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A number-based inventory of particle emissions by civil aviation and the influences on the particle number concentration near Zurich airport

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Abstract

With the rapidly growing global air traffic, the impacts of the particulate matter (PM) in the aviation exhaust on climate, environment and public health are likely rising. The particle number and size distribution are crucial metrics for toxicological analysis and aerosol-cloud interactions. The modern aircraft engines are characterized by decreasing levels of mass emissions of particulate matter, leading to little contribution to the mass concentration. However, the abundant ultrafine particles in the aviation exhaust with diameters less than 100 nm may significantly increase the particle number concentration (PNC). Here we will introduce our recent studies on utilizing the Automatic Dependent Surveillance-Broadcast (ADS-B) from OpenSky network to develop the black carbon (BC) particle number emission inventory for global civil aviation and to investigate the influences of aviation emissions on the particle number concentration near Zurich airport.

The developed inventory indicated that the BC particle number emission was approximately $(10.9 \pm 2.1) \times 10^{25}$ per year with an average emission index of $(6.06 \pm 1.18) \times 10^{14}$ per kg of burned fuel, which was about 1.3% of the total ground anthropogenic emissions, and 3.6% of the road transport emission.

The preliminary dispersion results showed that the number concentration of volatile particles emitted by aviation was about 2 orders of magnitude higher than that of non-volatile particles. The annual mean contributions of the Zurich airport to the particle number concentrations ranged from about 10^5 cm^{-3} at the airport entrance to about 10^3 cm^{-3} at ETH Honggerberg (about 6 km away). There were about 1000 hours per year

[*] Conceived the study, analyzed the ADS-B data for Zurich airport, and prepared the manuscript
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[‡] Air quality simulation using GRAL model
[§] Conceived the study, designed the development procedures, and prepared the manuscript.

for the investigated locations to have more than 1000 cm^{-3} from the airport, with medians of about 10^4 cm^{-3}.

The OpenSky network ADS-B database provides a new opportunity to estimate the aviation emission using the detailed flight trajectory data. The dataset will contribute to reducing the uncertainties in the development of emission inventory, and improve the air quality simulation in the vicinities of airports.

1 Introduction

With the rapidly growing global air traffic, the impacts of the particulate matter (PM) in the aviation exhaust on climate, environment and public health are likely rising. The particle number and size distribution are crucial metrics for toxicological analysis and aerosol-cloud interactions. The modern aircraft engines are characterized by decreasing levels of mass emissions of particulate matter, leading to little contribution to the mass concentration.

However, the abundant ultrafine particles in the aviation exhaust with diameters less than 100 nm may significantly increase the particle number concentration (PNC). The ultrafine particles could enter the human respiratory system and translocate to the key organs, e.g. heart, liver, kidneys and brain, causing adverse health effects.

Aviation is also the unique anthropogenic emission source at high altitudes, and it may influence the climate. The black carbon (BC) particles are an important component of the emissions. They are agglomerates of nearly spherical primary particles mainly composed of graphene lamellae (Liati et al., 2014). It is shown that the formation of the contrail and the contrail cirrus is dependent on the BC number emission (Burkhardt et al., 2011; Kärcher et al., 2017), hence the number and the size distribution of aviation emitted particles are required to investigate such climate effects (Moore et al., 2017).

Here we will introduce our recent studies on utilizing the ADS-B data from OpenSky network (Schäfer et al., 2014) to develop the BC particle number emission inventory for global civil aviation and to investigate the influences of aviation emissions on the particle number concentration near Zurich airport.

2 Nonvolatile particle number emission inventory

For the black carbon emission estimation, the key parameters, e.g. fuel consumption, geometric mean diameter (GMD) and the geometric standard deviation (GSD) of the emitted particles, are dependent on the flight condition. In order to analyze the flight durations of each sub-phase during CCD (Climb/Cruise/Descent), more than 13000 records of the Automatic Dependent Surveillance-Broadcast (ADS-B) were first collected from the OpenSky network (https://opensky-network.org/). The data contained about 1500 regular flight routes on 9 different days (operated by American Airlines and Lufthansa). The flight altitudes, speeds and durations for each CCD sub-phase were estimated based on the dataset.

Airlines were grouped into three classes with respect to the total duration of CCD phases: short (< 60 min), medium (60 – 120 min) and long (> 120 min) as shown in Figure 1. The cruise duration was rather scattered for short flight and it got concentrated as flight duration went longer. The duration of descend contributed largely to the total CCD duration for short flight (more than 50% for a commercial aircraft with 30 min CCD), and it might be distinctly influenced by weathers and air traffic controls.

The developed inventory indicated that the BC particle number emission was approximately $(10.9\pm2.1)\times10^{25}$ per year with an average emission index of $(6.06\pm1.18)\times10^{14}$ per kg of burned fuel, which was about 1.3% of the total ground anthropogenic emissions, and 3.6% of the road transport emission. The global aviation emitted BC particles followed a lognormal distribution with a geometric mean diameter (GMD) of 31.99 ± 0.8 nm and a geometric standard deviation (GSD) of 1.85 ± 0.016. The variabilities of GMDs and GSDs for all flights were about 4.8 nm and 0.08 respectively. The inventory provides new data for assessing the aviation impacts. More details about the emission inventory can be found in our recent article (Zhang et al., 2019).

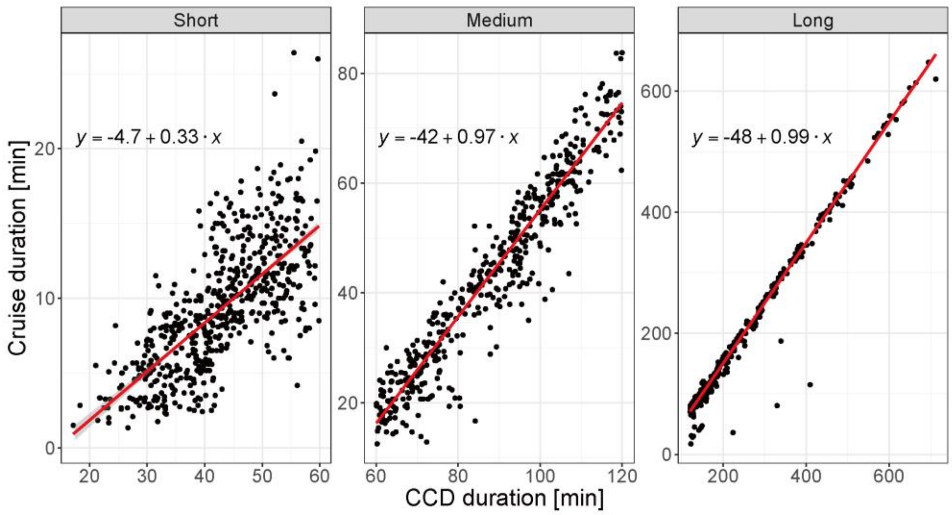

Figure 1: Cruise duration of the flight with different distances

3 Emission at Zurich Airport

At the airport scale, the emission is normally estimated using the ICAO default LTO cycle. However, the duration of flights at taxiing, the largest contributor to the emission, may be significantly different from the default values. The current spatial distribution of the emission within the airport is usually missing. The OpenSky network provides a new opportunity to estimate the detailed emissions at the airport scale using the flight trajectories from the ADS-B database. The detailed emission can help improve the air quality simulation in the vicinities of airports.

3.1 Flight movement segmentation

In this study, we utilized the ADS-B data in January 2019 around Zurich airport, with a spatial range from 47.40 to 47.53 in latitude, from 8.48 to 8.64 in longitude, and below 1000 m barometric altitude. The time series data of one aircraft was separated if the intermission between two consecutive messages was longer than the defined interval, which was 30 minutes. The defined interval was comparable to the minimum time required for preparation and boarding activities between two consecutive flights.

Figure 2 showed the results of the aircraft with the ICAO24 identifier of 06A10E, which flied to Zurich airport on six different days in January 2019. Based on the defined time interval above, the whole sequence of this aircraft was divided into 12 fragments. Each fragment was utilized as the basic analysis unit. It was assumed that there was normally only one landing or taking off movement within each separated period. However, in some situations, the aircraft still sent messages when they were waiting at the boarding gates, so there were both landing and taking off movements within one fragment. The emission would be mainly from auxiliary power unit (APU) during the long time stop. The APU emission was not included in the current study yet, so it was assumed that there was no emission from jet engines if the stop was longer than 30 minutes, and the corresponding time would be excluded from the taxiing phase. We also considered the influence of the push-back area, which were close to the constructions and the jet engines were not allowed to use due to the purposes of building protection. The ground service vehicles pushed the aircrafts back to the freeway, so the emission and taxiing time within this area were also excluded. The push-back area at Zurich airport was defined as the yellow area in Figure 3 (b) according to the airport report (Fleuti and Maraini, 2017).

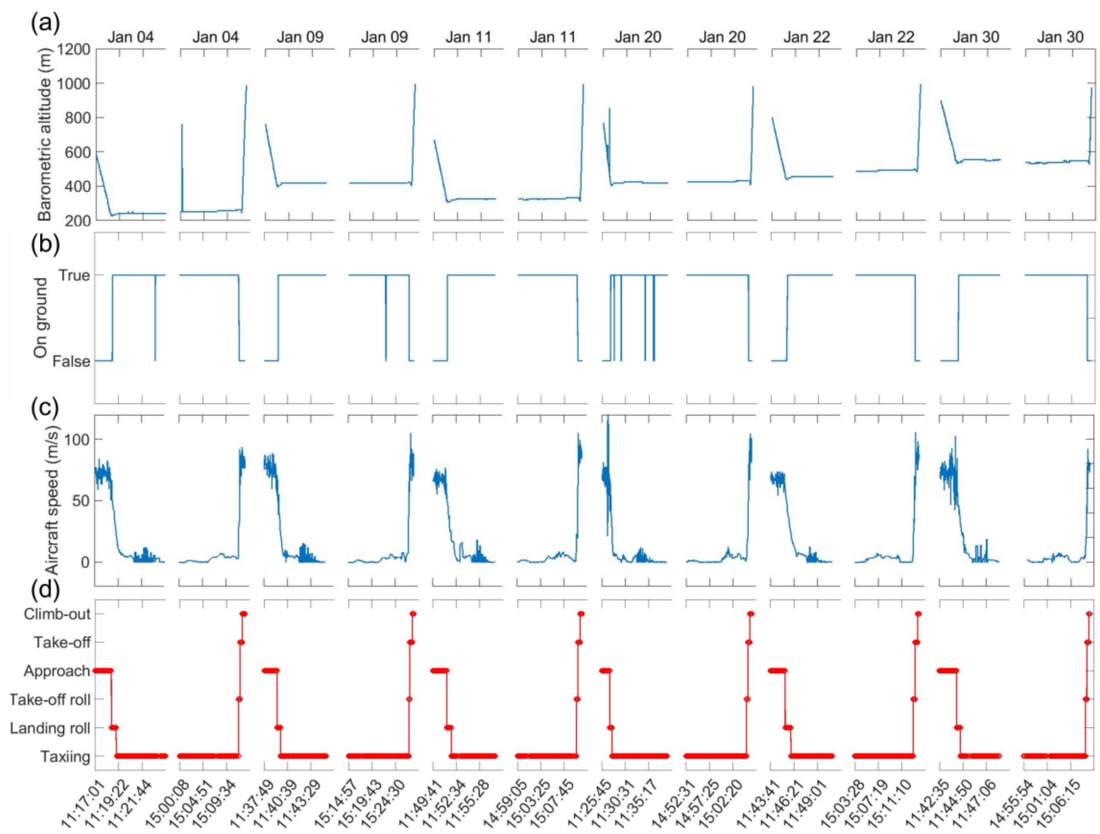

Figure 2: (a) Barometric altitude, (b) on-ground flag, (c) speed in the ADS-B data of the aircraft 06A10E in January 2019 at Zurich airport and (d) the separated six flight phases

The movement of each flight was divided into six different phases mainly based on the barometric altitude, on-ground flag, speed as shown in Figure 2 (a) to (c), and the calculated heading direction. As shown in Figure 2 (d), the six phases were respectively taxiing, landing roll, take-off roll, approach, take-off and climb-out, since the engine thrusts and altitudes of emissions are significantly different during these phases.

One dimensional moving average and median filters were first applied to the raw data to remove the noise and spikes as shown in Figure 2 (a) and (b). The spatial distribution of the separated trajectories of 06A10E was shown in Figure 3(a). The developed method accurately identified the taking off and approaching movements along the runways, as well as the taxiing activities in the airport. The same procedure was applied to all the flights in January. The longest phase was taxiing (taxiing-in and taxiing-out), which was estimated as about 20 minutes for each flight. It was 6 minutes less than the ICAO default duration for taxiing.

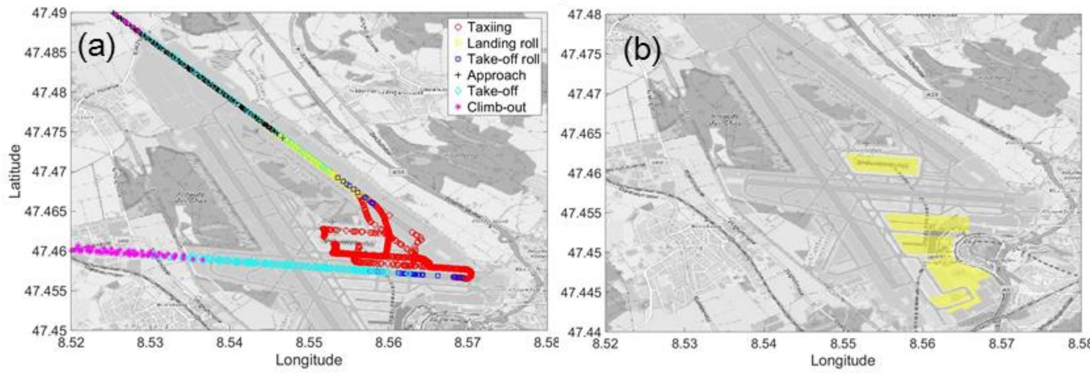

Figure 3: (a) Spatial distribution of the six separated aircraft movements; (b) the push-back area in Zurich airport

3.2 Emission estimation

The ADS-B data provides detailed movement data, but currently it is unable to cover all the flights. According to the airport report, there were 21223 aircraft movements in January, including both arrival and departure flights. The estimation based on the ADS-B was 19140 movements, namely about 90.2% of the official number. Another problem was that only the ICAO24 identifiers were available in ADS-B data. However, about 10% of the aircraft type information was missing in the current ADS-B dataset for 2019, so the emission information was unavailable due to the unknown aircraft type or engine information.

As a preliminary study, here we utilized the scheduled flight data from Official Aviation Guide (OAG) in conjunction with the International Civil Aviation Organization (ICAO) engine emission databank (ICAO, 2019) and our proposed nonvolatile particle number emission estimation method (Zhang et al., 2019) to estimate the fleet averaged emissions of pollutant *p* during each phase at Zurich airport, $\overline{E_{p,OAG}(phase)}$. The spatial distribution of the emission, $E_p(x, y, phase)$, was then estimated by using the aircraft presence time as a surrogate.

$$E_p(x, y, phase) = T(x, y, phase) \cdot \frac{N_{OAG}}{N_{ADS-B}} \cdot \frac{\overline{E_{p,OAG}(phase)}}{T_{std}(phase)}, \quad (1)$$

where $E_p(x, y, phase)$ was the emission of pollutant *p* at location (x, y) during one of the six phases. The pollutants included nonvolatile particle number, mass, NOx, Sox and HC. $T(x, y, phase)$ was the aircraft presence duration within the cell at (x, y), which had the size of 5×10^{-5} degree, roughly 5 m. The total duration of aircrafts within that cell was calculated based on the ADS-B data. N_{OAG} and $N_{ADS\text{-}B}$ were respectively the number of aircraft movements directly from OAG database and estimated based on the ADS-B dataset. $T_{std}(phase)$ is the ICAO standard duration for each flight phase.

The spatial distribution of nonvolatile particle number emissions was shown in Figure 4 as an example. The taxiing phase was the largest contributor for the emission. The emission of particle number ranged from about 10^{14} to about 10^{18} particles per m^2 per year. The area near the terminals had the highest emissions, since they had the highest aircraft densities. The estimation also captured the high emission at the starting point of the runway, where aircrafts were usually waiting in queues. The emissions during other phase mainly happened along the directions of the runways.

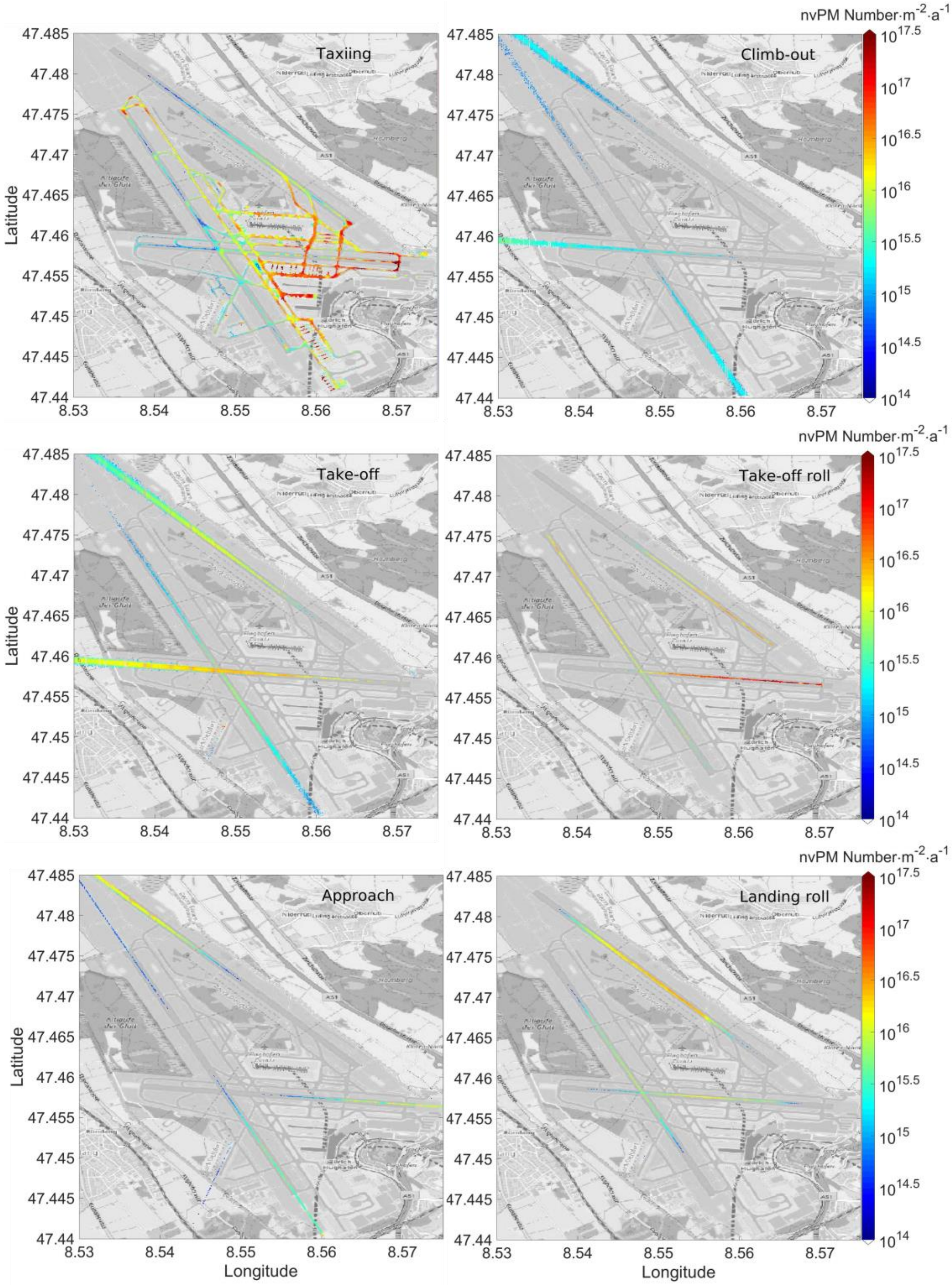

Figure 4: The estimated nonvolatile particle number emissions during different phases at Zurich airport

4 Preliminary results for atmospheric dispersion

We investigated the influences of aviation emissions on the particle number concentration near Zurich airport based on the simplified emission estimation and the atmospheric dispersion model. Atmospheric dispersion model is useful tool to investigate the impacts of emission on the surrounding areas (Zhang et al., 2014, 2015a,b)The Graz Lagrangian Model (GRAL) (Berchet et al., 2017) was utilized to calculate the atmospheric dispersion of the non-volatile and volatile ultrafine particles emitted from aircrafts in Zurich airport for the whole year of 2017. The results indicated that the number concentration of volatile particles emitted by aviation as about 2 orders of magnitude higher than that of non-volatile particles. The annual mean contributions of the Zurich airport to the particle number concentrations ranged from about 10^5 cm^{-3} at the entrance to about 10^3 cm^{-3} at Honggerberg (about 6 km away). There were about 1000 hours per year for the investigated locations to have more than 1000 cm^{-3} from the airport, with medians of about 10^4 cm^{-3}.

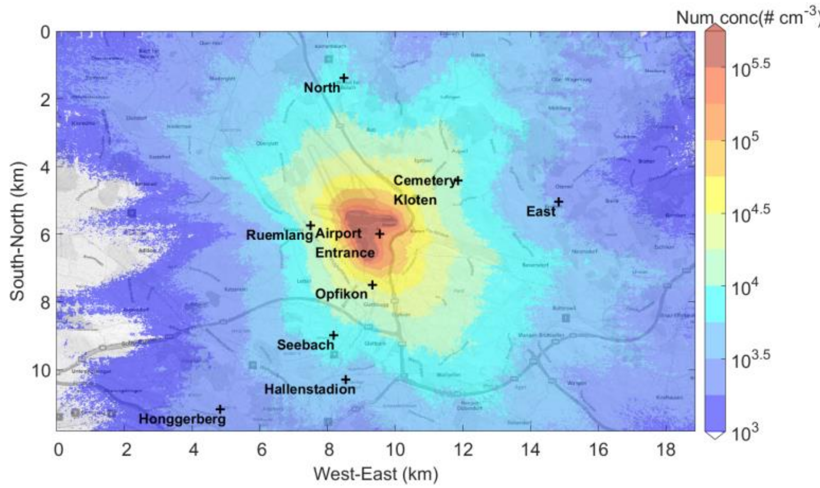

Figure 5: Particle number concentration due to the airport emission

5 Summary

Here we introduced our recent studies on utilizing the ADS-B data from OpenSky network to develop the BC particle number emission inventory for global civil aviation and to investigate the influences of aviation emissions on the particle number concentration near Zurich airport.

The OpenSky network ADS-B database provides a new opportunity to estimate the aviation emission using the detailed flight trajectory data. The dataset will contribute to reducing the uncertainties in the development of emission inventory, and improve the air quality simulation in the vicinities of airports. The results would be also beneficial for the airport to identify the high emission area, improve the management and reduce the environmental impacts of the airport.

Currently, the detailed emission inventory is not fully implemented into the air quality model GRAL. In the next step, the detailed emission based on ADS-B data introduced here will be integrated into the model to improve the calculation.

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