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Hourly disaggregation of industrial CO_2 emissions from Shenzhen, China☆

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A B S T R A C T

Shenzhen's total industrial CO_2 emission was calculated using the IPCC recommended bottom-up approach and data obtained from the China High Resolution Emission Gridded Data (CHRED). Monthly product yield was then used as the proxy to disaggregate a facility's total emission into monthly emissions. Since a thermal power unit's emission changes with daily and hourly power loads, typical power load curves were used as the proxy to disaggregate the monthly emissions on a daily and hourly basis. The daily and hourly emissions of other facilities were calculated according to two specially designed models: the "weekdays + Spring Festival holidays" model for February and the "weekdays + weekends" model for non-February months. The uncertainty ranges associated with the process of the total amount calculation, monthly disaggregation, daily disaggregation and hourly disaggregation were quantitatively estimated. The total combined uncertainty of the hourly disaggregation of "weekdays + weekends" mode was ±26.19%, and that of the "weekdays + Spring Festival holidays" mode was ±33.06%. These temporal-disaggregation methods and uncertainty estimate approaches could also be used for the industrial air pollutant emission inventory and easily reproduced in the whole country.

1. Introduction

There are three important parts that should be considered in an emission inventory: the total-amount calculation of emissions, temporal disaggregation and spatial distribution (Saide et al., 2009). With the time and space emissions details, emission inventories could serve as the first important step for an air quality model by providing the essential input data, which is directly related to the accuracy of the simulated pollutant concentration and then further linked to the emission control measurement (Jiang et al., 2017; Liu et al., 2016; Shi et al., 2016).

Anthropogenic carbon dioxide (CO_2) emission is the largest net carbon flux to the atmosphere and a major contributor to radiative forcing (Gurney et al., 2012; Zhu and Yoshikawa-Inoue, 2015). 2006 IPCC Guidelines for National Greenhouse Gas Inventories provides approaches to estimate the total amount of CO_2 emissions (IPCC, 2006). With the aid of testing methods and modeling software, CO_2 emissions have been quantified down to the scale of road segment and single building on an hourly basis (Ryu et al., 2013; Gurney et al., 2012; Gately et al., 2017; Mattinen et al., 2014; Nejadkoorki et al., 2008; Zhou and Gurney, 2014). However, this quantification is more challenging for the industrial emission, which comprises up to 65% of the worldwide anthropogenic CO_2 emissions (IEA, 2006) and 84% of China's (NDRC, 2013). Various approaches to calculating the gross volume of the industrial emission—from simple to complicated, and general to precise—have reached maturity (Baldasano et al., 1999; Kennedy et al., 2010; Dodman, 2009; Larsen and Hertwich, 2010; Ramaswami et al., 2008). There have been some studies on the spatial distribution of the industrial CO_2 emission already (Xu, 2011; Cai and Zhang 2014). As for the temporal disaggregation, due to the great variety within industrial sectors and their differences in production seasons, an hourly disaggregation of the annual industrial CO_2 emission still presents a huge challenge in the absence of detailed temporal source profiles.

Recently, Kumar and Nagendra (2016) estimated the hourly CO_2 emission from a power plant, the only industrial source in Chennai

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city, according to the daily load curve profiles in different seasons. In the “Hestia project”, Gurney et al. (2012) have successfully disaggregated Indianapolis's industrial CO_2 emissions into each facility or industrial building on an hourly basis with not only the National Emission Inventory data but also direct CO_2 stack monitoring data of power plants, the building parcel data, and monthly, weekly, and daily profile data specific to source classification codes from the Environmental Protection Agency of United States.

If the emission inventories for air pollutants are referenced, there are some useful constraints: (1) when monthly emissions data are absent, monthly product yields for different sub-categories can be used as proxies for emission variations in the production cycles (Zheng et al., 2009), for example, the monthly patterns of coal-fired industrial boilers were obtained according to the monthly heat output and steam product yields (Xue et al., 2016); if there is no daily production data, it would be the most practical way to associate the emissions with working shifts and working hours (Friedrich et al., 2003). In this way, Sowden et al. (2008) delineated the emission profiles of weekdays and weekends from small industrial point sources in Cape Town when developing a high-resolution emission inventory of atmospheric reactive pollutants.

Another key challenge is the uncertainty estimate of the high-resolution emission inventory (Reis et al., 2008). The common approach is to compare with previous study results, or only provide the total-amount uncertainty analysis (Brondfield et al., 2012; Guevara et al., 2013; Xue et al., 2016). Only a few cases qualitatively analyzed the influence of temporal-spatial disaggregation on the uncertainty range (Sowden et al., 2008; Olivier et al., 1999). Andres et al. (2016) recently quantified the uncertainty of the gridded CO_2 emission map with the uncertainty combining all the individual uncertainties from the spatial and proxy input data. That provides a way to quantify the uncertainty ranges of temporal disaggregation of an emission inventory.

The First China Pollution Source Census conducted in 2007 is the most authoritative and thorough investigation of the national pollution sources. Taking Shenzhen as the study area, we quantified all of the on-site industrial CO_2 emissions in the city at the facility level, described the temporal characteristics of emissions on the monthly, daily and hourly basis, and quantified the uncertainty ranges related to the temporal disaggregation in the Monte Carlo simulation approach.

2. Methods

Shenzhen is a coastal city located in the south of Guangdong province and adjacent to the Hong Kong special administrative region. As the first special economic zone of China's reform and opening up policy, this city has been rapidly expanding with thousands of industrial facilities, making it an ideal research area.

Detailed industrial source activity data were obtained from the China High Resolution Emission Gridded Data (CHRED) based on the First China Pollution Source Census in 2007 and other auxiliary data (Supporting Information, Text 1). A total of 8082 manufacturing plants and 1827 CO_2 emissions facilities in Shenzhen were included (Supporting Information, Fig. 1). For each, the following information was provided: plant name, the industrial facilities, geographical location (latitude and longitude), annual production hours, raw materials and consumptions, fuel type and consumptions, and power consumption.

2.1. Calculation of total industrial emissions

The total industrial emission is composed of on-site direct CO_2 emissions from energy combustion and industrial processes. The bottom-up Tier 2 approach, recommended by the IPCC 2006, was used to calculate the CO_2 emissions from fossil fuel combustion (IPCC, 2006). The emissions from industrial processes were calculated following the four steps provided by Ummugulsum and Kadir (2014). The productions of glass, ceramics and steel were then selected according to industry type as well as the available activity data. The emission factors were derived from the Chinese Guidelines for Provincial Greenhouse Gas Inventories (NDRC, 2011) and activity data from CHRED. Then Shenzhen's total industrial CO_2 emission in 2007 could be calculated by aggregating all of these facilities' emissions together:

$$E_a = \sum_i E_a(i), E_a(i) = EF_i \times A_i$$

where E_a is the total industrial CO_2 emissions in Shenzhen (2007); $E_a(i)$ is the annual emissions from facility i in 2007; and EF_i and A_i are the emissions factor and activity data of facility i.

Emissions from different industrial sectors, fuel types, and industrial processes can also be calculated accordingly.

2.2. Monthly disaggregation

A total of 305 sector-based monthly product yields in the year of 2007 were collected from the Bureau of Statistics of Shenzhen. They were used as the proxy to disaggregate the annual industrial CO_2 emissions of each emission facility into monthly emissions. Then, Shenzhen's monthly industrial CO_2 emissions could be obtained by aggregating all of these facilities' emissions together month by month:

$$E_m = \sum_i E_m(i), E_m(i) = w_m(i) \times E_a(i), w_m(i) = \frac{p_m(i)}{\sum_m^{12} p_m(i)}$$

where E_m is the monthly industrialCO_2 emissions in Shenzhen (2007), $m = 1, 2 \ldots 12$; $E_m(i)$ is the monthly emissions from facility i in 2007; $w_m(i)$ is the monthly emissions weight of facility i; and p_m is the sector-based monthly product yield of facility i.

2.3. Daily and hourly disaggregation

The monthly emissions would be disaggregated into daily and hourly emissions according to the facility's assumed hourly emissions intensity. A thermal power unit's emissions change with daily and hourly power loads; therefore, the typical power load curves were used as a proxy to disaggregate the monthly emissions on a daily and hourly basis. As for a facility running 24 h a day for most of the year (e.g., blast furnace), the hourly emissions intensity was assumed constant over the whole month. Other facilities' daily and hourly emissions were calculated according to working times and working shifts, assuming that their hourly emissions intensities remained constant throughout the year. An anomaly arose during the Spring Festival period. This important national holiday in China always exerts an enormous influence on citizens' daily lives and industrial production, therefore the “weekdays + Spring Festival holidays” model was designed to disaggregate a facility's emissions during this period.

2.3.1. Thermal power plants

The power plants in Shenzhen can be categorized into three major types: thermal, nuclear, and waste incineration power (Wang et al., 2013). Their generated energy is disbursed throughout the power grid according to efficient and accurate prediction of power loads (Huang, 2006). Except for the nuclear power serving as a base