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Air pollutant emissions from aircraft landing and take-off cycles at Chinese airports

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ABSTRACT

Research on flight emissions at airports is very important for environmental policymaking. This study analysed the trend of aircraft air pollutant emissions at mainland China airports from 1990 to 2017, mainly focusing on standard landing and take-off (LTO) cycles. Total flight movements increased 29-fold from 1990 to 2017 at Chinese airports. Over the same period, the emissions of NO_x, SO_x, CO, hydrocarbons (HC), and particulate matter (PM) increased 46, 27, 12, 5, and 4 times, respectively. Emissions at the 216 public airports showed a growth trend. It was estimated that in 2017, Chinese airports emitted 12,875 kilotons of CO_2, 59 kilotons of NO_x, 3 kilotons of SO_x, 38 kilotons of CO, 5 kilotons of HC, and 0.4 kilotons of PM. The largest 30 airports produced 68.2% of the total emissions. Emissions from B737-800, A320, A321, B737-700, A330-300, and A319 aircraft accounted for more than 75% of aircraft LTO emissions at Chinese airports in 2017. Results show that average emissions per passenger have decreased for CO_2, CO, HC, SO_x, PM, and NO_x from 1990 to 2017.

Keywords: Aircraft; LTO; Pollutant emissions; Airport; Mainland China

NOMENCLATURE

E_p	annual emissions of pollutant p
P	the type of pollutant
Fi	the annual movement of aircraft type i
i	the type of aircraft
m	the aircraft operation mode
N	the number of specific aircraft type

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T_m	the operating time in mode
$AR_{i,m}$	the engine fuel flow factor of aircraft type i at mode m
$EI_{i,m,p}$	the emission index for pollutant p of aircraft type i at operation mode m
SN	the exhaust smoke of the engine
AFR	the air/fuel ratio
δ	the ratio of $EI_{PMvol\text{-}o}$ and EI_{HC}
$EI_{PMvol\text{-}o}$	the emission index of nonvolatile particulate matter
EI_{HC}	the emission index of HC
FSC	the fuel sulphur content
ε	the sulfur conversion rate

1.0 INTRODUCTION

Aircraft pollution emissions and their environmental impacts have become hot topics in recent years[(1)]. Pollutants generated by aircraft activities are harmful to the environment and human health. The main pollutants emitted by airplanes include NO_x, CO, CO_2, SO_x, hydrocarbons (HC), and particulate matter (PM)[(2)]. Of these, CO_2 makes up the vast majority of greenhouse gas emissions from the sector, while NO_x, SO_x, HC, and PM may cause serious damage to the environment and human health[(3,4)].

Research has shown that aircraft movements have small impact on overall global environmental air quality[(5,6)]. However, the influence of airports on regional air quality cannot be ignored[(7)]. According to figures published by the United States Environmental Protection Agency, NO_x emissions from aircraft engines account for 2% of the total NO_x generated by mobile sources in the USA, and the proportion reaches 4% at some airports[(8)]. With the rapid development of aviation in China, flight movements of China's civil aviation have grown by 13.3% annually from 1990 to 2017[(9)], leading to increased emissions of pollutants. This situation will require increased attention considering the predicted future growth of Chinese civil aviation.

Some studies on airport pollution emissions have been carried out recently. Calculations of aircraft emissions at Beijing Capital International Airport were analysed based on data from the Aircraft Meteorological Data Relay program for aircraft, in various modes of landing and take-off (LTO) cycles[(10)]. Emission inventory and spread of pollutants were also analysed for Chengdu Shuangliu International Airport[(11)]. However, these studies in China only investigated individual airports or a limited number of airports. Some studies on aircraft emissions at airports have been conducted in other countries. Emissions of aircraft at Greek airports were modeled with EMEP/CORINAIR Atmospheric Emission Inventory Guidebook[(1)]. Emissions of aircraft at Turkish airports were analysed in 2005. An emissions inventory of 95% of UK airports was formed in 2011[(12)]. A similar study in Korea was carried out in 2012[(13)].

To estimate the total NO_x, CO, CO_2, SO_x, HC, and PM emissions of aircraft in China, a comprehensive study of all 216 public transport airports in China in 2016 was conducted.

2.0 MATERIALS AND METHODS

2.1 Method

In this study, a calculation model was established to estimate the aircraft pollution emissions during LTO stages[14,15], as shown by Equation (1):

$$E_p = \sum_{i=1}^{N} \left(F_i \times \sum_m AR_{i,m} \times T_m \times EI_{i,m,p} \right) \qquad \ldots (1)$$

where E_p is the annual emissions [kg year^{-1}] of pollutant p; N is the number of specific aircraft type (i.e., B737, A320, etc.); F_i is the annual movement [LTO year^{-1}] of aircraft type i; m is the aircraft operation mode, such as approach, landing, taxi-in, taxi-out, take-off, climb-out; T_m is operating time in mode m (min); p is the type of pollutant (i.e. NO_x, CO_2, CO, SO_x, PM, HC), and HC refers to total of hydrocarbon compounds of all classes and molecular weights contained in a gas sample, including methane; $AR_{i,m}$ is the engine fuel flow factor [kg min^{-1}] of aircraft type i at mode m; $EI_{i,m,p}$ is the emission index for pollutant p of aircraft type i at operation mode m.

The International Civil Aviation Organization (ICAO) has developed an engine emissions database and provides HC, CO, and NO_x emission indices, but does not include an index for PM emissions. Therefore, ICAO established the FOA3.0 (first-order approximation) method to calculate PM emissions using the reported Smoke Number. This method calculates the volatile and nonvolatile component particles separately to obtain a more accurate aircraft engine PM emission index. While SO_x is also emitted by aircraft engines, its emission level depends on the composition of the aviation kerosene, and the value of its emission index is independent of aircraft engine performance[16–18].

The emission index of nonvolatile particulate matter (EI_{PMnvol}) can be calculated according to Equation (2):

$$EI_{PMnvol} = 0.054 \times (SN)^{1.234} \times (AFR) + 0.877 \qquad \ldots (2)$$

where SN refers to the exhaust smoke of the engine; AFR is the air/fuel ratio.

The emission index of volatile organic particulate matter ($EI_{PMvol\text{-}o}$) can be calculated according to Equation (3):

$$EI_{PMvol-o} = \delta \times EI_{HC} \qquad \ldots (3)$$

where δ is the ratio of $EI_{PMvol\text{-}o}$ and EI_{HC} for specific engines in the FOA3.0 test (mg/kg); EI_{HC} is the emission index of HC (g/kg).

The emission index of SO_x can be calculated according to Equation (4):

$$EI_{SOx} = \frac{SO_x}{S} \times FSC \times \varepsilon \qquad \ldots (4)$$

where FSC is Fuel Sulphur Content. The default value of FSC is 0.068%, which is based on the international average of actual measurements of aviation kerosene. However, because of stricter oil quality airworthiness validation requirements and higher control standards, the

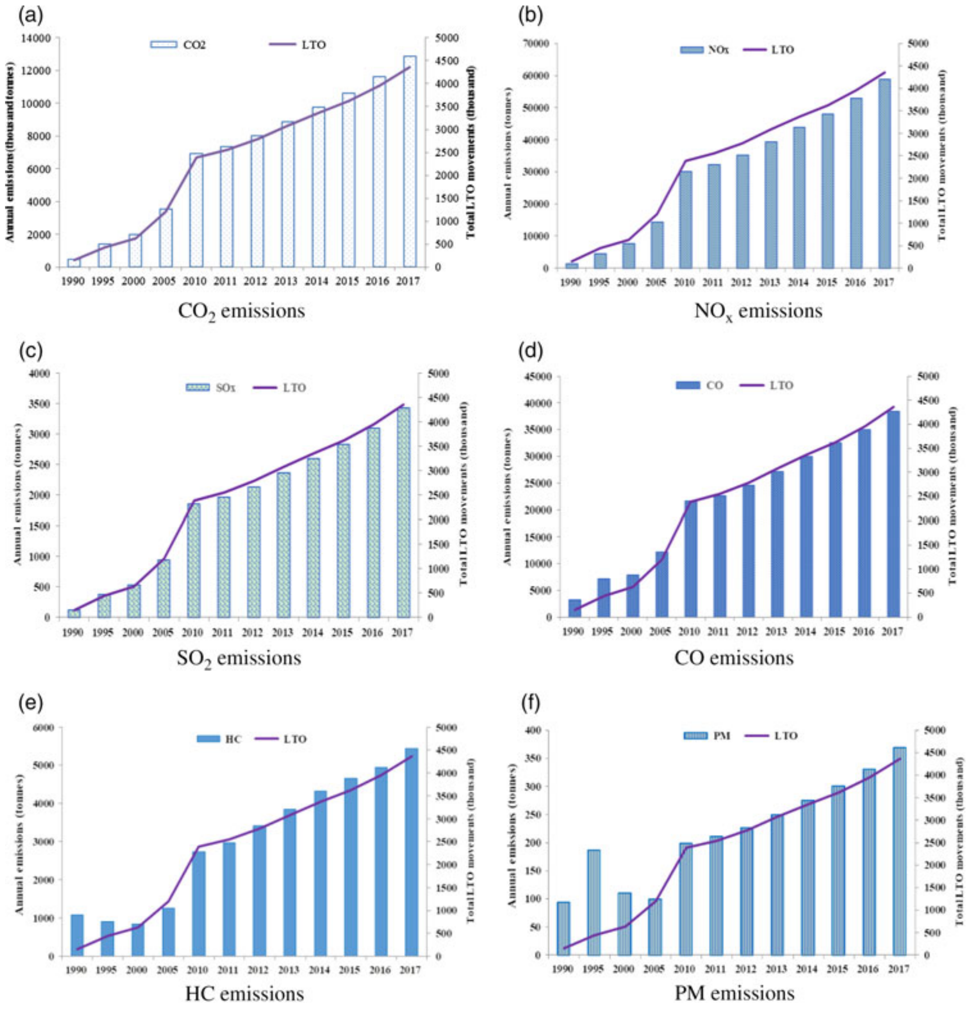

Figure 1. Aircraft emissions at mainland China airports during period of 1990 to 2017.

average sulfur content of Chinese aviation kerosene is 0.02%. ε is the sulfur conversion rate, if all sulfur is converted to SO_x, ε equals 1, which was assumed for the analysis in this study.

2.2 Data sources

Flight data for Chinese airports for the period of 1990 to 2017 were obtained from the Civil Aviation Administration of China [9], including the type and number of different aircraft. Chinese airports in this study are mainland China airports and don't include airports and flights from Hong Kong, Macao, and Taiwan. In mainland China, 216 civil aviation airports were in operation in 2016 and 228 airports were in operation in 2017.

Fuel rates and pollutant emission factors of aircraft engines were obtained for each aircraft type from the ICAO Aircraft Engine Emissions Databank[13,14] and the EMEP/EEA guidebook[19–21]. The individual airport emission inventory for 2016 was developed based

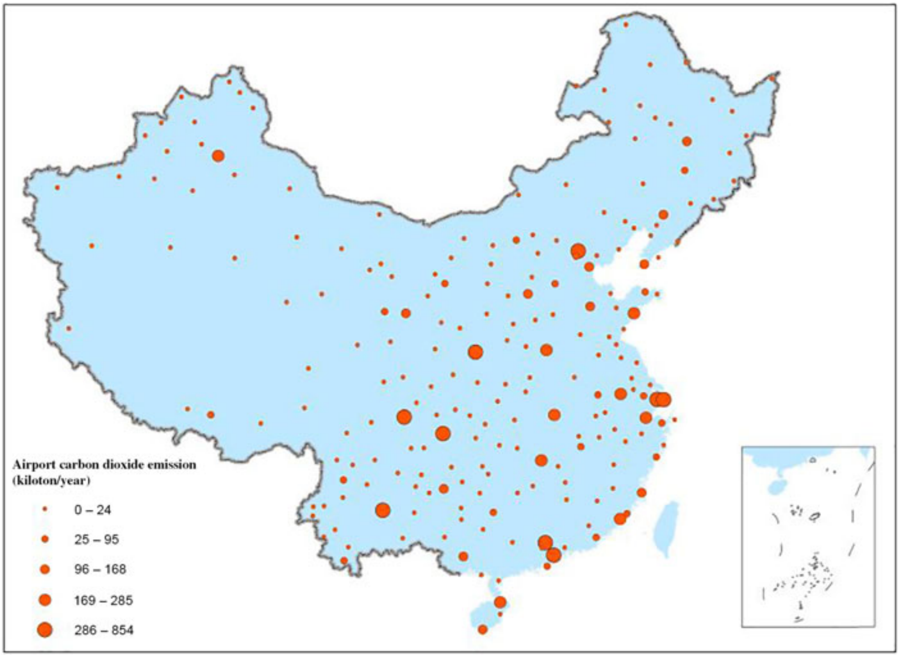

Figure 2. CO_2 emissions from aircraft LTOs at mainland China airports in 2016.

on schedule information from the International Air Transport Association (IATA) Airport Intelligence Services (AIS)[22], which provided detailed flight information for all of the 216 public transport airports in mainland China.

3.0 RESULTS

3.1 Aircraft emissions inventory for Chinese airports

Air traffic emissions for the years 1990 to 2017 at airports in mainland China are shown in Fig. 1. Results show that CO_2 emissions from aircraft LTOs increased 29-fold from 1990 to 2017. Over the same time period, the emissions of NO_x, SO_x, CO, HC, and PM increased by 46, 27, 12, 5, and 4 times, respectively. It was estimated that in 2017, Chinese airports emitted 12,875 kilotons of CO_2, 59 kilotons of NO_x, 3 kilotons of SO_x, 38 kilotons of CO, 5 kilotons of HC, and 0.4 kilotons of PM.

In terms of China's overall emissions, emissions from aircraft LTOs at airports are relatively small. Data show that emissions of CO_2, NO_x, SO_x, and PM from aircraft at airports accounted for 0.12%, 0.44%, 0.03%, and 0.01%, respectively, of each total emission in China in 2017. It is obvious that aviation is a minor contributor to overall emissions.

3.2 Emissions at top 30 airports in China

Aircraft emissions at 216 airports in mainland China were explicitly modeled in 2016. In general, each airport differs greatly in aircraft LTO emissions. Figure 2 shows that larger airports usually have more emissions.

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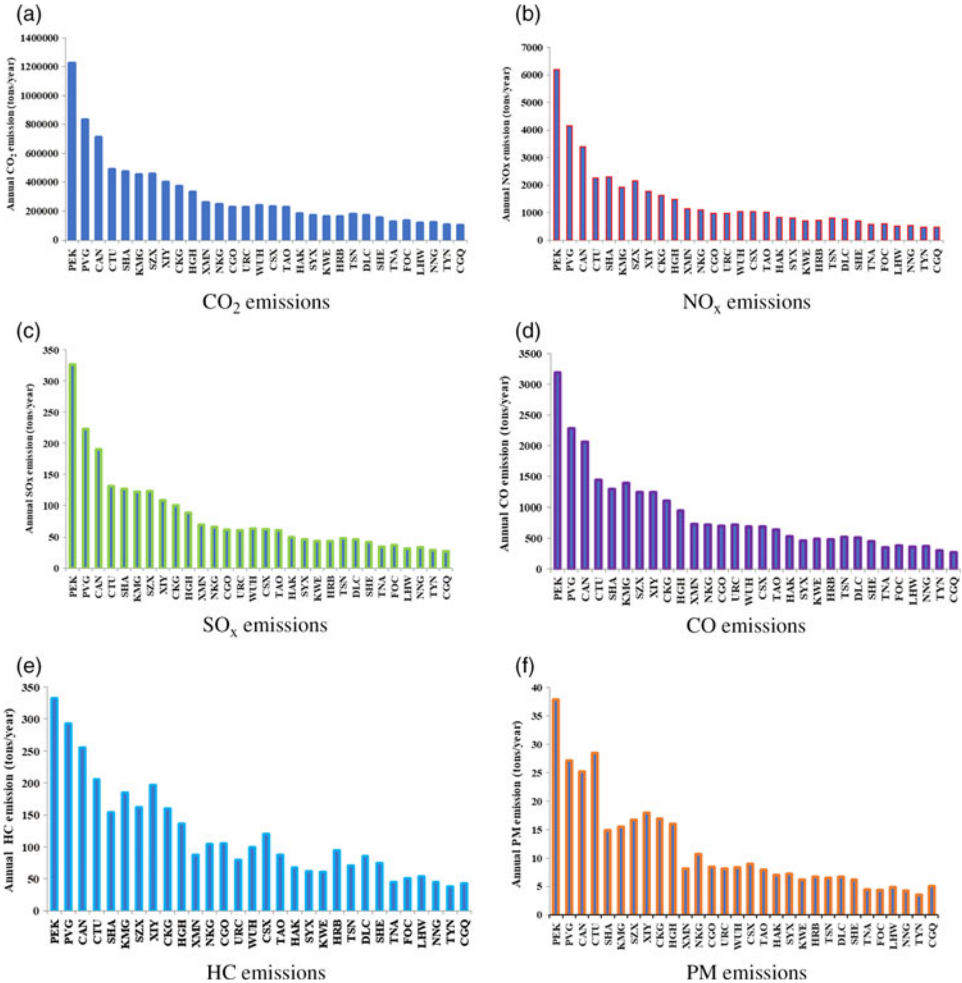

Figure 3. Air pollutant emissions for top 30 airports from aircraft LTOs in China in 2016.

Figure 3 shows the air pollutant emissions for the top 30 busiest airports from aircraft LTOs in 2016. Beijing Capital Airport had the highest emissions, followed by the Shanghai Pudong and Guangdong Baiyun Airports. The contributions of CO_2 and NO_x emissions from the top 30 busiest airports for all 216 Chinese airports were around 80%, while the contributions of CO, HC, and PM emissions from the top 30 busiest airports were slightly lower than 80%, as shown in Fig. 4.

There were some noticeable differences in the contributions to emissions, aircraft LTOs, and passengers for different airports in China. For example, the percentages of total air traffic for the top three airports, Beijing Capital (PEK), Shanghai Pudong (PVG), and Guangzhou Baiyun (CAN) International Airport, were 6.6%, 5.2%, and 4.7%, respectively. However, the contributions of CO_2 emissions from PEK, PVG, and CAN were 10.6%, 7.2%, and 6.2% of the total, respectively, as shown in Fig. 5. The other airports showed small differences in their contributions. Pollution emissions per LTO and per passenger varied from airport to airport, as shown in Fig. 6 PEK was the highest, followed by PVG and CAN. Multiple factors have led

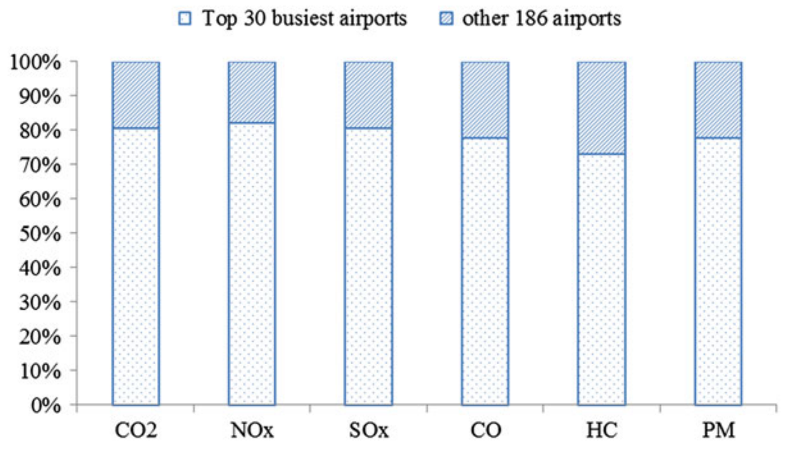

Figure 4. Proportion of aircraft LTO emissions for top 30 airports in China in 2016.

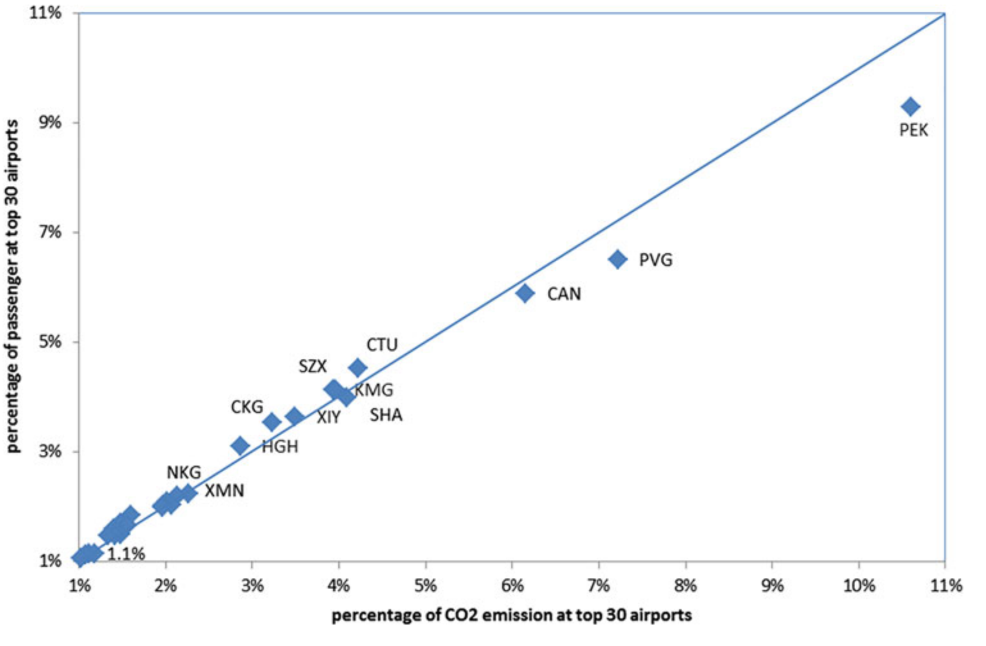

Figure 5. Proportion of passenger throughput vs proportion of CO_2 emission for top 30 airports in China in 2016 (points that fall below the 45° line are considered to be weak performers, such as PEK, PVG, and CAN).

to this result. First, the aircraft flying from PEK, PVG, and CAN were predominantly larger with a higher proportion of international flights. These aircraft would have comparatively higher take-off weights hence higher LTO take-off emissions. Second, PEK, CAN, and PVG have significantly longer taxi times than other airports, which would lead to increased LTO emissions.

Large amounts of pollutants are discharged because of aircraft ground taxiing at airports[23], and taxiing takes longer at the busiest airports, as shown in Table 1. This means

Table 1
Minutes taken to taxi-out at China's busiest airports in 2016 and 2018

Airport	PEK	CAN	PVG	CTU	KMG	SZX	SHA	XIY	CKG	HGH
Taxi-out time in 2016	30.5	22.9	27.0	18.2	21.4	18.8	21.5	17.7	16.3	20.0
Taxi-out time in 2018	21.6	17.7	19.8	17.7	13.8	16.4	15.5	16.9	13.9	17.6

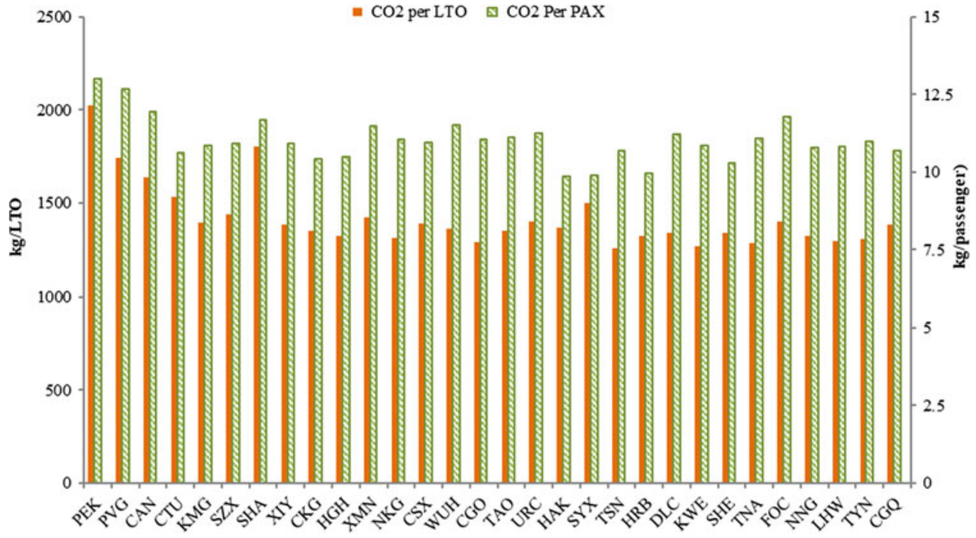

Figure 6. Total CO_2 emissions per LTO and per passenger (PAX) for top 30 airports in 2016.

that decreasing taxiing time will greatly reduce pollution emissions. Research shows that a 1-min decrease in taxiing time can lead to a 6% reduction in taxiing emissions for ICAO default taxiing time[20]. Calculations also show that emissions reductions are related to the airport's current taxiing time. For example, a 1-min reduction at PEK will have less impact than at airports with relatively shorter taxiing times, such as CKG. In recent years, the Civil Aviation Administration of China has worked hard to reduce taxiing times at major airports. The average taxi-out time at PEK reduced by 8.9 min from 2016 to 2018, and fell by 7.2 min at PVG, as shown in Table 1.

3.3 Emissions from different aircraft types

Figure 7 compares aircraft LTO movements in 1990 and 2017 in China. Trends show that the proportion of LTO movements of B737-800, A320, and A321 aircraft has increased. In 2017, the percentages of LTO movements of the top five aircraft types in China were 33.1% (B737-800), 24.6% (A320), 9.3% (A321), 6.1% (A319), and 5.6% (B737-700). When looking at the most prominent aircraft mix in China from 1990 to 2017, it is apparent that aircraft size has increased. The three predominantly used aircraft in 1990 were the MD-82 (147 seats), B737-200 (104 seats), and Y7 (52 seats). These have been replaced (in 2017) by aircraft with larger capacities: 737-800 (164 seats), A320 (170 seats), and A321 (236 seats). The average number of seats increased from 124 in 1990 to 175 in 2017.

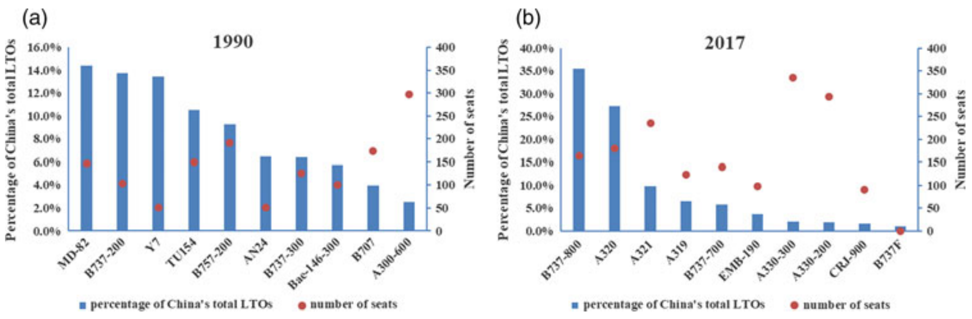

Figure 7. Aircraft LTO movement composition at China's airports in 1990 and 2017.

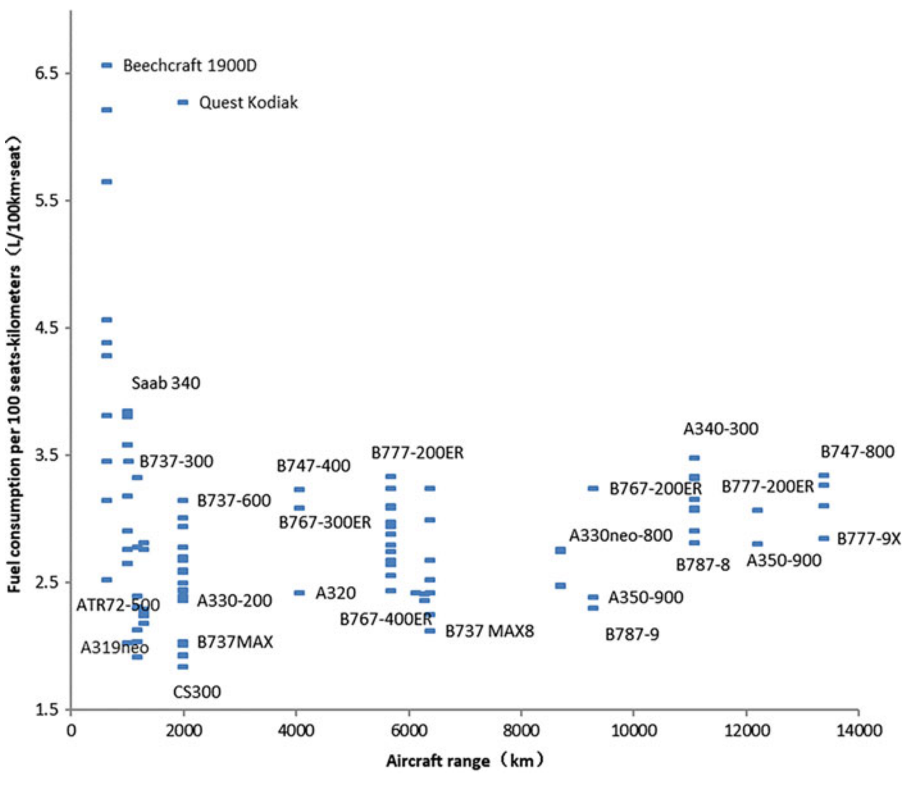

Figure 8. Fuel consumption per 100 seat-kilometers and ranges for different aircrafts.

Larger scale and longer range have been recent trends in global civil aviation, along with global integration and internationalisation. Larger aircraft usually lead to greater take-off weight and more pollutant emissions per flight. Because of the increasingly stringent requirements to address global environmental and climate change, successive CAEP (Committee on Aviation Environmental Protection) cycles have reduced the NOx limits as well as pollutant emissions. More up-to-date engines are also being developed, including the GEnx, CFM-LEAP, and Trent XWB, which are more fuel efficient. Data shown in Fig. 8 shows that

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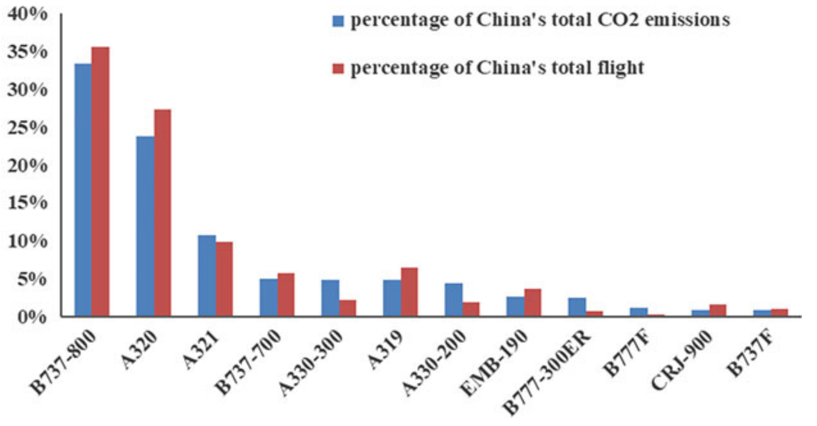

Figure 9. Contrast of percentage of China's total CO_2 emissions and percentage of China's total flights in 2017.

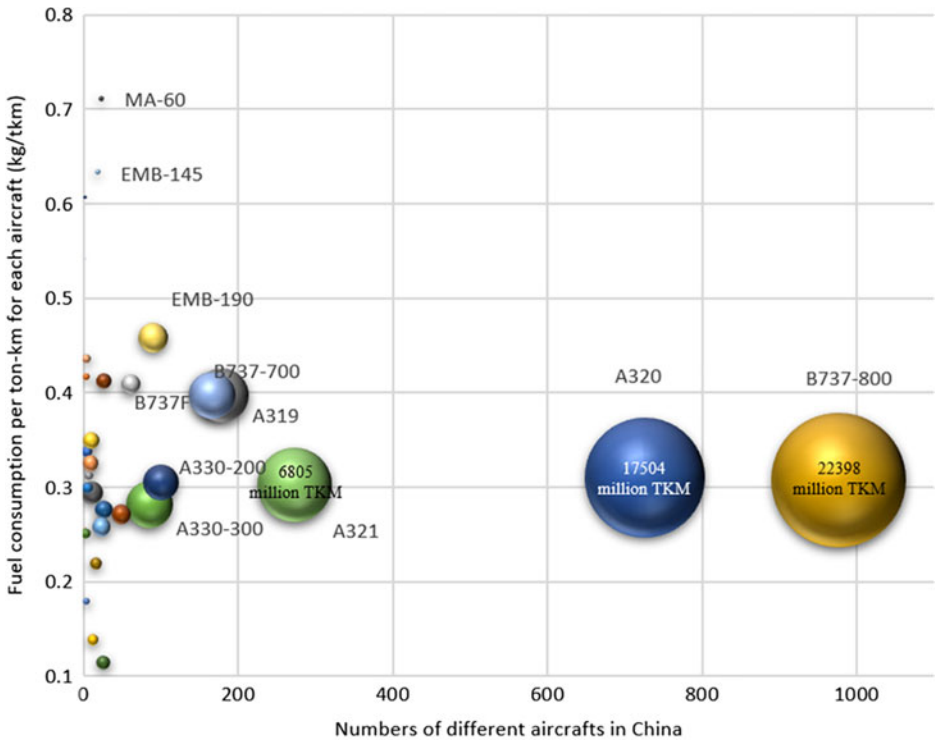

Figure 10. Total number and fuel consumption per ton-km for different aircraft in China (the size of sphere represents in this figure is annual transport turnover of different aircrafts in 2016).

modern aircraft perform better in the environment and have lower fuel consumption per 100 seat-kilometers.

The CO_2 emissions from B737-800, A320, A321, B737-700, A330-300, and A319 were 4290, 3060, 1390, 650, 630, and 620 kilotons, respectively, which accounted for 33.4%,

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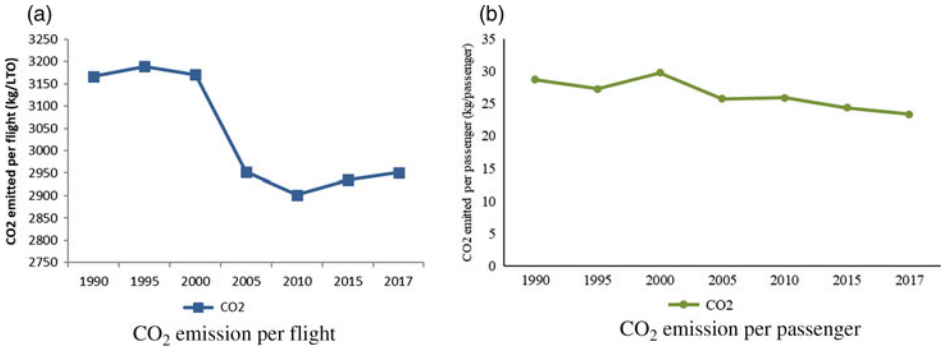

Figure 11. Variation of CO_2 emission per flight and per passenger from 1990 to 2017 at China airports.

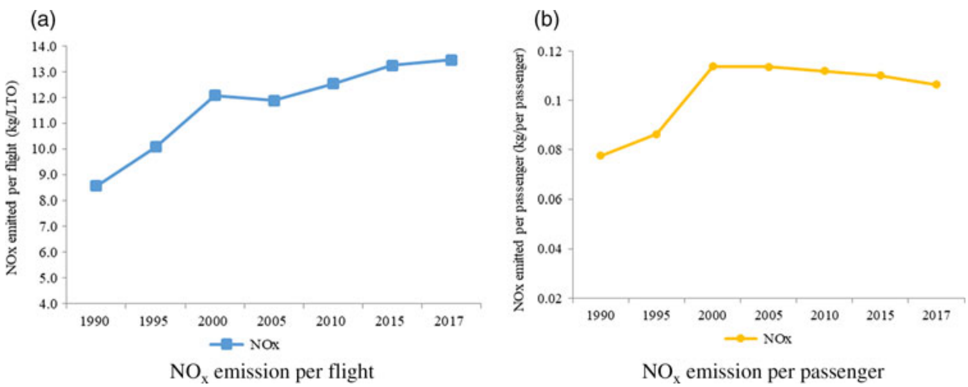

Figure 12. Variation of NO_x emission per flight and per passenger from 1990 to 2017 at China airports.

23.8%, 10.8%, 5.1%, 4.9%, and 4.8% of total aircraft LTO CO_2 emissions at China's mainland airports in 2017 (see Fig. 9). By comparing the percentage of China's total CO_2 emissions and the percentage of China's total flights in 2017, it can be seen that the B737-800, A320, B737-700, and A319 have better environmental performance. The most important reason for this is that many aircraft have undergone engine upgrades and energy-saving retrofits since 2010. Figure 10 shows that the majority of aircraft in China's fleet have relatively lower fuel consumption per ton-kilometers.

Data illustrated in Figs. 11–13 show that average emissions per passenger have decreased for CO_2, CO, HC, SO_x, PM, and NO_x from 1990 to 2017.

However, the data also show that CO_2 and NO_x emissions per flight have increased during recent years. As mentioned previously, aircraft size has increased from 1990 to 2017, and the pollutants produced by a single aircraft LTO cycle may also increase depending on engine type. As can be seen from Fig. 14 and 15, pollutant emissions per seat during one LTO cycle are directly related to the update year for aircraft as well as the engines. For example, the first flight year for the A321 was 1993, A320 was 1987, B737-800 was 1997, B737-300 was 1984, A319 was 1995, A300-600 was 1984, and B757-200 was 1982. This trend aligns with the situation described in Fig. 12, which shows that newly developed aircraft have lower emissions per seat during one LTO, because of more stringent emission standards of CAEP. In addition,

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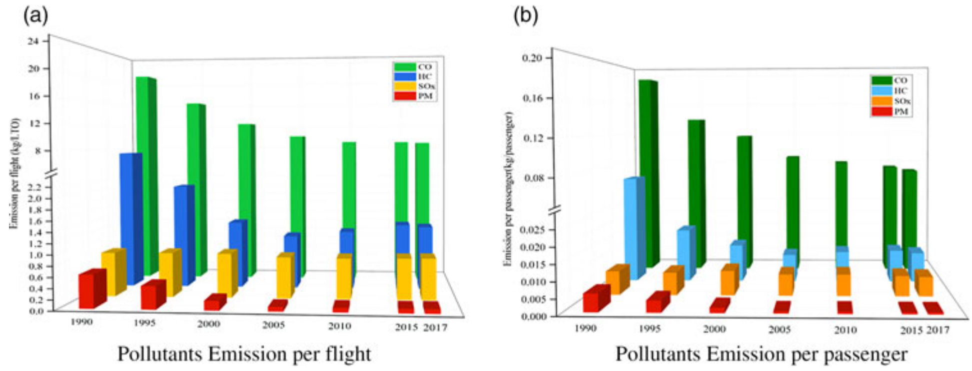

Figure 13. Variation of other pollutants emission per flight and per passenger from 1990 to 2017 at China airports.

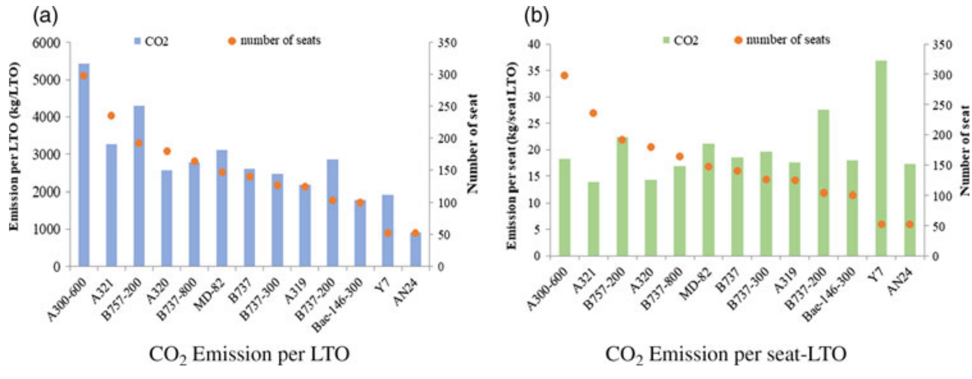

Figure 14. CO_2 emission per LTO and per seat-LTO for different aircraft types.

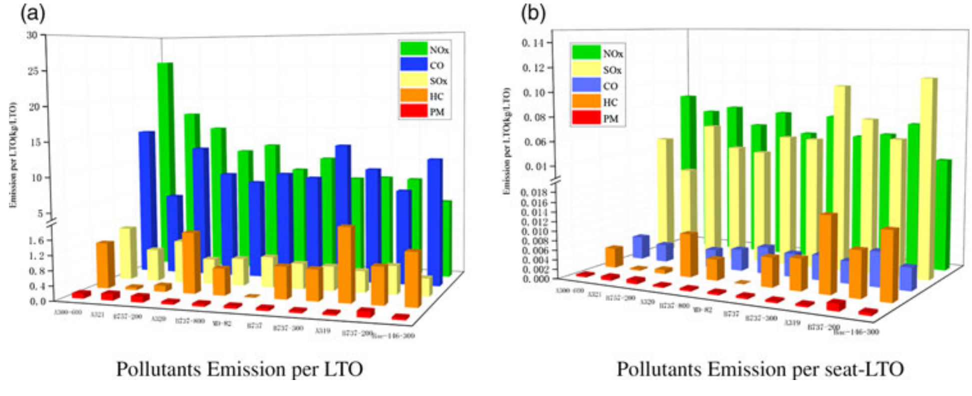

Figure 15. Pollutants emission per LTO and per seat-LTO for different aircraft types.

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ongoing NOx reductions brought about over successive CAEP cycles have reduced the impact of aircraft engines, with recently adopted nvPM standards anticipated to also improve emissions in future CAEP cycles. There will be a potential trade-off between NO_x and nonvolatile PM for RQL (rich burn, quick mix, lean burn) technologies. At the same time, lower emissions may also be a by-product of aircraft fuel efficiency improvement and noise reduction. According to the guidance policy of the Civil Aviation Administration of China, more energy-efficient and environmentally friendly aircraft with modern engines (e.g. GEnx, CFM-LEAP, Trent XWB) will be adopted in the future.

4.0 DISCUSSION

This study analysed the trend of aircraft air pollutant emissions at mainland China airports from 1990 to 2017. Results show that aircraft emissions of CO_2, NO_x, SO_x, CO, HC, and PM in 2017 increased by 27, 46, 27, 12, 5, and 4 times, respectively, over the 1990 levels. Therefore, research on airport pollution emissions as well as their environmental impacts has become very urgent and necessary, considering the rapid growth of civil aviation in China.

The influence of airports on regional air quality cannot be ignored, especially for the busiest airports. Results show that the top 30 busiest airports in China account for almost 80% of aircraft emissions at Chinese airports. Large amounts of pollutants are discharged because of ground taxiing of aircraft at airports. This means that decreasing taxiing time can greatly reduce emissions of pollutants at airports. To reduce the congestion and taxiing times, more large-scale and energy-efficient aircraft need to be used at the busiest airports.

Results also show that average emissions per passenger have decreased for CO_2, CO, HC, SO_x, PM, and NO_x from 1990 to 2017, which indicates that the Civil Aviation Administration of China has successfully implemented strategies to cope with climate change and enforce environmental protection with the adoption of larger, newer aircraft that adhere to ever-tighter ICAO CAEP emissions standards. Continuous research on adjustment and optimisation of the Chinese aircraft fleet structure will be necessary to continue downward pressure on civil aviation emissions, e.g. encourage carriers to utilise ever more modern and larger capacity aircraft models to meet growing passenger demand with fewer flight movements.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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AUTHOR CONTRIBUTIONS

Conceptualisation, Jinglei Yu and Huaqing Hu; methodology, Jinglei Yu and Chao Gao; software, Qin Jia and Jinglei Yu; validation, Jinglei Yu, Qin Jia, Chao Gao, and Huaqing Hu; formal analysis, Jinglei Yu and Qin Jia; investigation, Huaqing Hu; resources, Qin Jia; data curation, Chao Gao; writing—original draft preparation, Jinglei Yu; supervision, Huaqing

Hu; project administration, Jinglei Yu and Huaqing Hu; funding acquisition, Huaqing Hu. All authors have agreed to publication of the manuscript.

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