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Atmospheric emission inventory of multiple pollutants from civil aviation in China: Temporal trend, spatial distribution characteristics and emission features analysis

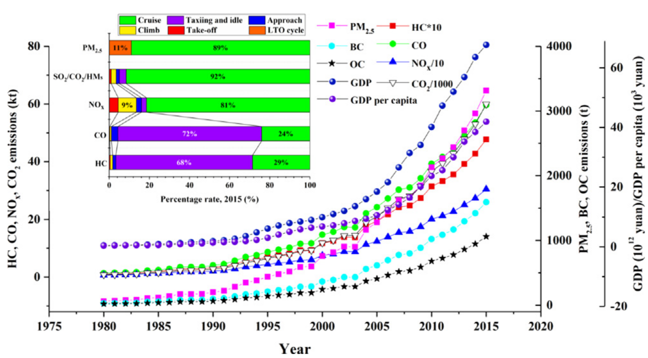
Huanjia Liu [a,b], Hezhong Tian [a,b,*], Yan Hao [a,b], Shuhan Liu [a,b], Xiangyang Liu [a,b], Chuanyong Zhu [b,c], Yiming Wu [a,b], Wei Liu [a,b], Xiaoxuan Bai [a,b], Bobo Wu [a,b]

[a] *State Key Joint Laboratory of Environmental Simulation & Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China*
[b] *Center for Atmospheric Environmental Studies, Beijing Normal University, Beijing 100875, China*
[c] *School of Environmental Science and Engineering, Qilu University of Technology, Jinan 250353, China*

HIGHLIGHTS

- A dedicated multi-pollutants emission inventory from China's civil aviation is established.
- Temporal trend of multi-pollutants emission for historical period 1980–2015 is investigated.
- Spatial distribution characteristics by varied airports and airlines are presented.
- Multi-pollutants emissions features of LTO and cruise operation modes are analyzed.
- Pollution from aviation can't be ignored due to rapid growth in aviation activities.

GRAPHICAL ABSTRACT



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ABSTRACT

A detailed comprehensive emission inventory of multiple air pollutants from civil aviation in China for the historical period of 1980–2015 is developed by using an approach of combining bottom-up with top-down for the first time. Annual emissions of various pollutants present a rapidly ascending trend along with the increase of economic volume and population, which are estimated at approximately 4.77 kt HC, 59.63 kt CO, 304.77 kt NO_x, 59,961 kt CO_2, 19.04 kt SO_2, 3.32 kt $PM_{2.5}$, 1.59 kt BC, 1.06 kt OC and 5.44 t heavy metals (HMs), respectively, by the year 2015. We estimate the local emissions in 208 domestic civil airports and allocate the total cruise emissions onto 299 main domestic flight segments with surrogate indexes, such as route distance, cargo and passenger turnover. The results demonstrate that emission intensities in central and eastern China are much higher than those in northeastern and western China, and these regions are characterized with high population density, huge economy volume, as well as transit convenience. Furthermore, we have explored emission characteristics of multiple pollutants under different operation modes in 2015. For $PM_{2.5}$, SO_2/CO_2/HMs and NO_x, the emissions from cruise process constitute the dominant contributor with a share of 89%, 92% and 81%, of the associated total emissions, respectively, comparing with 76% and 71% of the total CO and HC emissions release from Landing and Take-off (LTO) process. Consequently, there are notably different emission characteristics from different flight processes due to various combustion status of aviation fuel. In addition, we predict the future trends of multi-pollutants emissions from China's civil aviation industry through 2050 under three scenarios, and the results

* Corresponding author at: Center for Atmospheric Environmental Studies, Beijing Normal University, Beijing 100875, China.
E-mail address: hztian@bnu.edu.cn (H. Tian).

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indicate that the reduction from the improvement of new technology or new national standards would be largely offset by the rise in multi-pollutants emissions from rapidly aviation fuel growth.

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1. Introduction

Along with the rapid economic development since the implementation of opening and reforms and globalization process, China has become the secondary largest aviation transportation market in the world, followed with the United States since 2005. Total volume of transport turnover (including cargo and passenger turnover) of China's civil aviation industry is reported to be 55.9 billion ton-km in 2015, increased by 201 times over 1980 (CAAC, 2016a). Therein, the passenger turnover volume exceeds 556.6 billion capita-km, increased by 197 times compared with that in 1980 (CAAC, 2016a). The growth rate is far more than that of national GDP and other transportation modes, and the increase in aviation industry is forecasted to continue in the foreseeable future (Chen et al., 2017). Though civil aviation industry brings more convenience for human beings travelling, its growth is related to increased negative effects on environment and human health due to large amounts of aviation fuels combustion. Because it releases various hazardous air pollutants and greenhouse gases including carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), a large volume of hydrocarbons (HC), fine particles containing organic and inorganic components, as well as carbon dioxide (CO_2) (Harrison et al., 2015; Lund et al., 2017; Meleo et al., 2016). Previous studies find that emissions from aircraft are related to ozone (O_3) depletion in stratosphere and contribute 3.5–4.9% of anthropogenic radiative forcing as aircrafts often operate in upper troposphere and lower stratosphere (Dessens et al., 2014; Lee et al., 2009). Moreover, about 8000 premature mortalities per year around the world are relevant with aircraft activities evaluated by combining with GEOs-chem model (Barrett et al., 2010; Voigt et al., 2012). Furthermore, the International Civil Aviation Organization (ICAO) predicts the total greenhouse gases emissions from aviation industry increase by 400–600% in 2050 compared with that in 2010 (ICAO, 2014). Consequently, risks to local air quality, climate change and human health effects imposed by emissions of multiple atmospheric pollutants from aviation industry capture extensive concerns around the world, especially in China.

China, especially North China Plain region, has been frequently suffering from severe haze problems in autumn and winter during the past years (Han et al., 2017; Liu et al., 2017; Ma et al., 2017; Sun et al., 2013; Yang et al., 2016), causing regional joint prevention and control of atmospheric pollution has been a routine control policy and practice for China. More and more pollutants discharge reduction measures are implemented in order to alleviate extent of severe haze. However, most control measures are performed on the major sources such as power plants, iron and steel smelting, cement plants and residential coal burning. Little attention has been paid to atmospheric pollutants emitted from civil aviation, though their regional contributions are evident and cannot be ignored.

An integrated aviation emission calculation can be divided into two processes: the LTO (Landing and Take-off) process and high altitude cruise stage. Therein, the emissions from LTO cycle mainly affects airport ground-level atmospheric conditions while cruise process can influence regional air quality and even global climate change. ICAO defines four work modes of the standard airplane LTO cycle: approach, taxiing, take-off, and climb process. The emissions of airports include four operation processed emissions from land surface to the top of atmospheric boundary layer at 915 m (ICAO, 2014). The aviation engine emission database is developed by ICAO according to measurement data under different thrust conditions from aircraft engine manufactures, which can provide pollutants emission factors of HC, CO and NO_x, and is used to calculated LTO cycle emissions (Fan et al., 2012; Pejovic et al., 2008; Xia et al., 2008; Xu et al., 2016). Researchers established the aircraft emission inventory for Beijing Capital International Airport by improved LTO cycle, including NO_x, CO, HC, SO_2 and $PM_{2.5}$ as well as other domestic airports (Chen, 2013; Xia et al., 2008; Xu et al., 2016). Whereas, cruise process is the dominant contributor of pollutants during the whole flight compared with LTO cycle (Wilkerson et al., 2010), thus establishing emission inventory from this process is of great significance for examining the effects of aircraft on atmospheric composition and climate to regional or worldwide air quality. Gardner et al. (1997) developed a three dimensional (latitude, longitude, and altitude) global aviation emissions inventory for NO_x with a resolution of $2.8° \times 2.8°$ by 1 km in altitude, demonstrated that 60% of NO_x the global was emitted at cruise altitude of 10–12 km and Northern Hemisphere accounted for 93% of global emissions. Although some regional aviation emission inventory has been developed, comprehensive emission inventories of multiple air pollutants from aviation industry for mainland China are not publicly published so far. Thus, developing an integrated emission inventory of China's aviation industry which covers various pollutants (including conventional air pollutants, greenhouse gas and heavy metals) and accounts for airport's LTO cycle and cruise process between airports is quite essential.

In this paper, based on refined information on airports' flight schedule, civil aviation aircraft/engine comparison list, revised pollutants emission factors from ICAO database under cruise conditions, we calculate and analyze the spatial distribution characteristics of typical air pollutants (HC, CO, NO_x, CO_2, SO_2, $PM_{2.5}$ and heavy metals) emitted from civil aviation industry of China including LTO cycle and cruise process for the year 2015. Furthermore, we investigate and present the historical temporal of pollutants emission for aviation industry from 1980 to 2015, and predict the future emission trends until 2050 with scenario analysis.

2. Methodologies and data sources

2.1. Targeted pollutant species, domain and time period

In this work, we have made efforts to establish an integrated aircraft emission inventory of multiple pollutants (HC, CO, NO_x, CO_2, SO_2, $PM_{2.5}$, BC, OC, and heavy metals (including As, Cu, Ni, Se, Cr, Cd, Hg, Pb, Zn)) of 208 civil airports and 299 main domestic flight segments in mainland China for the base year of 2015. Furthermore, we analyze the historical temporal variations of pollutants emissions from 1980 to 2015 and predict the future trends till 2050 under different scenarios.

2.2. Data sources and quality assurance/quality control

(1) Flight schedules dataset

The flight schedules are used to calculate the airports' LTO cycle emissions, which are obtained from Civil Aviation Administration of China (CAAC) and main airports' official website. The data needed to collect including airline name, aircraft type, flight number, departure time and place, destination and time, etc. We take great cares to check and compile the collected datasets so as to avoid the omission or double counting flight information during the calculation.

(2) Aircraft/engine matching

Boeing and Airbus planes are the main airplane types of China civil airplanes, whereas, many different types of engines, which are

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