National emissions inventory and future trends in greenhouse gases and other air pollutants from civil airports in China

Kai Wang · Xiaoqi Wang · Shuiyuan Cheng · Long Cheng · Ruipeng Wang

Abstract
Civil aviation is an important source of air pollutants, but this field has received insufficient attention in China. Based on the standard emissions model of the International Civil Aviation Organization (ICAO) and actual flight information from 241 airports, this study estimated a comprehensive emissions inventory for 2010–2020 by considering the impacts of mixing layer height. The results showed that annual pollutant emissions rapidly trended upward along with population and economic growth; however, the emissions decreased owing to the impacts of the COVID-19 pandemic. In 2020, the emissions of carbon monoxide (CO), nitrogen oxides (NOX), particulate matter (PM), methane (CH4), nitrous oxide (N2O), carbon dioxide (CO2), and water vapor (H2O) were 34.34, 65.73, 0.10, 0.34, 0.40, 14,706.26, and 5733.11 Gg, respectively. The emissions of total volatile organic compounds (VOCs) from China’s civil airports in 2020 were estimated at 17.20 Gg; the major components were formic acid (1.70 Gg), acetic acid (1.62 Gg), 1-butylene (1.03 Gg), acetone (0.96 Gg), and acetaldehyde (0.93 Gg). The distribution of pollutant emissions was consistent with the level of economic development, mainly in Beijing, Guangzhou, and Shanghai. In addition, we estimated future pollution trends for the aviation industry under four scenarios. Under the comprehensive scenario, which considered the impacts of economic growth, passenger turnover, cargo turnover, COVID-19, and technological efficiency, the levels of typical pollutants were expected to increase by nearly 1.51-fold from 2010 to 2035.

Keywords Scenario analysis · Emission inventory · Spatial and temporal distribution · Civil aviation

Introduction
With the rapid development of China’s economy, civil aviation transportation plays an increasingly prominent role in the transportation industry (Liu et al. 2018). The growth rate of the aviation industry far exceeds that of the gross domestic product (GDP), and its development prospects are good (Chen et al. 2017). Therefore, civil aviation has a growing impact on the surrounding environment (Ashok et al. 2013). Moreover, the pollutants emitted by aviation activities pose a hazard to human health. Among these pollutants, PM2.5 can contain many harmful substances (Arunachalam et al. 2011); volatile organic compounds (VOCs) and NOX are precursors of photochemical smog (Stettler et al. 2011; Yim et al. 2013). In addition, emissions of greenhouse gases (GHGs) from aviation have an impact on the global greenhouse effect and will increase nearly sixfold from 2010 to 2050 (ICAO 2011).

In recent years, many scholars have studied the impacts of aircraft emissions and created emissions inventories. Song and Shon (2012) estimated the emissions of greenhouse gases (GHGs) from aviation have an impact on the global greenhouse effect and will increase nearly sixfold from 2010 to 2050 (ICAO 2011). Song and Shon (2012) estimated the emissions of greenhouse gases and other air pollutants from Korean airports. Inventories of airport emissions began only recently in China, and there are few published studies on this topic. Li et al. (2018) estimated the aircraft emissions inventory for the Capital International Airport in 2016 based on the mixing layer height and operation data. He (2012) estimated the air pollutant emissions from Chinese civil aviation aircraft from 1980 to 2009 based on fuel consumption. Huang et al. (2014) estimated the air pollutant emissions from aircraft at Baiyun Airport from 2008 to 2012 and analyzed their emission characteristics. Han et al. (2020a) estimated the air pollutant emissions inventory for the aircraft takeoff and landing cycles of the Beijing-Tianjin-Hebei airport group.
during the 2018–2019 flight season, while considering the impacts of changes in the atmospheric mixing layer. Wang et al. (2020) established the Tianjin Binhai International Airport air pollutant emissions inventory and used the Weather Research Forecast Community Multiscale Air Quality model to analyze the impact of airport emissions on PM$_{2.5}$ concentrations in the surrounding area. Certainly, these studies aid in understanding the current situation concerning airport emissions. However, most of these studies have deficiencies, such as (1) lacking a detailed analysis on airport VOC emissions; (2) not considering the effects of boundary layer height changes during takeoff and landing; and (3) focusing only on urban areas (Li et al. 2018; Xu et al. 2020, 2016).

In this study, the emissions of GHGs (CH$_4$, CO$_2$, H$_2$O, and N$_2$O) and other air pollutants (VOCs, NO$_X$, PM, and CO) from civil airports in China were estimated based on the standard emission model from the ICAO and actual flight information from 241 airports. The analysis also considers the impact of the mixing layer height (MLH). A lack of data exists on VOC pollution from civil airports in China owing to inherent difficulties in data collection; we used the Beijing Capital International Airport (ZBAA) as an example and analyzed the VOC emission characteristics around the airport runway. The VOC emissions inventory for civil airports in China was then calculated based on the results of Kilic et al. (2017). With the development of the aviation industry, the pollutant emissions baseline of civil aviation in China has been substantially affected, potentially rendering previous studies unsuitable for the current situation. Therefore, it is necessary to reevaluate future trends, considering current policy initiatives and technological improvements. Hence, we estimated future emission trends for aviation industry in 2035 under four scenarios.

Materials and data sources

This study presents a comprehensive aircraft emissions inventory for air pollutants (VOCs, NO$_X$, PM, and CO) and GHGs (CH$_4$, CO$_2$, H$_2$O, and N$_2$O) from 241 civil airports in China (excluding Taiwan Province). The names and ICAO codes of the 241 airports are shown in Table S1. The historical temporal variations in pollutant emissions from 2010 to 2020 were analyzed, and future trends for 2025 and 2035 were estimated based on four scenarios.

Data sources

We obtained flight schedules from the official websites of major airports and the Civil Aviation Administration of China (CAAC) to calculate airport emissions. Emission characteristics for CO, NO$_X$, and PM during the landing and takeoff (LTO) cycle were obtained from the ICAO aircraft engine emission databank (ICAO 2021) (Table S2). Emission characteristics for N$_2$O, CH$_4$, and CO$_2$ originated from Santoni et al. (2011), and different characteristics were used for each operation mode. A constant value of 1228 g kg$^{-1}$ was used for H$_2$O (Song and Shon 2012). In this study, the VOC components from airport emissions were analyzed using offline gas chromatography–mass spectrometry (GC–MS). See the supplementary material for sample collection and analysis, quality assurance measures, and meteorological conditions during sampling. For the composition spectra of VOCs for different operation modes, please refer to Kilic et al. (2017).

Calculation methods

A series of emission standards for aviation have been formulated by the ICAO and involve LTO (climb, approach, idle, takeoff) and cruise processes. The pollutants emitted by the LTO process have a direct impact on the areas surrounding the airport; therefore, this study only considers the emissions from the LTO process. The standard ICAO cycle defines the climb as the processes of an aircraft from takeoff to the MLH. We improved the calculation method for single aircraft emissions by fully considering the variability in MLH in various regions and at various times (Yang et al. 2018; Zhou et al. 2019). MLH values in major cities were from previous research results (Zhou et al. 2019). Air pollutant emissions were calculated according to Eq. (1) (Winther et al. 2015), as follows:

$$E_{i,m} = \sum_j n_j F_{j,m} E_{I_{i,j,m}}$$

where $E_{i,m}$ is the emissions (g) of pollutant $i$ (e.g., NO$_X$, CO, PM, or HC) during working mode $m$; $E_{I_{i,j,m}}$ are the emission indices (g kg$^{-1}$ of fuel) for pollutant $i$ during mode $m$ for each engine on aircraft type $j$; $n_j$ is the number of engines on the $j$ aircraft; $F_{j,m}$ is the fuel flow (kg s$^{-1}$) during mode $m$ for aircraft type $j$; and $t_{j,m}$ is the time (min) for mode $m$ for the aircraft type $j$.

In this study, the times for the climbs and approaches were calculated using Eqs. (2) and (3) using the standard time for takeoff (0.7 min) and idle (26 min) from the ICAO.

$$t_{j,m} = \frac{H_j - 304}{915 - 304}$$

$$t_{j,m} = \frac{H_j}{915}$$

where $t_{j,m}$ is the adjusted climb and approach time (min); $t_m$ is the standard time for the climb (2.2 min) and approach (4 min) from the ICAO; $H_j$ is the actual MLH, 304 is the
starting height of aircraft climb specified by the ICAO (m); and 915 is the aircraft approach altitude from the ICAO (m).

Scenario design

The future scenarios for 2025 and 2035 were created by defining characteristics for each scenario based on historical data. The business-as-usual (BAU) scenario assumes that the number of LTOs is affected by GDP, passenger turnover, and cargo turnover. Engine fuel efficiency, aviation emission regulations, and development policies were considered the same as those in previous years. Nevertheless, the economy in China has changed from high-speed to high-quality development. The 14th Five-Year Plan (from 2021 to 2025) and the long-term goal for 2035 both estimate that the per capita income in China will reach the level of a medium-developed country by 2035 (https://www.gov.cn/). Considering a per capita income of US$18,000–40,000 for medium-developed countries, the respective GDP annual growth rate should be at least 4.7% (http://www.gov.cn/). The 14th Five-Year Development Plan for comprehensive transportation services predicts that from 2021 to 2025, the average annual growth rates of passenger and cargo turnover will be 4.3% and 2.3%, respectively (http://www.gov.cn/); hence, these values were used in our analysis. Multiple linear regression was used to simulate the relationships between multiple independent variables and response variables by fitting linear equations to the observation data (Shu and Lam 2011). Utilizing historical data from 2001 to 2019, a multiple linear regression model was used to predict the LTOs in 2025 and 2035 by establishing the relationship between LTOs and GDP, passenger turnover, and cargo turnover.

COVID-19 scenario

In 2020, COVID-19 caused substantial impact to the civil aviation industry. Nevertheless, the aviation market in China has become the fastest-recovering and best-operating aviation market worldwide. However, to curb the risk of COVID-19 contamination from abroad, CAAC reduced the number of international flights. Furthermore, CAAC stipulated that each domestic airline could only retain one route to any country, and each route should not operate more than one flight per week. Therefore, international flights were reduced by 87% (http://www.caac.gov.cn/). Epidemiologists have been providing short- and long-term forecasts for the spread and impacts of the COVID-19 pandemic. Although predictions and timelines vary, there is a consensus that impacts associated with COVID-19 will persist for a long time (Ayukekbonk et al. 2020). Under this scenario, we assumed that these impacts on the aviation industry will decrease yearly and that the impacts on international flights in 2025 and 2035 would be 70% and 10%, respectively.

Maximum feasible technological reduction (MFTR) scenario

The aviation fuel consumption in China increased from 22.07 million tons in 2014 to 36.84 million tons in 2019, which is an annual growth rate of 10.82%. China has also become the second largest aviation fuel consumer globally (https://www.chyxx.com/). To reduce emissions from the aviation industry, governments and organizations have proposed various fuel efficiency goals. In 2008, at the Kuala Lumpur annual meeting, the International Air Transport Association proposed an increase of 1.5% in average annual fuel efficiency (https://www.iata.org/). The same year, the Air Transport Action Group drafted a plan for the sustainable development of the global civil aviation industry at the Third Aviation and Environment Summit and proposed support for the formation of relevant ICAO resolutions (https://www.atag.org/). In 2016, the 39th General Assembly of ICAO proposed the Carbon Offsetting and Reduction Scheme for International Aviation and formed the first global industry emission reduction market mechanism. Under the CORSIA plan, the fuel consumption efficiency was expected to increase by 2.5% in the following years (https://www.icao.int/). Airlines for America plans to increase the average annual aviation fuel efficiency by 1.5% in accordance with ICAO emission reduction plan (https://www.airlines.org/). Based on these pledges, under a MFTR scenario, we assumed that the average annual aviation fuel efficiency will increase by 1.5% from 2020 to 2035.

Comprehensive (CP) scenario

The CP scenario is expected to be the closest to the real scenario, and it considers factors such as economic growth, passenger turnover, cargo turnover, COVID-19 impacts, and technological improvements. Under this scenario, airport emissions would meet the following three assumptions simultaneously. First, the annual growth rates of GDP, passenger turnover, and cargo turnover would be 4.7%, 4.3%, and 2.3%, respectively. Second, the COVID-19 impacts on the aviation industry would decrease yearly, and the impacts on international flights in 2025 and 2035 would be 70% and 10%, respectively. Third, the average annual aviation fuel efficiency would increase by 1.5% from 2020 to 2035.

Results and discussion

GHG emissions

The CAAC is composed of seven regional aviation administrations, namely the Central and Southern Regional Administration (CSRA), Xinjiang Regional Administration (XJRA), Southwest Regional Administration (SWRA), Northwest
Regional Administration (NWRA), East China Regional Administration (ECRA), North China Regional Administration (NCRA), and Northeast Regional Administration (NERA). The number of LTOs by aircraft type in these seven administrations in 2020 is shown in Table S3. The number of LTOs in ECRA and CSRA was 1.2 and 1.1 million, respectively, which accounted for 26.05% and 24.67% of the total, respectively. The dominant aircraft types were the B738 and A320, which accounted for 19.13–35.11% and 26.35–43.62% of all aircraft, respectively. Table 1 lists the CH4, N2O, CO2, and H2O emissions of the seven regional aviation administrations. The total CH4, N2O, CO2, and H2O emission in 2020 were estimated as 0.34, 0.40, 14,706.26, and 5733.11 Gg, respectively. However, the global warming potential of N2O is more than 300 times that of CO2, and its impact on global warming cannot be ignored (IPCC 2007). Unlike other GHGs, the emission factors for CH4 varied greatly owing to different engine power conditions; in a high-power operation mode (takeoff, climb, approach), the engine consumes CH4 (Kilic et al. 2017). For CH4 and N2O, the maximum emissions from all airports were attributed to the idle mode. This occurred mainly because different emission factors were used for each operation mode when calculating CH4 and N2O. In addition, the period during which the idle mode was used was 27 times that of the takeoff mode. Constant emission factors were used to calculate CO2 and H2O emissions, which led to similar CO2 and H2O emissions for different operation modes.

To facilitate comparisons with other research, the GHG emissions per LTO were calculated, which were 0.075, 0.087, 3250.29, and 1267.10 kg LTO−1 for CH4, N2O, CO2, and H2O, respectively. Based on the Emissions and Dispersion Modeling System (EDMS), Song and Shon (2012) established emission inventories for CH4, N2O, CO2, and H2O at four major airports (RKSI, RKSS, RKPK, RKPC) in Korea. The emissions of CH4, N2O, CO2, and H2O were −0.007 to −0.001, 0.028–0.046, 1560.47–3141.95, and 604.26–1024.04 kg LTO−1, respectively. Liu et al. (2019) estimated the CO2 emissions from 2015 as 1120.04 kg LTO−1 considering only the LTO mode. However, in this

| Operational mode | CH4*1000 | N2O*1000 | CO2 | H2O | CO | NOX | PM*1000 |
|------------------|----------|----------|-----|-----|----|-----|---------|
| CSRA             |          |          |     |     |    |     |         |
| Take off         | −6.98    | 2.37     | 372.51 | 145.22 | 0.06 | 3.36 | 6.49    |
| Climb            | −21.11   | 8.37     | 1146.33 | 446.89 | 0.26 | 7.98 | 15.09   |
| Approach         | −10.74   | 11.79    | 663.24  | 258.56 | 0.44 | 2.05 | 0.86    |
| Idle             | 136.09   | 77.71    | 1295.16 | 504.91 | 8.11 | 1.82 | 0.66    |
| XJRA             |          |          |     |     |    |     |         |
| Take off         | −0.75    | 0.25     | 40.16  | 15.66 | 0.01 | 0.31 | 0.61    |
| Climb            | −4.05    | 1.60     | 219.76  | 85.67 | 0.05 | 1.36 | 2.16    |
| Approach         | −1.82    | 1.99     | 112.20  | 43.74 | 0.44 | 2.05 | 0.86    |
| Idle             | 15.19    | 8.68     | 144.59  | 56.37 | 1.00 | 0.20 | 0.09    |
| SWRA             |          |          |     |     |    |     |         |
| Take off         | −4.68    | 1.59     | 250.03  | 97.47 | 0.05 | 2.18 | 4.19    |
| Climb            | −18.85   | 7.48     | 1024.00 | 399.20 | 0.24 | 6.93 | 13.49   |
| Approach         | −8.95    | 9.82     | 552.60  | 215.43 | 0.09 | 0.35 | 0.05    |
| Idle             | 92.72    | 52.94    | 882.36  | 343.98 | 5.51 | 1.22 | 0.45    |
| NWRA             |          |          |     |     |    |     |         |
| Take off         | −1.82    | 0.62     | 97.07  | 37.84 | 0.02 | 0.82 | 1.57    |
| Climb            | −9.88    | 3.92     | 536.70  | 209.23 | 0.14 | 3.54 | 6.05    |
| Approach         | −4.40    | 4.83     | 271.46  | 105.82 | 0.39 | 1.66 | 0.73    |
| Idle             | 36.11    | 20.62    | 343.64  | 133.97 | 2.15 | 0.47 | 0.13    |
| ECRA             |          |          |     |     |    |     |         |
| Take off         | −7.26    | 2.46     | 387.69  | 151.14 | 0.07 | 3.47 | 6.71    |
| Climb            | −23.00   | 9.12     | 1249.05 | 486.93 | 0.29 | 8.68 | 16.11   |
| Approach         | −11.55   | 12.69    | 713.63  | 278.20 | 0.20 | 0.80 | 0.15    |
| Idle             | 141.77   | 80.95    | 1349.17 | 525.96 | 8.41 | 1.89 | 0.64    |
| NCRA             |          |          |     |     |    |     |         |
| Take off         | −3.38    | 1.15     | 180.66  | 70.43 | 0.03 | 1.66 | 3.18    |
| Climb            | −17.67   | 7.01     | 959.85  | 374.19 | 0.20 | 6.85 | 13.77   |
| Approach         | −7.88    | 8.65     | 486.69  | 189.73 | 0.47 | 2.20 | 0.79    |
| Idle             | 65.91    | 37.63    | 627.25  | 244.53 | 3.98 | 0.89 | 0.42    |
| NERA             |          |          |     |     |    |     |         |
| Take off         | −1.41    | 0.48     | 75.42  | 29.40 | 0.02 | 0.64 | 1.27    |
| Climb            | −5.47    | 2.17     | 297.25  | 115.88 | 0.07 | 2.00 | 3.46    |
| Approach         | −2.62    | 2.88     | 161.81  | 63.08 | 0.12 | 0.49 | 0.08    |
| Idle             | 27.95    | 15.96    | 266.00  | 103.70 | 1.66 | 0.37 | 0.08    |
| Total            | 341.47   | 395.72   | 14,706.26 | 5733.11 | 34.34 | 65.73 | 100.15  |
study, the influence of the boundary layer on the working time of the climb and approach modes was considered when calculating the emissions. Therefore, the emissions estimated by this method were greater than those recommended by ICAO, and the results of previous studies were similarly underestimated (Han et al. 2020a, 2020b; Zhou et al. 2019).

**VOC emissions**

The VOC components around the ZBAA runway were analyzed by GC–MS. A total of 53 VOCs were detected, and the total VOC (TVOC) mass concentration was 78.30 μg m⁻³, including 15 aromatics, 9 alkenes, 28 alkanes, and acetylene. Owing to the limitations of the test method, oxygenated VOCs were not detected. Figure 1 shows the top 20 VOC species by mass concentration. The main components near the ZBAA runway were alkanes (41.65%), aromatics (38.26%), alkenes (16.23%), and alkynes (3.86%). Additionally, the main VOC species were toluene (10.08 μg m⁻³), benzene (5.85 μg m⁻³), ethylene (4.45 μg m⁻³), isopentane (3.12 μg m⁻³), and ethane (3.06 μg m⁻³). Samples were collected at aircraft ignition and idle mode areas. Some studies have shown that aircraft release highly volatile alkanes (isopentane and pentane) and aromatics (toluene) during the ignition phase (Herndon et al. 2006; Knighton et al. 2007). Similar to the results of this study, Lai et al. (2013) reported that the concentration of TVOCs in the apron of Taipei International Airport was 85.38–89.70 μg m⁻³, with aromatics and alkanes as the main components. Sheng et al. (2021) used proton transfer reaction mass spectrometry to test the VOC emissions from the apron of Beijing Shahe Airport, where oxygen-containing VOCs and aromatics were the main components. Additionally, Schürmann et al. (2007) reported that a large amount of ethylene and aromatic hydrocarbons were emitted near the Zurich Airport runway, which is also similar to the results of this study.

Figure 2 and Table S4 list the emissions of 109 VOC components, with a TVOC emission of 17.20 Gg in 2020. Carbonyl compounds were the most abundant compounds, accounting for 36.85% of the TVOC emissions. Hydrocarbons were the second most abundant category, accounting for 29.11% of the total emissions; they included unclassified hydrocarbon fragments, aromatics, alkenes, alkynes, and alkanes with contribution rates of 15.97%, 9.00%, 2.61%, 1.06%, and 0.47%, respectively. The top five VOC species were formic acid, acetic acid, 1-butylene, acetone, and acetaldehyde with emissions of 1.70, 1.62, 1.03, 0.96, and 0.93 Gg, respectively. TVOC emissions decreased with increased aircraft operating power, which is consistent with the results of Anderson et al. (2006). This mainly occurred because of the long working time and large emission factor of the idle operation mode. Additionally, the mass fraction of the
Oxygenated species increased with engine thrust, ranging from 11.29 to 19.51%. Moreover, the proportion of aromatics in all operation modes increased with increased engine operating power. This occurred mainly because aromatics are decomposed in the engine combustion chamber as the temperature increases (Herndon et al. 2006).

Emissions of other air pollutants

The emissions of several atmospheric pollutants in 241 airports in China, 2020, are summarized in Table 1. The annual emissions of CO, NO\(_X\), and PM were 34.34, 65.73, and 0.10 Gg, respectively. Similar to the GHGs, the highest and lowest pollutant emissions occurred at ECRA (25.51%) and XJRA (3.36%), respectively. Moreover, the regions with the highest and lowest GDP were ECRA and XJRA, which was consistent with the emission rates. The emissions for the seven regions were in the order of ECRA > CSRA > SWRA > NCRA > NWRA > NERA > XJRA. The main reason for the uneven distribution of pollutants was the unbalanced economic development among the regions. To facilitate comparisons, these results were also converted into emissions per LTO, and the emissions of CO, NO\(_X\), and PM were 7.62, 14.64, and 0.02 kg LTO\(^{-1}\), respectively. Unal et al. (2005) estimated the emissions inventory of Atlanta International Airport based on an EDMS model, the emissions of CO and NO\(_X\) were 12.28 and 11.57 kg LTO\(^{-1}\), respectively. Wang et al. (2020) estimated the air pollutant emissions of six typical airports in North China in 2017, and the emissions of CO, NO\(_X\), and PM were 6.45–11.99, 12.57–28.00, and 0.11–0.18 kg LTO\(^{-1}\), respectively. The PM emission factor adopted in this study was the most recent non-volatile particulate matter emission factor of ICAO. Aviation fuel emits a large number of particles after combustion, and most of these particles have aerodynamic diameters between 30 and 100 nm. Therefore, the PM emissions calculated in this study were lower than those reported in previous studies.

The highest emissions of all civil airports were observed at ZBAA; its NO\(_X\), CO, and PM emissions were 4.50, 1.44, and 0.01 Gg, respectively. In addition, the spatial distributions of the pollutants were similar, according to ArcGIS 10.2 calculations. Figure 3 shows the distribution of and annual change in NO\(_X\) in 2020. The distributions of pollutant emissions were consistent with the level of economic development; emissions were highest in Beijing, Guangzhou, Shanghai, Shenzhen, Kunming, Hangzhou, and Chongqing. ZBAA, ZGGG, ZUUU, ZGSZ, ZSPD, ZUCK, ZPPP, ZLXY, ZSSS, and ZSHC airports reported large pollutant emissions, with contribution rates of 5.88%, 4.74%, 3.82%, 3.65%, 3.21%, 3.18%, 3.12%, 3.00%, and 2.59%, respectively. ZBAA, ZGGG, ZGSZ, ZSPD, and ZSSS are in four developed cities, whereas ZUUU, ZUCK, ZPPP, ZLXY, and ZSHC in tourist cities. Moreover, ZBAD started operations in 2019; owing to the COVID-19 pandemic, NO\(_X\) emissions increased from 0.22 Gg in 2019 to 1.37 Gg in 2020. In addition, ZYHB, ZJSY, and ZWWW are the busiest airports in northern, southern, and western mainland China, respectively. From 2010 to 2019, the NO\(_X\) emissions from major airports increased. Nevertheless, the operations at large airports were mostly stable; therefore, their inter-annual fluctuations in NO\(_X\) were small. However, the NO\(_X\) emissions from small airports fluctuated greatly.

Historical trends in emissions

The GHG and other air pollutant emissions from airports in China from 2010 to 2020 were estimated (Fig. 4). The total amount of pollutants in civil airports increased from
From 2013 to 2019, the GDP growth rate in China decreased, which was consistent with the airport emissions. The COVID-19 pandemic, which began at the end of 2019, has affected the aviation sector in several countries worldwide. Because airports are densely populated public spaces, they have been classified as high-risk areas for virus infection, and people have reduced the number of plane trips. From 2017 to 2020, the yearly emissions of air pollutants were 120.04, 128.28, 135.28, and 103.68 Gg, which were changes of 9.78%, 6.86%, 5.46%, and −23.36% compared to the previous years, respectively. The changes of pollutants in main months in 2019 and 2020 are shown in the Fig. S1. In February 2020, pollutant emissions decreased by 69.03% compared with February 2019, due to COVID-19. From March to June, pollutant emissions showed an increasing trend.
Scenario analysis for future emission trends in 2021–2035

The actual airport emissions from 2001 to 2019 were compared with the estimated values, and the differences ranged from −5.18 to 0.81%, which indicated that the multiple regression model was sufficiently reliable for predicting future values. Figure 5 shows the future emission trends for pollutants from civil airports in China under four scenarios (BAU, COVID-19, MFTR, and CP). In the BAU scenario, the sum of the GHGs and other air pollutants is expected to increase from 26,491.26 Gg in 2019 to 35,318.47 Gg in 2025 and 52,594.87 Gg in 2035, under the assumption that fuel efficiency, aviation emission regulations, and development policies would remain the same as those in previous years. In 2019, China’s aviation passenger throughput was 1.351 billion passengers, but the number of flights per capita was only 0.48, which was lower than the 2.55 in the USA, 2.36 in Canada, 3.00 in Australia, and 2.21 in the UK. Compared with these countries, China’s aviation transport market presents high development prospects. Under the COVID-19 scenario, the emissions of HC, CO, NOx, and PM show a slow growth trend compared with that in 2020, but the emissions are still slightly lower than those in 2019. After the COVID-19 outbreak, the Chinese government established effective containment measures, and domestic flights returned to their normal levels the same year. However, the COVID-19 pandemic in foreign countries is still developing and is expected to affect the aviation industry for a long time. Under the MFTR scenario, emissions are expected to decrease from 26,491.26 Gg in 2019 to 24,786.65 Gg in 2025 and 21,309.84 Gg in 2035, thus indicating that improving fuel efficiency can significantly reduce pollutant emissions. Under the CP scenario, the emissions of VOCs, CO, NOx, PM, and GHGs in 2035 are estimated at 33.76, 67.41, 130.38, 0.20, and 40,868.00 Gg, respectively. Thus, considering the impacts of GDP, passenger turnover, cargo turnover, the pandemic, and improved fuel efficiency, these pollutants are expected to increase by nearly 1.51 times from 2010 to 2035.

Uncertainty analysis

As shown in Eq. (1), the establishment of an airport emissions inventory is an integrated calculation process that includes activity level and emissions information. This data inevitably carries uncertainties, which will be transmitted to the inventory. If this uncertainty is not correctly evaluated, the accuracy of the emission inventory cannot be determined, which would diminish the effectiveness and feasibility of pollutant reduction schemes based on the inventory. Therefore, determining the uncertainty is a necessary step in the process of establishing the emissions inventory (Brown et al. 2001; Lumbreras et al. 2009). We used a Monte Carlo simulation to estimate the uncertainty for the airport emission estimates in China. This method is widely used in uncertainty analyses for air pollutant emissions (Lang et al. 2016; Zhao et al. 2011). In this study, the variables used to calculate airport emissions included LTOs, time, and emission factors. The LTOs were obtained directly from official websites, and thus, presenting minimal uncertainty. Therefore, we assumed that the coefficient of variation (CV) of the LTOs was a normal distribution of 5%. The CV of the mode times was from Stettler et al. (2011) and was assumed to be 10%. Masiol and Harrison (2014) summarized emission factors for H2O (1230 ± 20 g kg−1) and CO2 (3160 ± 60 g kg−1), and the CVs for H2O and CO2 in this paper were derived from their results. Li et al. (2020) indicated that the emission factor of NOx fluctuated by less than ±28%, and that of CO and VOCs fluctuated by less than ±27%. Santoni et al. (2011) found that the average emission rates of CH4 and N2O were 170 ± 160 mg CH4 (kg fuel)−1 and 110 ± 50 mg N2O (kg fuel)−1. The uncertainty in the PM emission factor was assumed to be 40% based on the results of Stettler et al. (2011). In addition to mathematical distributions and CV, the number of trials is another important parameter that can directly affect accuracy. To ensure the accuracy of the results, the trial number was set to 10,000. The simulation results showed that the uncertainty ranges at a confidence level of 95% in 2020 for CO, PM, NOx, CH4, N2O, CO2, H2O, and VOCs was −28.42 to 28.70%, −30.80 to 32.71%, −19.52 to 20.79%, −44.42 to 44.14%, −78.59 to 81.02%, −5.82 to 5.84%, −5.87 to 5.86%, and −26.94 to 27.82%, respectively.
Conclusions

In this study, the emissions of GHGs (CH₄, CO₂, N₂O, and H₂O) and air pollutants (VOCs, NOₓ, CO, and PM) from civil airports in China were estimated based on the standard emissions model from the ICAO, actual flight information from 241 airports, and the impact of MLH. In addition, we estimated the future trends in aviation industry emissions by 2035 under four scenarios.

In 2020, the emissions of CO, NOₓ, PM, CH₄, N₂O, CO₂, H₂O, and VOCs were estimated at 34.34, 65.73, 0.10, 0.34, 0.40, 14.706.26, 5.733.11, and 17.20 Gg, respectively. From 2010 to 2019, the total emissions of GHGs and other air pollutants from the domestic civil aviation industry increased dramatically with the significant GDP growth, but the emissions presented a downward trend in 2020 owing to the impacts of the COVID-19 pandemic. The distribution of pollutant emissions was consistent with the level of economic development; emissions were highest in Beijing, Guangzhou, Shanghai, Shenzhen, Kunming, Hangzhou, and Chongqing. Among the 241 airports, ZBAA was the largest contributor to air pollution, accounting for 5.88% of the total emissions in 2020. From the perspective of the seven regional aviation administrations, ECRA had the highest contribution rate, at 25.51%, and XJRA had the lowest, at 3.36%. Under the CP scenario, the studied pollutants are expected to increase by 25.51%, and XJRA had the lowest, at 3.36%. Under the CP scenario, the studied pollutants are expected to increase by nearly 1.5 times from 2010 to 2035, considering the impacts of economic growth, passenger turnover, cargo turnover, COVID-19, and technological emissions reduction. Therefore, the results of this study provide a useful background for governments and stakeholders to develop policies to mitigate the air pollution associated with civil aviation in China.

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LC: data collection and investigation, methodology.
XW: supervision and manuscript revision.

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Data availability Raw data will be made available on request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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