Tang area and 16.56 g Kg^{-1} for the rest (see Table 5), which are 55 % lower and 7.5 % higher than the one used in the INTEX-B inventory (ca. 15.4 g Kg^{-1}, Zhang et al., 2009), respectively. For countries in Asia, implied emission factors from the REAS inventory (Ohara et al., 2007) were selected in the EDGAR-CIRCE inventory. Because SO_2 emissions in China depended strongly on the sulfur content of coal, province-by-province data for power plants and other sectors were used in their estimation. Hence, we would expect that the emission factors used in the EDGAR-CIRCE for China are variable by regions, but on average equal to 10.8 g Kg^{-1} (plus some reduction factors). The uncertainties due to emission factors are larger for other pollutants like EC and OC mainly due to the wide ranges of emission factors reported in the literature for these pollutants. Note that in our inventory we used for the EC and OC emission factors a lower value than what is used in other inventories. For example, the emission factor of EC used in our inventory is 0.15 g Kg^{-1} for industrial coal burning and 0.03 g Kg^{-1} for coke production (see Table 5), an order of magnitude lower than the values used in the INTEX-B inventory (ca. 15.4 g Kg^{-1}, Zhang et al., 2009). However, the uncertainties in the EC emission factors for straw burning (±20 %) and traffic sectors (±70 %) are not so large. We expect that the uncertainties in the total emissions of primary pollutants in Huabei would be at the same levels as those estimated by Zhang (2009) for China. Note that while the economy and energy use increased dramatically in the early 2000s in China, Chinese government has intensified the effort in energy saving and emission reduction since then. Some anti-pollution laws and regulations have been released (e.g. SEPA, 2003). For example, the efforts to reduce the emissions of air pollutants from thermal power plants have been stepped up by using the devices for wet flue gas

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desulfurization, denitrification and dust removal. These measures were implemented in different years for different regions, increasing the variability in the emission factors from year to year.

Although monthly emissions are not available in our inventory, we consider seasonal variations in the estimated emissions by separating the entire year into heating (1 January–15 March and 15 November–31 December) and non-heating (16 March–14 November) periods. Central heating is taken into account only for the heating period. There are large uncertainties in the ratios of the civil coal used and straw burned during the heating period over those during the non-heating period, and we assume a ratio of 2 between them. The emissions from other activities, e.g. industrial and traffic, are assumed to be season-independent.

5 Summary

In this study we have estimated the emissions of primary pollutants SO_2, NO_x, VOC, CO, NH_3, PM_{10}, $PM_{2.5}$, EC, and OC in the Huabei region of China in 2003. In an administrative sense, Huabei includes Beijing and Tianjin Municipalities, Hebei and Shanxi Provinces, and Inner-Mongolia Autonomous Region. The estimated total emissions in the Huabei administrative region in 2003 are 4.73 Tg SO_2, 2.72 Tg NO_x (in equivalent NO_2), 1.77 Tg VOC, 24.14 Tg CO, 2.03 Tg NH_3, 4.57 Tg PM_{10}, 2.42 Tg $PM_{2.5}$, 0.21 Tg EC, and 0.46 Tg OC. For model convenience, we consider a larger Huabei region with Shandong, Henan and Liaoning Provinces included in our inventory. The estimated total emissions in the larger Huabei region in 2003 are 9.55 Tg SO_2, 5.27 TG NO_x (in equivalent NO_2), 3.82 Tg VOC, 46.59 Tg CO, 5.36 Tg NH_3, 10.74 Tg PM_{10}, 5.62 Tg $PM_{2.5}$, 0.41 Tg EC, and 0.99 Tg OC.

The estimated emission rates have been projected into fine-grid cells at a horizontal resolution of 0.1° latitude by 0.1° longitude. Our gridded emission inventory includes the area sources from industrial, civil, traffic, and straw burning activities plus 345 large industrial point sources from power plants, iron and steel plants, cement plants, and chemical plants. Although our inventory is comparable to previous global or Asian

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inventories in the total emissions in Huabei, large differences up to a factor of 2–3 for local emissions in some areas (e.g. Beijing and Tianjin) are found. Our inventory will be likely to provide more practical spatial distributions of pollutant emissions in comparison with existing global or Asian emission inventories.

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Table 1. Social and economic index of the larger Huabei region in 2003.

No.	Administrative region	Area (10^4 km^2)	Population (10^6)	GDP (10^8 ¥)	Ind-P (10^8 ¥)	Agr-P (10^8 ¥)	Energy Use (10^6 ton SC)
1	Beijing	1.68	11.49	3663.1	959.5	102.5	47.08
2	Tianjin	1.13	10.11	2447.7	4049.6	181.1	32.15
3	Hebei	18.77	67.69	7122.0	5708.8	958.3	134.77
4	Shanxi	15.63	33.14	2456.6	2414.4	249.5	103.87
5	Inner-Monglia	118.3	23.80	2150.4	2055.0	336.0	52.18
6	Shandong	15.38	91.25	12 435.9	19 891.5	1599.3	130.34
7	Henan	16.70	96.67	7048.6	3034.1	673.5	95.62
8	Liaoning	14.59	41.62	6002.5	2884.1	497.3	114.49

GDP: Gross domestic product; Ind-P: Industrial product; Agr-P: Agricultural product; ¥: Chinese currency, Yuan; SC: standard coal, and 1 kg SC is equivalent to any fuel that produces 29.27 MJ of heat energy. Sources are from China Statistical Bureau (2004a, e).

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Table 2. Annual energy use in the larger Huabei region in 2003.

No.	Administrative region	Coal (10^4 ton SC)	Coke (10^4 ton SC)	Oil (10^4 ton SC)	Natural Gas (10^8 m^3)	Coal Gas (10^8 m^3)	LPG (10^4 ton SC)
1	Beijing	2007.4	462.0	485.7	22.6	139.5	32.8
2	Tianjin	1642.3	140.6	271.2	5.0	2.3	79.7
3	Hebei	9873.0	300.0	145.7	2.2	189.3	22.4
4	Shanxi	13275.0	469.9	359.7	423.7	7.62	0.73
5	Inner-Monglia	5953.0	472	360	9.7	106.7	189.2
6	Shandong	12800.0	475.9	538.6	55.3	126.8	73.0
7	Henan	7691.9	128	233.9	0.01	13.8	4.6
8	Liaoning	7041.6	58.7	127.6	24.0	5.0	276.0

Oil includes gasoline, diesel oil, fuel oil, crude oil, and others excluding automobile usage. LPG: liquefied petroleum gas; SC: standard coal. Sources are from China Statistical Bureau (2004a).

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Table 3. Annual straw masses burned in the larger Huabei region in 2003.

No.	Administrative region	Wheat Straw (10^4 ton)	Corn Straw (10^4 ton)	Rice Straw (10^4 ton)	Cotton Straw (10^4 ton)	Oil Straw (10^4 ton)	Other Straw (10^4 ton)
1	Beijing	25.1	64.4	0.6	1.0	6.6	4.2
2	Tianjin	49.1	129.6	0	28.4	6.2	18.6
3	Hebei	1391.7	2147.2	25.6	156.6	326.2	151.6
4	Shanxi	349.7	953.9	23.9	27.5	72.7	143.2
5	Inner-Monglia	127.8	1777.4	44.8	0.78	217.8	131.1
6	Shandong	2137.8	2822.0	57.9	263.0	723.6	268.8
7	Henan	3131.6	1532.6	183.5	113.0	619.8	187.3
8	Liaoning	8.3	1861.0	208.7	1.0	122.8	204.0

Sources are from China Ministry of Agriculture/US Department of Energy Project Panel (1998) and China Statistical Bureau (2004a).

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Table 4. Numbers of motor vehicles in the larger Huabei region in 2003.

No.	Administrative region	Passenger Vehicles (10^4)				Goods Vehicles (10^4)				Motorcycles (10^4)	Tractors (10^4)
		Large	Middle	Small	Mini	Heavy	Middle	Light	Mini		
1	Beijing	3.24	10.59	106.73	20.84	3.04	6.89	16.39	0.53	27.68	3.11
2	Tianjin	1.38	2.97	22.78	11.11	3.45	3.88	11.57	1.68	36.39	5.34
3	Hebei	2.85	2.15	59.02	23.37	29.90	17.30	107.77	3.99	425.81	142.07
4	Shanxi	1.37	2.28	26.30	10.72	12.55	10.73	76.58	4.08	73.29	21.54
5	Inner-Monglia	1.27	1.84	19.67	5.87	10.91	9.18	50.20	0.97	87.41	54.11
6	Shandong	3.86	7.55	64.85	27.94	13.83	21.22	423.44	7.24	749.08	183.40
7	Henan	4.22	6.29	41.38	17.40	19.91	15.27	148.13	6.78	290.01	198.54
8	Liaoning	5.20	4.91	48.08	6.39	13.65	12.37	45.86	1.02	99.13	10.38

Buses are included in the middle passenger vehicles, and cars and taxi in the mini passenger vehicles. Trailers and farm transporters are included in the heavy and light goods vehicles, respectively. Sources are from China Statistical Bureau (2004a).

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Table 5. Emission factors for power generation, industrial and civil fuel combustion.

Fuel	SO_2	NO_x	VOC	CO	NH_3	PM_{10}	$PM_{2.5}$	EC	OC	Units
Power Generation										
Coal	8.46–16.56*	6.58	0.032[1]	2.48[2]	0	0.870	0.620	0.010[3]	0.250[3]	g kg^{-1}
Industrial Fuel										
Coal	10.0–15.38*	4.00	0.032[1]	15.0[2]	0	1.61	0.74	0.150[4]	0.500[4]	g kg^{-1}
Coke	19.0[1]	4.80[1]	0.032[1]	6.60[5]	0	0.288[5]	0.144[5]	0.030[4]	0.006[4]	g kg^{-1}
Gasoline	1.60	16.7[6]	0.087[1]	0.473[1]	0	0.250[5]	0.125[5]	0.026[4]	0.004[4]	g kg^{-1}
Diesel oil	2.24	9.62[6]	0.093[1]	0.780	0	0.310	0.310	0.026[4]	0.004[4]	g kg^{-1}
Fuel oil	2.24	5.84[6]	0.093[1]	0.780	0	0.310	0.310	0.040[4]	0.015[4]	g kg^{-1}
Crude oil	2.75	5.09[6]	0.093[1]	0.860	0	1.60	0.060	0.040[4]	0.015[4]	g kg^{-1}
Other oil	2.24	7.46[6]	0.093[1]	0.780	0	0.310	0.310	0.040[4]	0.015[4]	g kg^{-1}
Natural gas	0.180	1.76	0.285[1]	0.350	0	0.240	0.170	0	0	g m^{-3}
LPG	0.180	2.10	0.185[5]	0.420	0	0.220	0.150	0	0	g kg^{-1}
Coal Gas	0.080	0.800	0.243[1]	0.160	0	0.240	0.170	0	0	g m^{-3}
Civil Fuel										
Coal	8.62	1.88[6]	0.032[1]	52.3[2]	0	1.62	0.770	0.280[7]	0.470[8]	g kg^{-1}
LPG	0.180	2.10	0.088[5]	0.420	0	0.220	0.150	0	0	g kg^{-1}
Natural gas	0.180	1.76	0.088[5]	0.350	0	0.240	0.100	0	0	g m^{-3}
Coal gas	0.080	0.800	0.088[5]	0.160	0	0.240	0.170	0	0	g m^{-3}
Coal gas BS	0.008	0.800	0.088[5]	0.160	0	0.240	0.150	0	0	g m^{-3}

* The values are used for different regions. Sources are from Jiang and Tang (2002) except for [1] UK NAEI (2006b); [2] Wang et al. (2005a); [3] Reddy and Venkataraman (2002), [4] Bond et al. (2004), [5] US EPA (2006a), [6] Tian et al. (2001), [7] Cao (2005), and [8] Cooke et al. (1999).

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Table 6. Emission factors for industrial processing and other civil activities.

Activities	SO_2	NO_x	VOC	CO	NH_3	PM_{10}	$PM_{2.5}$	EC	OC	Units
Industrial Processing										
Fertilizer	0	0	0	0	5.00[9]	0.400[10]	0.040[10]	0.008[3]	0.016[3]	g kg^{-1}
Sulfuric acid	6.75[10]	0	0	0	0	0.375[10]	0.375[10]	0.008[3]	0.016[3]	g kg^{-1}
Amonia	3.00[10]	0.900[10]	0	0.030[10]	1.00[9]	0	0	0	0	g kg^{-1}
Cement	0.043	1.037	0.012[5]	22.9[2]	0	0.801	0.401	0.0813[3]	0.271[3]	g kg^{-1}
Sintering	0.850	0	0	22.0[2]	0	0.270	0.190	0	0	g kg^{-1}
Iron	0.070	0	0	40.5[2]	0	0.160	0.080	0.0162[3]	0.0541[3]	g kg^{-1}
Steel	2.53	0	0	46.1[2]	0	0.140[11]	0.130[11]	0.0264[3]	0.0878[3]	g kg^{-1}
Rolled steel	0.430	0	0	0	0	0.046	0.046	0	0	g kg^{-1}
Coke	0.910	1.23	0	6.66	0	1.45	1.20	0.600[12]	0.430[12]	g kg^{-1}
Crude oil	3.62[6]	0.560[6]	0.459[5]	0	0	0	0	0	0	g kg^{-1}
Paints	0	0	15.0[5]	0	0	0	0	0	0	g kg^{-1}
Vegetable oil	0	0	3.70[5]	0	0	0	0	0	0	g kg^{-1}
Other Civil Activities										
Central heating	10.0–15.38*	4.00	0.032[1]	15.0[2]	0	1.61	0.74	0.150[4]	0.500[4]	g kg^{-1}
Oil & paints	0	0	500	0	0	0	0	0	0	g kg^{-1}
Cooking	0	0	1.04	0	0	1.18	0.701	0	0	g kg^{-1}
Man	0	0	0	0	1.30[9]	0	0	0	0	kg yr^{-1}
Soil fertilization	0	0	0	0	0.291[9]	0	0	0	0	g g^{-1}
Traffic dust	0	0	0	0	0	0.784	0.332	0	0	g km^{-1}

Sources are the same as in Table 5 except for [9] Sun and Wang (1997), [10] UNEP (1996), [11] Zhang et al. (2006), and [12] Bond et al. (2004) and Streets et al. (2001).

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Table 7. Emission factors for crop straw burning (units: g kg^{-1}).

Crop Straw	SO_2	NO_x	VOC	CO	NH_3	PM_{10}	$PM_{2.5}$	EC	OC
Wheat	0.530[13]	1.29[13]	3.5[14]	61.1[14]	0	60.1[15]	30.05[15]	0.84[16]	3.02[16]
Corn	0.530[13]	1.29[13]	2.93[14]	40.3[14]	0	47.4[15]	23.7[15]	0.83[16]	2.01[16]
Rice	0.530[13]	1.29[13]	9.39[14]	48.7[14]	0	19.6[15]	9.80[15]	0.63[16]	1.07[16]
Cotton	0.630[13]	0.700[13]	0.141[14]	23.6[14]	0	20.0[17]	10.0[17]	0.82[7]	1.83[7]
Oil	0.530[13]	1.29[13]	8.49[14]	65.6[14]	0	25.2[18]	12.6[18]	1.00[20]	3.55[20]
Other	0.530[13]	1.29[13]	2.93[14]	40.3[14]	0	24.0[19]	12.0[19]	1.00[20]	3.55[20]

Sources are from [13] Tian et al. (2002), [14] Zhu (2004), [15] Zhu et al. (2005), [16] Cao (2005), Cooke et al. (1999), Jenkins et al. (1996), and Streets et al. (2001); [17] Fine et al. (2001), [18] Crutzen and Andreae (1990), [19] Seiler and Crutzen (1980), [20] Reddy and Venkataraman (2002), Streets et al. (2001), Jenkins et al. (1996), and Andreae and Merlet (2001).

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Table 8. VOC emission factors of oil depot.

Type	Breath Coefficient ($kg \cdot m^{-3}/yr$)	Working Loss ($g\,kg^{-1}$)	Submerged Discharge ($g\,kg^{-1}$)	Splashed Discharge ($g\,kg^{-1}$)	Discharge in Average ($g\,kg^{-1}$)
Gasoline	7.01	1.36	1.08	1.95	1.52
Disele Oil	Neglected	0.017	0.014	0.024	0.019

Sources are from Jiang and Tang (2002).

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Table 9. Ammonia emission factors of animals (units: $kg\,yr^{-1}$).

Animals	Cow	Horse	Pig	Sheep	Poultry
NH_3	21.0[21]	16.9[9]	5.0[21]	3.10[21]	0.250[21]

Sources are from [9] Sun and Wang (1997) and [21] Van Aardenne (2002).

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Table 10. Emission factors for motor vehicles (units: g km^{-1}).

Vehicles	SO_2	NO_x	VOC	CO	NH_3	PM_{10}	$PM_{2.5}$	EC	OC	Mileage (10^4 km yr^{-1})
Passenger Vehicles										
Large	1.20	21.0	4.28	13.7[22]	0	0.146	0.113	0.0243	0.0191	3.00
Middle	0.800	4.61	1.51	20.4[22]	0	0.140	0.110	0.0237	0.0186	2.80
Bus	1.20	10.0	1.51	5.00	0	4.34	4.15	0.891	0.702	6.57
Small	0.400	1.30	7.96	21.9[22]	0	0.0153	0.0119	0.006	0.004	2.00
Mini	0.400	1.30	7.96	21.9[22]	0	0.0153	0.0119	0.006	0.004	2.00
Taxi	0.096	0.843[23]	6.08	16.9[23]	0	0.0153	0.0119	0.006	0.004	9.32
Car	0.096	1.94[a]	6.08	39.8[24]	0	0.0153	0.0119	0.006	0.004	2.00
Goods Vehicles										
Heavy	1.00	20.0	4.28	10.0	0	4.82	4.61	0.99	0.78	3.00
Trailer	1.60	35.0	4.28	17.5	0	8.44	8.07	1.10	0.83	3.00
Middle	0.700	4.61[25]	1.51	20.4[22]	0	0.140	0.110	0.023	0.018	2.80
Light	0.600	2.75[22]	4.68	21.9[22]	0	0.0537	0.0417	0.021	0.016	2.00
Farm	0.120	2.75[22]	4.68	53.0	0	0.0537	0.0417	0.021	0.016	1.00
Mini	0.096	0.830	6.08	16.3[24]	0	0.0153	0.0119	0.006	0.004	1.50
Other Vehicles										
Motorcycles	0.032	0.100	5.25[22]	17.0	0	1.15	1.11	0.05	0.35	1.00
Tractors	0.700	4.00	1.51[22]	2.00	0	1.90	1.82	1.10	0.83	0.10

The emission factors of VOC are from Li et al. (2003), and the factors for EC and OC are from Cao (2005), Reddy and Venkataraman (2002), and Wang (2002). Mileage data are from Tang et al. (1999). The rest are from Jiang and Tang (2002) except for [22] Li et al. (2003), [23] Wang et al. (2002), [24] Yang et al. (2003), and [25] He et al. (1998).

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Table 11. Anthropogenic emissions by sector in the larger Huabei region in 2003 (units: 10^4 ton yr^{-1}).

Sectors	SO_2	NO_x	NMVOC	CO	NH_3	PM_{10}	$PM_{2.5}$	EC	OC
Power generation	115.6	51.4	3.51	19.4	0	6.79	4.84	0.077	1.93
Industrial enegery	578.0	187.0	3.29	593.4	0	64.9	30.5	6.29	19.0
Civil energy	97.4	28.0	0.519	355.0	0	15.8	7.49	3.17	5.13
Industril processing	142.0	75.7	6.37	1782.2	7.61	55.4	36.6	9.54	18.0
Straw burning	10.1	24.0	69.1	876.2	0	854.7	427.3	16.0	44.6
Oil and solvents	0	0	87.9	0	0	0	0	0	0
Manure	0	0	0	0	527.7	0	0	0	0
Traffic	13.4	161.2	210.9	1033.5	0	78.9	56.5	6.06	10.2
Total	955	527	382	4658	535	1074	562	41	99

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Table 12. Anthropogenic emissions by province in the larger Huabei region in 2003 (units: 10^4 ton yr^{-1}).

No.	Administrative region	SO_2	NO_x	NMVOC	CO	NH_3	PM_{10}	$PM_{2.5}$	EC	OC
1	Beijing	18.7	30.9	34.6	258.0	8.7	16.8	9.0	2.45	2.60
2	Tianjin	25.9	17.7	22.4	132.6	7.4	18.6	10.0	0.982	2.12
3	Hebei	162.2	109.2	75.7	1220.2	103.1	229.1	121.4	7.95	21.2
4	Shanxi	205.7	80.7	22.4	536.9	34.7	98.1	52.4	6.62	12.9
5	Inner-Monglia	60.8	33.1	21.9	266.7	49.3	94.6	49.0	2.93	6.99
6	Shandong	245.7	110.6	92.5	1008.9	134.3	268.4	138.7	8.41	24.1
7	Henan	133.5	87.4	64.3	694.8	147.3	228.4	119.5	7.48	18.8
8	Liaoning	102.8	57.4	48.6	540.4	50.8	120.3	62.1	4.39	10.3
	Total	955	527	382	4658	535	1074	562	41	99

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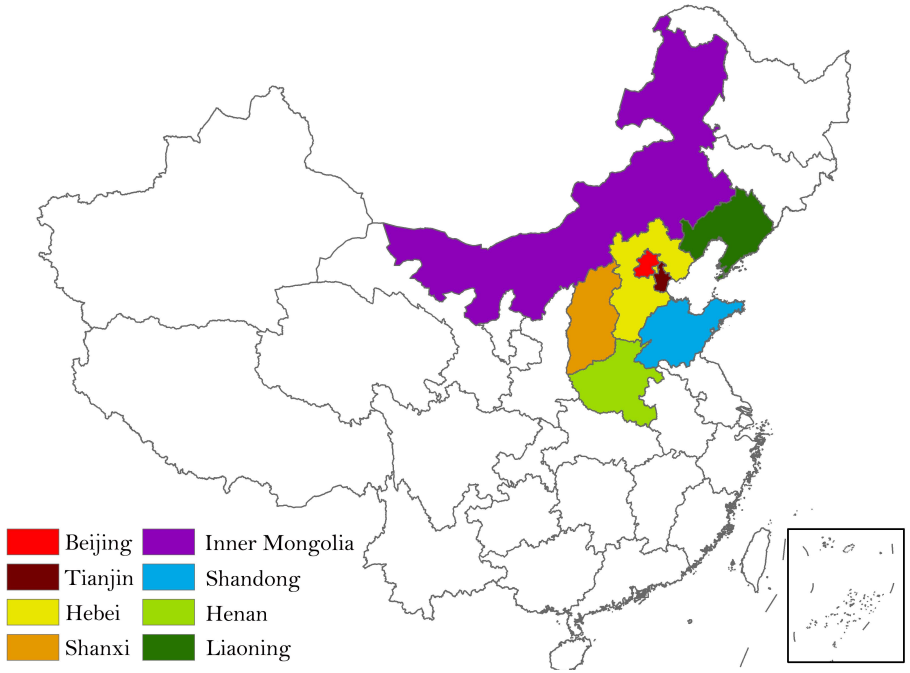

Fig. 1. The larger Huabei region (highlighted in colour) and its location in China.

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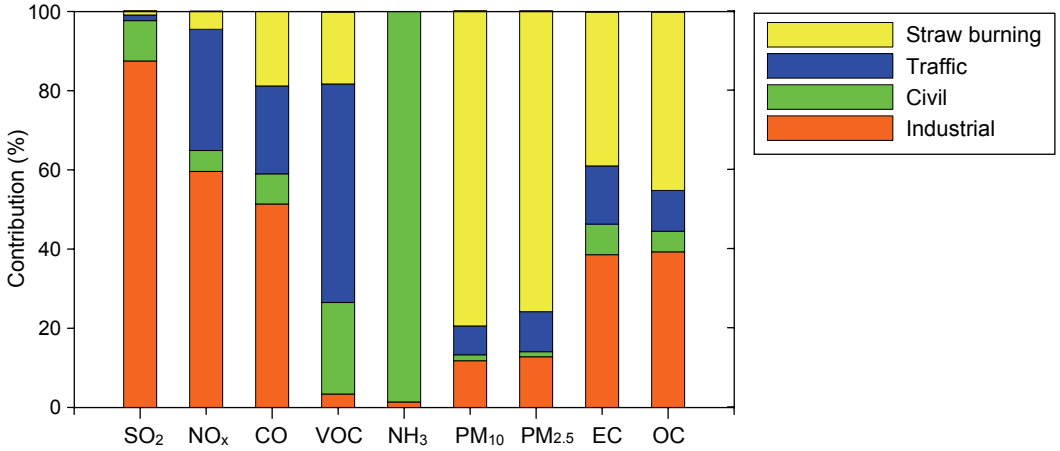

Fig. 2. Percent contributions from different sectors to the total emissions in the larger Huabei region for the year 2003.

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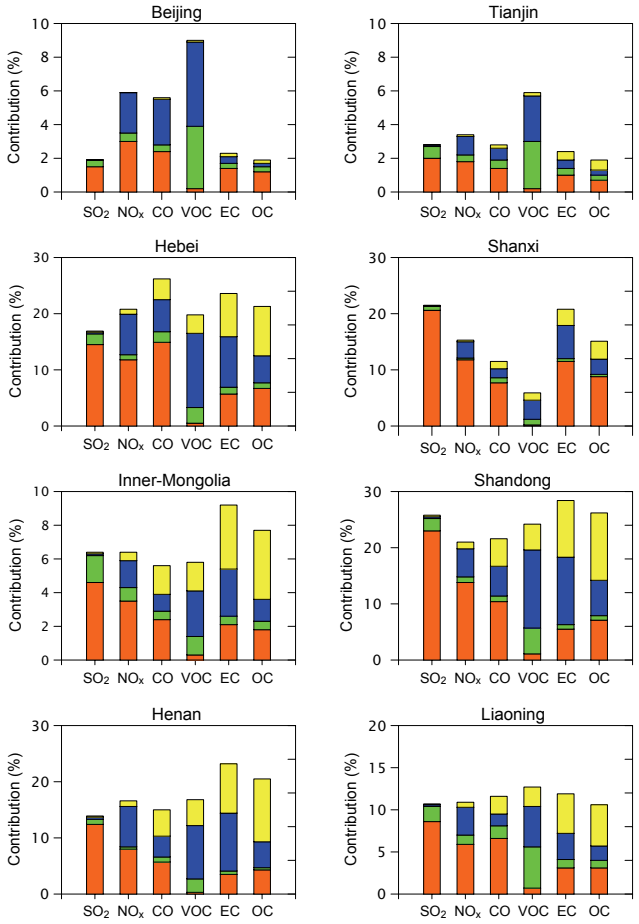

Fig. 3. Percent contributions from each province to the total emissions in the larger Huabei region for the year 2003. Different colours refer to the same sectors as indicated in Fig. 2.

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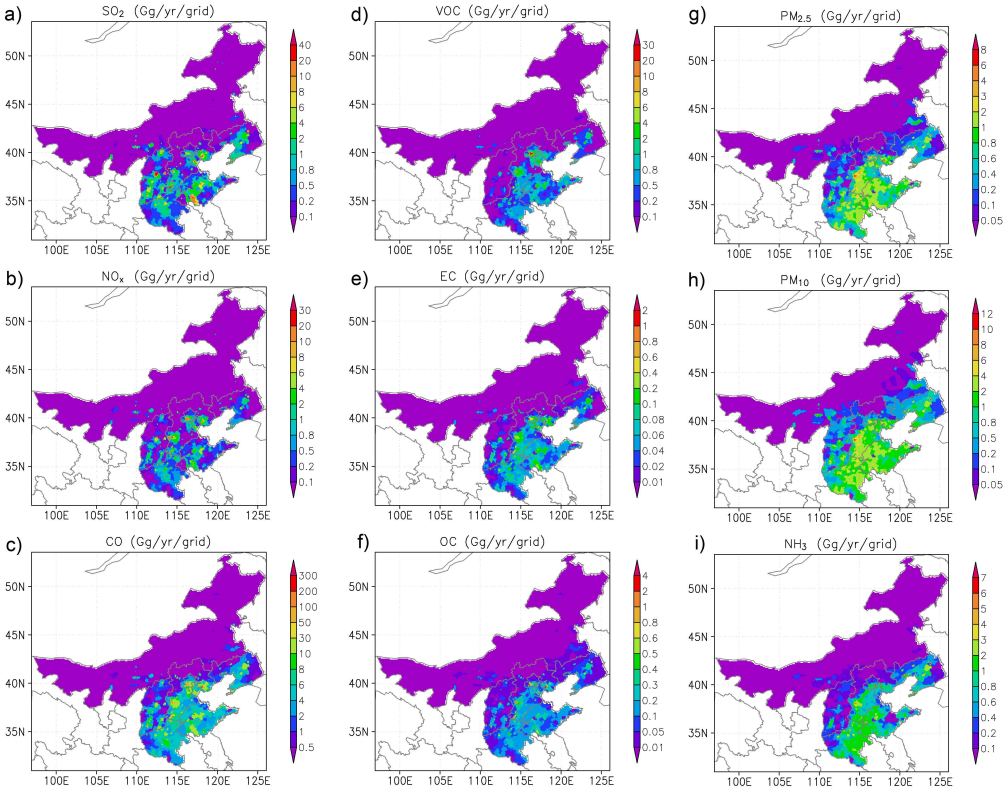

Fig. 4. Spatial distributions of anthropogenic emissions in the larger Huabei region for the year 2003. Units are Gg yr^{-1} per grid with a cell size of 0.1° latitude × 0.1° longitude.

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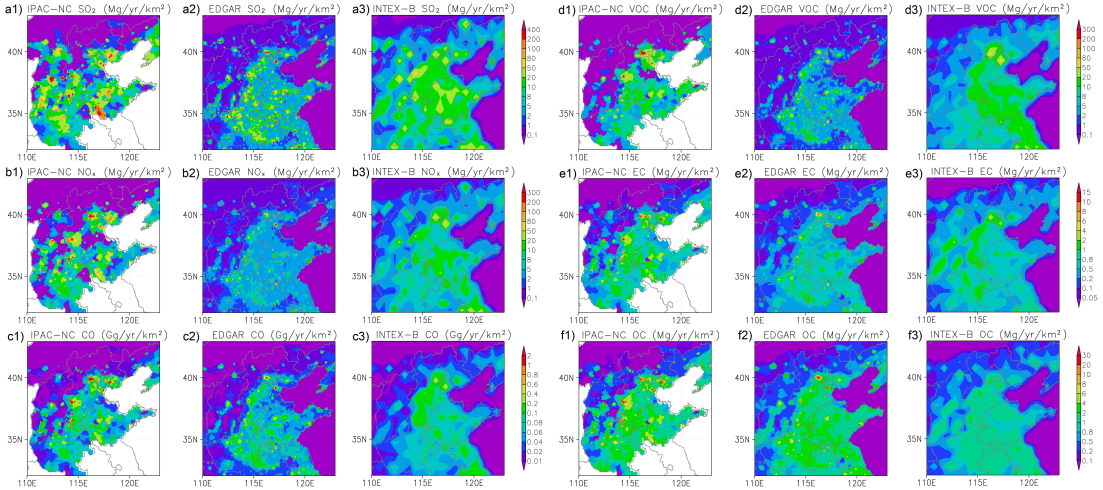

Fig. 5. Comparisons of the 2003 IPAC-NC inventory developed in this study with the 2005 EDGAR-CIRCE inventory and the 2006 INTEX-B inventory in respect of emission distributions in Huabei. Units are Mg yr^{-1} per square kilometre except for the CO emission rates, which have a unit of Gg yr^{-1} per square kilometre.

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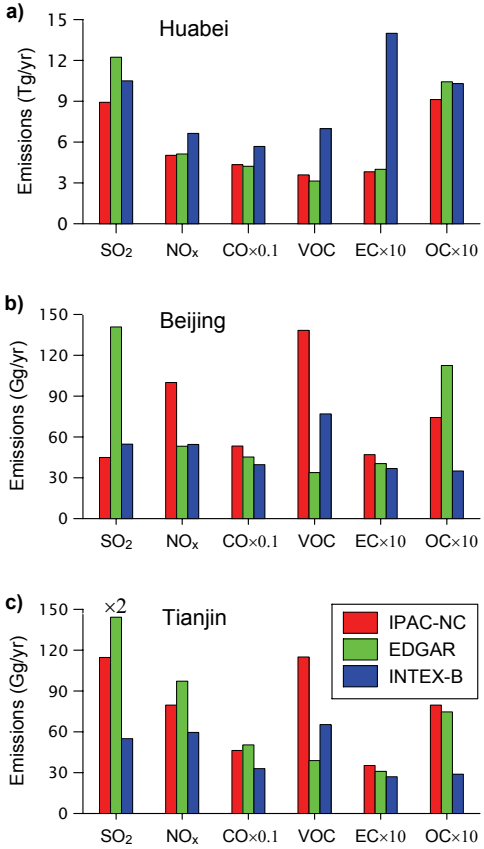

Fig. 6. Comparisons of the 2003 IPAC-NC inventory developed in this study with the 2005 EDGAR-CIRCE inventory and the 2006 INTEX-B inventory in respect of total emissions in the Huabei area **(a)**, the Beijing megacity area **(b)**, and the Tianjin megacity area **(c)**. See the text for detail description of the areas. Note that different scaling factors are used for CO, EC and OC in all the cases and for SO_2 in the EDGAR-CIRCE inventory for the Tianjin area.

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