https://doi.org/10.5194/egusphere-2023-2197
Preprint. Discussion started: 6 October 2023

International airport emissions and their impact on local air quality: Chemical speciation of ambient aerosols at Madrid-Barajas Airport during AVIATOR Campaign

Saleh Alzahrani[1], Doğuşhan Kılıç[1,2], Michael Flynn[1], Paul I. Williams[1,2] and James Allan[1,2]

[1]Department of Earth and Environmental Sciences, University of Manchester, Manchester, UK
[2]National Centre for Atmospheric Science, University of Manchester, Manchester, UK

Correspondence to: Saleh Alzahrani (Saleh.alzahrani@manchester.ac.uk)

Abstract. Madrid-Barajas International Airport (MAD), located in Spanish Capital Madrid, is the fourth-busiest airport in Europe. As part of the AVIATOR campaign, chemical composition of particulate matter and other key pollutants were measured at the airport perimeter during October 2021, to assess the impact of airport emissions on local air quality. A high-fidelity ambient instrumentation system was deployed at Madrid Airport to measure: composition of ambient aerosol and concentrations of black carbon (*e*BC), carbon dioxide (CO_2) carbon monoxide (CO), nitrogen dioxide (NO_x), sulphur dioxide (SO_2), particulate matter ($PM_{2.5}$, PM_{10}), total hydrocarbon (THC), and total particle number. The average concentration for the entire campaign of *e*BC, NO_x, SO_2, $PM_{2.5}$, PM_{10}, CO and THC at the airport were, 1.07 (µg/m³), 22.7 (µg/m³), 4.10 (µg/m³), 9.35 (µg/m³), 16.43 (µg/m³), 0.23 (mg/m³) and 2.30 (mg/m³) respectively. The source apportionment analysis of the non-refractory organic aerosol (OA) using positive matrix factorisation (PMF) allowed us to discriminate between different sources of pollution, namely: Semi Volatile Oxygenated Organic Aerosol (SV-OOA), Alkane Organic Aerosol (AlkOA), and More Oxidised Oxygenated Organic Aerosol (MO-OOA) source. The results showed that SVOOA and MO-OOA accounts for more than 80% of the total organic particle mass that was measured near runway at the airport. Trace gases correlate better with AlkOA factor more than SVOOA and MO-OOA which indicate that AlkOA is mainly related to the primary emissions of combustion. Bivariate polar plots were used for the source identification. Significantly higher concentrations of the obtained factors were observed at low wind speeds < 3m/s from the southwest where two of runways, as well as all terminals are located. Higher SO_2/NO_x and CO/*e*BC ratios were observed when the winds originating from the northeast where the 18L/36R runways are located. This is attributed to the aircraft influence and the lack of a local road source in the northeast area.

1. Introduction

Several studies have linked particulate matter (PM) to a range of harmful health effects, including respiratory and cardiovascular ailments (Boldo *et al.*, 2006; Li *et al.*, 2003a; Pope and Dockery, 2006; Schwarze *et al.et al.*, 2006). In recent years, a number of researchers have found an association between aviation emissions and potential adverse human health impacts. These emissions can lead to immune system malfunction, various pathologies, the development of cancer, and premature death. Hence, it is increasingly recognised as a serious, worldwide public health concern (Yim *et al.*, 2013; He *et al.*, 2018; Jonsdottir *et al.*, 2019).

A few studies have reported that air pollutants emitted from large airports can play a vital role in worsening the regional air quality (Rissman *et al.*, 2013; Hudda and Fruin, 2016). Hu *et al.*, (2009) and Westerdahl *et al.*, (2008) measured high ambient PM concentrations downwind of Los Angeles International Airport (LAX) and Santa Monica Airport (SMA) in California. A decline in the ambient air quality was observed over distances of up to 18 km downwind from international airports owing to gas turbine-emitted PM (Hudda *et al.*, 2014; Hudda and Fruin, 2016). Airports' contribution to primary and secondary inhalable and fine particulate matter (PM10 and PM2.5, mass of particles with aerodynamic diameters <10 µm and <2.5 µm, respectively) making them determinants of the air quality in cities and a significant issue for the local air quality management. To date, several questions still remain to be answered regarding the chemical composition of aircraft plumes, and the health risks associated with the exposure to the pollutants originating from airports in neighbouring communities. Responding to the growing concern about the risk of exposure to airport pollutants, studies have been conducted to gain a better understanding of airport emissions and their possible effects on local and regional air quality. Thus far, aircraft engines are considered to be one of the major sources of both gaseous and particulate pollutants at the airport (Masiol and Harrison, 2014). Various campaigns have reported both physical and chemical properties of

https://doi.org/10.5194/egusphere-2023-2197
Preprint. Discussion started: 6 October 2023

particulate and gaseous emissions (Kinsey, 2009; Kinsey *et al.*, 2010, 2011; Mazaheri *et al.*, 2011; Hudda *et al.*, 2016).

Aviation fuel Jet A1 is the most common type of fuel that is used in civil aviation. It's a complex mixture of aliphatic hydrocarbons, characterized by a mean C/H ratio of ~ 0.52 (with an average empirical molecular formula of $C_{12}H_{23}$) (Lee *et al.*, 2010). Several fuel combustion sources are present at airports, including aircraft operation and diesel ground transport that services the airport and brings in passengers for traveling. Fuel combustion likely caused maximum particle counts in 10 - 20 nm range based on the particle size distribution analysis (Zhu *et al.*, 2011). There are also other sources of airport-related PM emissions that contribute to air pollution at the local scale. Particulate pollution (38% of PM10 with a mean level of 48 µg/m³) at airports can periodically originate from the construction activities for terminal maintenance and construction (Amato *et al.*, 2010). Particles emitted by commercial aircraft can be divided into two main groups: non-volatile and volatile PM. Non-volatile PM (nvPM) is usually formed during the (incomplete) combustion process and then emitted from the aircraft combustion chamber. It consists mostly of carbonaceous substances such as soot, dust, and trace metals (Yu *et al.*, 2019). nvPM has the physical property of being resistant to high temperatures and pressure. On the other hand, volatile PM is formed through gas to particle conversion process, primarily by sulphur and organic compounds, which exist in the exhaust gas downstream of the engine after emission. Sulphuric compounds are formed as a result of sulphur in fuel, whereas organic particles are formed as combustion products, and from fuel and oil vapours (ICAO, 2016; Smith *et al.*, 2022). Aircraft and ground unit emissions have been documented in prior research (Masiol and Harrison, 2014), yet there is still a gap in knowledge about airport-related PM emissions in terms of (i) apportioning PM to individual sources at airports, (ii) specifying their chemical composition, and (iii) the wider impacts of PM on local communities. This study set out to obtain data that will help to address these research gaps by providing further in-depth information on particle composition measurements and key pollutants observed within an airport environment, through characterizing organic volatile PM emissions aiming to assess the effect of aviation emissions on the local air quality. Here we focus on Adolfo Suárez Madrid–Barajas Airport in Madrid. As part of the AVIATOR Project (Assessing aViation emission Impact on local Air quality at airports: TOwards Regulation), several experiments were conducted at the Madrid–Barajas Airport, for monitoring the chemical properties of sub-micron particles. Source apportionment analysis was performed based on the particle data collected via high resolution mass spectrometry and this analysis allowed us to discriminate between different sources of pollution at the airport microenvironment. These findings will serve as the foundation for additional comprehensive research, such as toxicological and health effect studies of PM originating from aviation activities.

2. Methods

2.1. Description of the sampling location

Adolfo Suárez Madrid-Barajas Airport is the main international airport, located within the municipal limits of Madrid, 13 km northeast of Madrid's city centre. It is the fourth-busiest airport in Europe based on passenger volume (Eurostat Database, 2021). In 2019, 62 million travellers used Madrid-Barajas and nearly half a million aircraft movements have been recorded, making it the largest and busiest airport in the country. In 2021, nearly one-third of the previous number travelled through Madrid Airport because of the COVID-19 pandemic. The airport has five passenger terminals named T1, T2, T3, T4, and T4S. Barajas Airport has four runways: two on the north-south axis and parallel to each other 18L/36R - 18R/36L and two on the northwest-southeast axis 14L/32R - 14R/32L. The runways enable takeoff and landing simultaneously at the airport, allowing 120 operations per hour (one takeoff or landing every 30 seconds). The sampling location was chosen in concert with AENA, the owner and operator of the Barajas Airport to facilitate the provision of power and access for servicing. Focusing on the temporal and spatial monitoring of the key pollutants, the site was positioned between runways 36L and 36R to sample the airport emissions from an optimal sampling point for aviation activities (Fig.1).

https://doi.org/10.5194/egusphere-2023-2197
Preprint. Discussion started: 6 October 2023

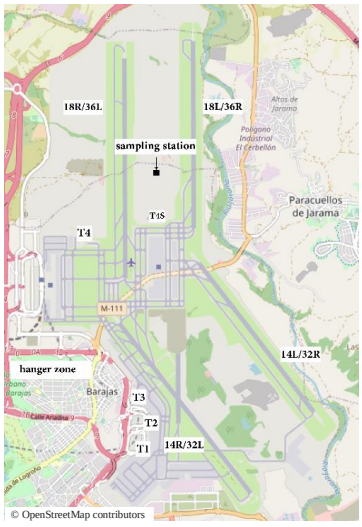

Figure 1. Locations of runways, terminals, and sampling site at Adolfo Suárez Madrid-Barajas Airport. Measurements were performed between October 8, 2021 and October 23, 2021. (Adapted from: https://www.openstreetmap.org)

2.2. Sampling and instrumentation

The autumn campaign of AVIATOR took place in October 2021. Sampling was conducted continuously, starting at 12:00 pm on October 8, 2021 and ending at 20:00 pm on October 23, 2021. An ambient instrumentation system with specific reference to PM was deployed at Madrid Airport to better characterise air quality at the airport microenvironment. The measurement equipment of the system includes an Aerodyne High-Resolution Time-of-Flight Aerosol Mass Spectrometer (AMS) for the chemical speciation of the particles. AMS measures concentration and chemical composition of non-refractory aerosols online. AMS provided high-resolution measurements of primary and secondary organic aerosol and inorganic aerosol including sulphates, nitrates, and ammonium, from approximately 60 nm to 600 nm with 100 % transmission, extending to smaller and larger sizes with reduced transmission (Canagaratna *et al.*, 2007). In addition to daily standard AMS flow, baseline and single ion calibrations, an ammonium nitrate solution was atomised to calibrate the AMS (for size-dependent ionisation efficiency). The analysis of the chemical characteristics of aircraft PM using an AMS have been described elsewhere in detail (Yu *et al.*, 2010; Anderson *et al.*, 2011; Smith *et al.*, 2022).
Equivalent black carbon mass concentration (*e*BC) based on aerosol optical absorption was monitored using the Multi-Angle Absorption Photometer (MAAP) during this campaign. The MAAP operates at 670nm wavelength, has a 10s-time response with a flow rate of 8 litre/min, for unattended long-term monitoring of carbonaceous particulate emissions from combustion sources (Petzold and Schonlinner, 2004). MAAP has been used for the monitoring of black carbon emission from aviation (Herndon *et al.*, 2008; Timko *et al.*, 2014). The instrument was set up to measure average *e*BC concentrations with one-minute intervals. By using a condensation particle counter (CPC), TSI model 3750 (D_{50}≈7nm), total particle number concentration was measured real-time to capture temporal variability in particle number concentrations with a measurement range of up to 100,000 particles/cm³ and a time resolution of one second. Ambient CO_2 concentration near runways were also measured by a LI-COR CO_2 Trace Gas Analysers at 1-sec intervals. In addition, meteorological parameters (temperature, pressure, relative humidity, wind speed, and direction) were measured at the site with the instrumentation system. The system was co-located with AENA (REDAIR) fixed monitoring site to provide additional spatially resolved data. The REDAIR station monitors the concentration of sulphur dioxide (SO_2), nitrogen dioxide (NO_x), carbon monoxide (CO), ozone (O3), suspended particles PM (including PM2.5, PM10), and total hydrocarbon (THC) with a time resolution of 30 minutes.

https://doi.org/10.5194/egusphere-2023-2197
Preprint. Discussion started: 6 October 2023

2.3. Data analysis

AMS was operating in Mass Spectrum (MS) mode to identify chemical species present in the aerosol ensemble and quantify the overall mass loading. AMS data were analysed using the data analysis toolkit TOF-AMS SQUIRREL v1.65B supplied by Igor Pro (WaveMetrics, Inc.). Source apportionment analysis is an approach to investigate the relative contributions of various source pollutants in a sample. Using the updated graphical interface source finder (SoFi) to carry out non-refractory OA source apportionment analysis with using PMF model implemented through the multilinear engine tool (ME-2) (Canonaco *et al.*, 2013). The software Source Finder (SoFi) run under IGOR 6.37 was used to deconvolve organic aerosol emissions via the Positive Matrix Factorization (PMF) model. PMF model implemented through the multilinear engine version 2 (ME-2) factorisation tool was used to determine the number of factors (sources). ME-2 is a multivariate solver that uses the same mathematical/statistical method as PMF to evaluate solutions (Paatero, 1999). ME-2 equations are designed for analysing and calculating the relative contributions of various source pollutants by measuring their concentration at receptor locations (Paatero and Tapper, 1994). The PMF model collects many variables and filters them into two types (i) source types which can be determined by matching these sources to measured reference profiles, and (ii) source contributions, used to quantify the amount of contribution from each source to a sample. PMF inputs were restricted to only non-negative concentrations since no sample can have a negative source contribution. A step-by-step approach was used to select the number of solutions (factors). The method used by Reyes *et al.* (2016) and Smith *et al.* (2022) was used to determine the optimal solution. This approach initially began with a two-factor model and then increased to a maximum of five factors. PMF analysis was performed with seed runs and different FPEAK values (ranging from -1 to 1 with steps of 0.1) to better separate organic aerosol sources. During the analysis, it has been noted that factor four seems to consistently correlate with factor five with identical time series and similarities in mass spectra. The difficult separation has been found previously in the case of well-mixed pollutants due to low temperatures and wind speed (Reyes *et al.*, 2018). Greater stability was found when analysing 3-factor solutions with different FPEAK values. During the analysis, seed runs and PMF with FPEAK solutions show no significant variation on the Q / Qexp with a value close to 1. This is reasonable given that PMF determines the solution by minimising this value. (Reyes *et al.*, 2016). The factorisation strategy has been completely successful to separate three different sources with distinct mass spectra and different time series. Consequently, 3-factor solutions were the optimal number of sources because of their best performance in terms of lowest residuals and Q/Qexp values which is close to 1.

3. Results and Discussion

3.1 Variations of organic, inorganic, and oil emissions

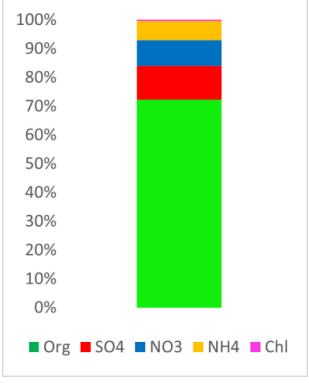

Figure 2. The bar chart shows aerosol fractions where organic and sulphate species account for more than 80% of the total aerosol mass.

Mass concentrations of organic and inorganic aerosols was 9.6 μg/m^3 on average for the entire campaign. Organic aerosols, with a significantly high fraction compared to the nearest sulphate with 15 % accounts for about 70% of the total aerosols measured by AMS. Figure 2 shows aerosol fractions where organics account for about 70% of the aerosol. The PMF analysis in this paper mainly focuses on the composition of the organic mass concentration. Lubrication oil has been detected in ambient air near runways, and it may further add to the total organic PM emissions due to aircraft engine operations (Timko *et al.*, 2010b; Yu *et al.*, 2010; Ungeheuer *et al.*, 2022). Aircraft plume measurements indicated that oil was found to contribute 5% to 100% (Yu *et al.*, 2012). The *m/z* 85 signal is a well-known oil signal in the AMS mass spectrum. Ratio of *m/z* 85:71 is used as a marker for oil (Fig. 3). The

https://doi.org/10.5194/egusphere-2023-2197
Preprint. Discussion started: 6 October 2023

ratio of 0.66 was used as a benchmark for oil contribution (Yu *et al.*, 2012). A value less than 0.66 can be considered oil-free organic PM and conversely, any value larger than 0.66 indicates the presence of lubrication oil. However, based on the AMS measurements during AVIATOR autumn campaign, lubrication oil accounted only up to 5% of the total aerosol mass, which is significantly less compared to the measurements of Yu *et al.* (2012). There are three probable explanations on the deficiency of AMS to detect oil precursors: (i) the oil particles are too small in diameter for AMS to detect, (ii) complete pyrolysis of the oil in the engine combustion zone forming carbon monoxide (CO) and carbon dioxide (CO_2) (Smith *et al.*, 2022) or (iii) oil particles contribute to an insignificant amount (by mass) of organic mass in engine exhaust therefore are not detected. Since PMF analysis is based on the organic masses measured via AMS, lubrication oil is not identified as a determinant and there is no oil organic mass profile reported in previous studies and here (Ulbrich *et al.*, 2009). PMF has been proven inefficient at detecting such levels (Ulbrich *et al.*, 2009), therefore, oil contribution to the organic mass can be under-represented in this study.

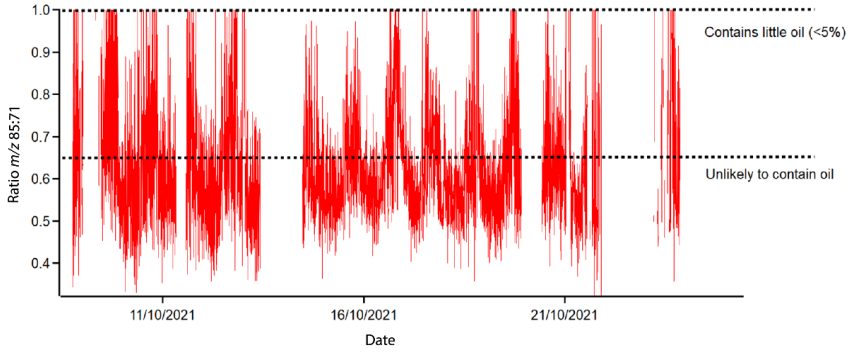

Figure 3. Temporal variability of lubrication oil fraction in total aerosol mass obtained from AMS measurements. The ratio of *m/z* 85/71 was used as the mass marker to identify lubrication oil. The analysis showed that no oil or very little (<5%) oil fraction was detected.

3.2 PMF Analysis

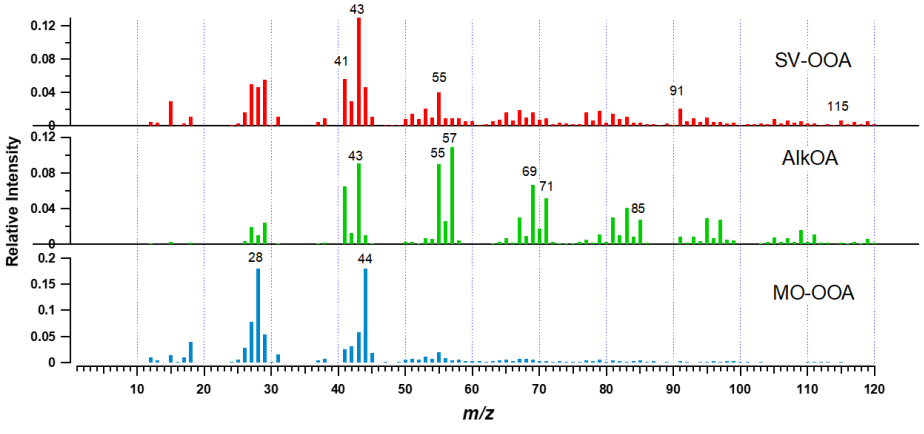

Figure 4. The mass spectral fingerprint of the three factors from the PMF solutions. Semi-Volatile Oxygenated Organic Aerosol (SV-OOA), Alkane Organic Aerosol (AlkOA), and More Oxidised Oxygenated Organic Aerosol (MO-OOA), which can be indicative of secondary aerosols. Selected mass markers with a relative intensity higher than 0.01 are numbered.

https://doi.org/10.5194/egusphere-2023-2197
Preprint. Discussion started: 6 October 2023

The PMF analysis in this study aims to provide relative contribution of the sources of aerosols near runway. In addition to determining the diurnal pattern of the obtained factors during the autumn campaign, PMF solutions were used to investigate how meteorology affects airborne particulate pollution. During AVIATOR Autumn Campaign at Madrid-Barajas International Airport three sources were identified via PMF (Fig. 4 shows the results of the PMF analysis, the mass spectral fingerprint). The first factor in Fig. 4 shows the presence of an aromatic marker at *m/z* 115, a marker used for identifying indene (C_9H_8) ion in an earlier studies focusing on aviation emissions (Timko *et al.*, 2014). The Semi-Volatile Oxygenated Organic Aerosol (SV-OOA) is associated with aromatic fragments at *m/z* 77, 91, 105, 115. It presents a high relative intensity (0.13) at *m/z* 43 (characteristic of SVOOA) and a lower relative intensity (<0.04) at *m/z* 91 which is related to toluene ion (C_7H_7) (Smith *et al.*, 2022). Due to the strong correlation (R = 0.91) and similarity in the mass spectra of SV-OOA in this study and the SV-OOA in Smith *et al.*, 2022, we consider that SV-OOA factor in our analysis potentially represent fresh secondary organic aerosols (SOA). This factor has high diurnal variation (varying with ambient temperature) since ambient temperature is a significant determinant of SV-OOA factor (Reyes *et al.*, 2016). Concentrations of SV-OOA is lowest at noon when the ambient temperature is highest (Fig. 5). In a previous PMF analysis of organic PM emitted by aircraft indicated that aromatic factor was strongly present in the organic PM with elevated signals at *m/z* 77, 91, 105, 115, 128 (Timko *et al.*, 2014). The aromatic factor determined by Timko *et al.*,2014 was found to dominate the organic PM emissions from turbo-jet engine at low-thrust engine settings. The factor was linked with the products of incomplete combustion and had a high variability, varying with the engine power settings (the sum of signals in the factor decreased with the increasing engine power).

The second factor, identified based on the PMF analysis of Madrid airport sample, is Alkane Organic Aerosol (AlkOA) factor. It is related to unburnt fuel and incomplete combustion emission with high relative intensities at *m/z* 43, 57, and 85 (typically decane, $C_{10}H_{22}$, which is an alkane found in jet fuel). Given that mass spectral fingerprint of decane is similar to the other aliphatic hydrocarbons (*e.g.*, long-chain alkanes) found in Jet A1 fuel (Yu *et al.*, 2012; Smith *et al.*, 2022). AlkOA factor referred here as a marker to identify emissions originating from unburnt fuel/incomplete fuel combustion products. Previously, primary aliphatic factor was found in PMF analysis by Timko *et al.* (2014) and was attributed based on *m/z* ratios such as 41/43, 55/57, 69/71, 83/85. Each of these masses correspond to an alkane. Aliphatic #1 was strongly correlated with black carbon soot emissions for the high-power conditions. The strong association of aliphatic #1 with soot emissions indicated that they have similar combustion sources. It was concluded that aliphatic #1 derived from combustion related sources and can potentially contain significant unburnt jet fuel. Further, there is a strong positive linear correlation between the determined AlkOA and decane factor from NIST webbook (R= 0.83) NIST Mass Spectrometry Data Center, 1990), and between the determined AlkOA factor in this study and the AlkOA factor reported by (Smith *et al.*, 2022) (R=0.93). The positive linear correlation among these three factors is indicative of similar primary pollutants derived from fuel vapours or incomplete combustion products originating from jet fuel. Results are consistent with previous findings of another study (Smith *et al.*, 2022). The third factor More Oxidised Oxygenated Organic Aerosol (MO-OOA) has a spectral fingerprint consists of more oxidised ions (compared to SV-OOA and AlkOA) indicating a secondary aerosol fraction in the sample. MO-OOA is identified by its characteristic high relative intensities (>0.18) at *m/z* 29 and 44. Given that MO-OOA has the highest *f44/43* ratio among the three factors, it is expected to be the most oxygenated (in chemical content) factor. Being more oxidised potentially makes MO-OOA less volatile than SV-OOA (Jimenez *et al.*, 2009; Smith *et al.*, 2022). Other sources may have been included in one or both factor solutions, consequently, this does not rule out the possibility of their existence.

3.3 The temporal distribution of factors and correlation with trace gases

https://doi.org/10.5194/egusphere-2023-2197
Preprint. Discussion started: 6 October 2023

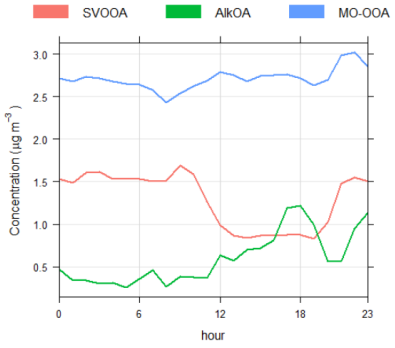

Figure 5. Diurnal pattern of the solved factors from October 8, 2021 to October 23, 2021. Compared to SV-OOA and AlkOA; MO-OOA has the smallest variation in its diurnal pattern.

Average hourly concentrations of the PMF determined factors were calculated to monitor the diurnal variation of the source contributions. The variation of the AlkOA concentration during the day mostly associated with aircraft emissions (Fig. 5). The concentration of AlkOA factor is relatively higher in the afternoon compared to the morning and midday. This diurnal AlkOA pattern is similar to the diurnal flight activity and indicates that the AlkOA increase starting at noon is related to the primary particles emitted by aircraft. This source is previously reported as the main determinant of the air quality in the vicinity of the airport (Masiol and Harrison, 2014). Ambient temperature is the major determinant of the SVOOA. SVOOA has the lowest concentrations in the afternoon and increases in the evening until noon. Decreasing ambient temperature causing SVOOA to partition to the particle phase is the probable cause of the increase in the evenings. Unlike other factors, MO-OOA has no significant diurnal variation. This gives an indication of the formation of aged secondary organic aerosols which is often due to atmospheric transport (Zhang *et al.*, 2007). AlkOA was moderately correlated with *e*BC, NO_x, SO_2, and CO at Madrid-Barajas Airport as the linear correlation coefficients are given in Table 1 (R=0.56, R =0.52, R =0.53, and R =0.52). In contrast, the correlation of these trace gases with the SVOOA and MO-OOA is lower compared to AlkOA since R values ranging from 0.2 to 0.5 (Table 1). The reason that AlkOA has a slightly higher correlation (R > 0.5) with BC, NO_x, SO_2 and CO compared to SVOOA and MO-OOA, AlkOA is considered to be a primary pollutant (directly emitted by the source) whereas SVOOA and MO-OOA are theoretically formed through condensation and/coagulation of primary pollutants.
Further, diurnal patterns of BC, NO_x, SO_2 and CO can be significantly affected by meteorological conditions (*e.g.*, wind speed, temperature) (Carslaw *et al.*, 2006; Reyes *et al.*, 2018) which explains their moderate correlation with AlkOA, R values ranging from 0.52 to 0.56 (Table 1). AlkOA and trace gases were normalized to compare their diurnal patterns. Figure 6 shows diurnal patterns of *e*BC, NO_x, CO, and particle number concentration. Their diurnal pattern is mostly similar, there are very pronounced increases in concentrations for *e*BC, NO_x, and CO during am and pm rush hours. Early morning AlkOA concentration is significantly lower compared to *e*BC, NO_x and CO. This could be due to the lower emissions from decreased aircraft activities in early mornings. Early morning increase in trace gases and *e*BC may be due to other airport activities. These other activities potentially include emissions from vehicles for ground services and ground service equipment at the airport (Masiol and Harrison, 2014). The total number concentration had a temporal pattern similar to AlkOA. Throughout the day, AlkOA and trace gases' temporal profiles were also similar. The similarity in temporal profiles indicates similar source origins which can be associated temporally with aircraft activity.

Table 1 Results of linear regression analysis between obtained factors (SVOOA, AlkOA, and MO-OOA) and external tracers

	*e*BC (µg/m³)	NO_x (µg/m³)	SO_2 (µg/m³)	CO (mg/m³)	THC (mg/m³)	PM2.5 (µg/m³)	Tot No. conc (particles/cm³)	CO2 (ppm)
SVOOA	0.49	0.28	0.21	0.32	0.63	0.36	-0.08	0.24
AlkOA	0.56	0.52	0.53	0.52	0.35	0.66	0.4	0.35
MO-OOA	0.48	0.36	0.26	0.45	0.41	0.55	0.1	0.22

https://doi.org/10.5194/egusphere-2023-2197
Preprint. Discussion started: 6 October 2023

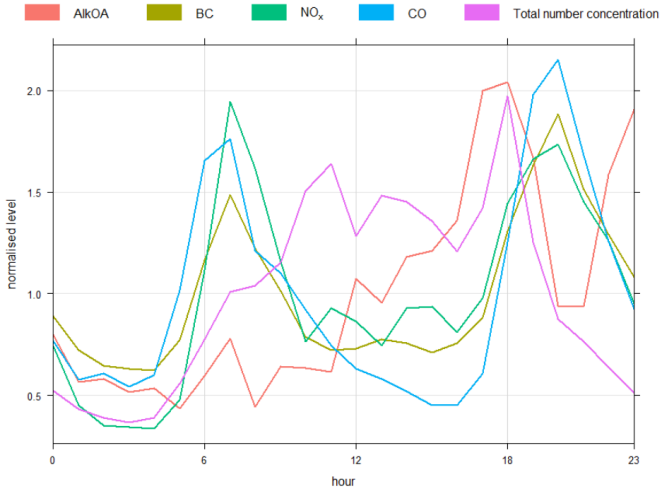

Figure 6. The diurnal cycle of AlkOA compared to *e*BC, NO_x, CO, and total number concentration. In this plot, the concentrations are normalised with the objective of comparing the patterns of different pollutants using the same scale.

3.4 Spatial analysis

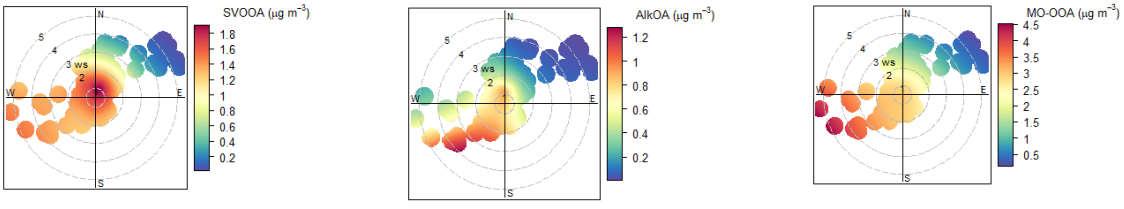

Figure 7. Bivariate polar plots for SVOOA, AlkOA, and MO-OOA (µg/m^3). The highest concentrations were measured when the winds were originated from the west and southwest. Runways 18R/36L and 14R/32L located at western and eastern sides of the measurement station and the hanger zone with terminals T1, T2, T3, T4, and TS4 were located at the south and southwest of the measurement site (Fig. 1).

Varying sources can be discriminated by means of bivariate polar plots techniques (Carslaw and Ropkins, 2012). Figure 7 shows how the airport activities impact the average concentrations of the factors (SVOOA, AlkOA and MO-OOA) determined via PMF. The highest concentrations of AlkOA, and MO-OOA were determined at low to moderate wind speeds (3~5 m/s) from the west and southwest (R= -0.35 and R= -0.42, respectively), where terminal buildings (T1, T2, T3, T4 and TS4), two of the runways (14R/32L and 18R/36L), and a nearby hanger zone are located. Highest SVOOA contribution determined at lower wind speeds (below 2 m/s) with a correlation between them (R= -0.45). Both SVOOA and MO-OOA are more likely to be mixed and determined by a local source at low wind speeds < 2 m/s (Crilley *et al.*, 2015; Helin *et al.*, 2018). By contrast, the minimum significant contribution from all factors identified when the winds were originating from the northeast of the airport, with relatively higher wind speeds (above 4 m/s). Thus, based on the polar plots shown in Fig. 7 the emissions from terminal buildings and hanger zone located at the southwest of the measurement station is the major source of the total organic particle concentrations at the measurement station. The average contribution of SVOOA, AlkOA, and MO-OOA was 1.63, 0.63, and 2.35 µg/m^3, respectively (Table S1). SVOOA and MO-OOA accounted more than 80% of the total organic mass during AVIATOR Campaign in October, 2021. The linear correlations (Pearson correlation) between (i) AlkOA with *e*BC and (ii) SVOOA with THC were measured under varying wind speed and directions (Fig. 8). The relative contribution of the derived factors was higher when the winds originating from southwest of the airport compared to the winds carrying air parcels to the sampling point from

https://doi.org/10.5194/egusphere-2023-2197
Preprint. Discussion started: 6 October 2023

the northeast as discussed. However, the correlation coefficient for both varies highly ($0.2 \leq R \leq 0.9$) for all samples (from all directions) within the airport perimeter. AlkOA, for instance, has a strong linear correlation with *e*BC (Pearson coefficient higher than 0.9) when the winds are originating from west, east or north-east as shown in Fig. 8. This is due to the effect of runways 18L/36R and 18R/36L locations (each located on east and west of the measurement site as shown in Fig. 1) where 90% of the aircraft take-off takes place. Both AlkOA and *e*BC are related to jet fuel emissions. Furthermore, a significant linear correlation was measured between SVOOA and THC when dominant winds were north easterlies (the air parcels move from runways 18L/36R to the sampling station). THC emissions at the airports depend mainly on the jet engine thrust setting (Anderson *et al.*, 2006; Onasch *et al.*, 2009). When the engines operate at low thrust settings (*e.g.*, during taxiing/idling), the combustion is less efficient and a higher amount of hydrocarbons is emitted. The association between SVOOA and (THC) at some parts of the airport could be interpreted as an indication of fresh emissions from the aircraft in service.

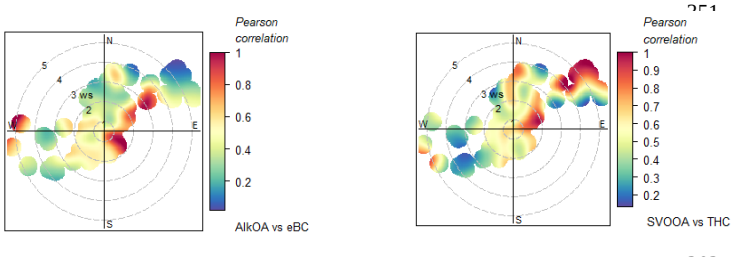

Figure 8. A Pearson correlation analysis using bivariate polar plots (above) shows a significant positive linear correlation between AlkOA with *e*BC and SVOOA with THC mass concentrations when prevailing winds were northeast. (The location of runways 18L/36R).

NO_x emitted by aircraft can potentially affect air quality up to 2.6 km away from the airport (Carslaw *et al.*, 2006), however, there are challenges in determining an accurate contribution of the airport to local NO_x concentration due to other sources (mostly mobile) of NO_x in cities. In this study, the potential contribution from road traffic surrounding the airport, particularly the motorways located south and southwest of the airport, are originating from same direction where runway 14R/32L and all the terminals are also located. Therefore, NO_x contribution was higher from the south and southwest of the airport (including local on-road NO_x) compared to the northeast. The lowest NO_x concentrations were measured under moderate wind speed conditions (above 4 m/s) (Fig. S1). This is possibly due to atmospheric mixing and plume dilution caused by advection (Carslaw *et al.*, 2006), since the ground-level source emissions are inversely proportional to wind speed. The measurements of sulphur dioxide (SO_2) and carbon monoxide (CO) were available during this campaign by AENA (REDAIR) station located at the airport (Fig. S1). Aviation activities were previously reported as a significant source of SO2, while CO and NO_x were mainly related to road traffic sources (Yu *et al.*, 2004). However, the bivariate polar plots presented in Fig. 9 higher SO_2/NO_x and CO/*e*BC ratios measured when the dominant winds originating from the northeast of the airport (with no- or little road traffic contribution). The analysis of the SO_2/NO_x and CO/*e*BC concentration ratios vary based on wind direction and speed in October 2021 at Madrid-Barajas Airport. The higher ambient SO_2/NO_x and CO/*e*BC ratios indicate the potential impact of aircraft taxing and taking off on local ambient SO_2 and CO concentrations when the winds originating from northeast where the 18L/36R runways are located. SO_2 emissions are associated primarily with the sulphur content of the fuel, as well as emissions during aircraft activities at the airport, such as approach, taxi-idle and climb (Yang *et al.*, 2018).

Black carbon (*e*BC) and carbon monoxide (CO) are mainly produced by incomplete/inefficient combustion. CO/*e*BC ratio varies significantly with the source (Bond *et al.*, 2004), which can be a sign of varying different sources in the vicinity of the airport as previously reported. The highest aircraft CO is emitted at low power engine settings (during taxiing and idling), this significantly affects the air quality within the airport as the idle and taxi phases account most of the time an aircraft spends at the airport (Stettler *et al.*, 2011; Yunos *et al.*, 2017). Higher CO/*e*BC ratios in the air parcels originating from northeast can also be attributed to the effect of aircraft activity at the runway 18L/36R located in the northeast of the measurement station. On the other hand, SO_2 /NO_x and CO/*e*BC ratios were lower (0-0.4) when the winds were originating from southwest due to the other significant sources of NO_x and *e*BC in this direction (nearby road traffic). Based on the polar plots shown in Fig. 9, an aircraft SO_2 and CO signal to the east and northeast is identified (different to wind-dependant NO_x pattern). Further details on daily variation of meteorological parameters and trace gases for the sampling period can be found in the supplementary material (Fig. S1).

https://doi.org/10.5194/egusphere-2023-2197
Preprint. Discussion started: 6 October 2023

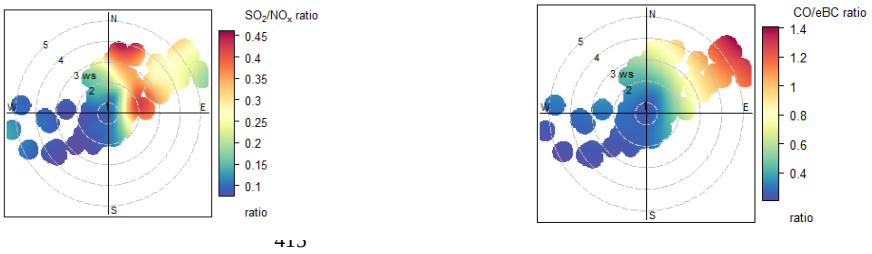

Figure 9. Bivariate polar plots of SO_2 /NO_x and CO/*e*BC ratios at the airport. The angular contributions of SO_2 and CO is different compared to the PMF determined factors. The plots indicates that the flight activities at the east and northeast where the 18L/36R runway is located are the source of increase in SO_2 and CO.

4. Conclusion

This study identified the impact of an international airport on the local air quality. As part of the AVIATOR campaign, several measurements were conducted at the Madrid–Barajas Airport, in October 2021 for monitoring the chemical composition of sub-micron particles and ambient trace gas concentrations near runway.

Total non-refractory particles were dominated by organics (more than 72% of the total). Sulphate particles were the second most abundant chemical species and accounted about 13% of the total aerosol. Based on AMS data (relative intensities of *m/z* 71 and 85), no significant oil fraction in the organic particulate matter (PM) samples were measured. This could be either there is no oil in sub-micron particle size range or due to the method used in this study (AMS) is not able to identify lubricant oil in PM. Thus, further measurements with improved measurement technique may be required to identify oil fraction in sub-micron organic aerosol.

Trace gases were also monitored along with the particle monitoring tools. Average ambient concentrations of *e*BC, NO_x, SO_2, $PM_{2.5}$, PM_{10} at the airport during October 2021 were 1.07, 22.7, 4.10, 9.35, and 16.43 (μg/m³), respectively. By comparing angular NO_x distribution with SO_2/NO_x and CO/*e*BC, take-off activities at the northeast of the measurement station were identified as a potential local source of SO_2 and CO in Barajas-Madrid. NO_x contribution at the sampling point was highest when the winds originating from south and southeast of the airport. There are two motorways with road traffic were located at the same direction as long as terminal buildings and southern runways in Madrid. Therefore, NO_x concentrations were more likely determined by on-road traffic compared to the aircraft activity at the sampling point. Sources of organic aerosols (as the most abundant non-refractory aerosol group) were identified via Positive Matrix Factorisation (PMF) analysis. PMF was able to discriminate three main significant sources: Semi Volatile Oxygenated Organic Aerosol (SV-OOA), Alkane Organic Aerosol (AlkOA), and More Oxidised Oxygenated Organic Aerosol (MO OOA). The sum of SV-OOA and MO OOA fractions accounting for more than 80% of the total organic mass throughout the campaign, SV-OOA had the highest relative intensity (RI) at *m/z* 43 (which is characteristic of SVOOA), MO-OOA had a high RI at *m/z* 28 and 44 these indicate a potential secondary aerosol fraction. Third factor, AlkOA, had high RIs at *m/z* 43, 57 and 85 (attributed to decane previously) which is related to jet fuel vapour (Smith *et al.*, 2022).

Bivariate polar plots were used to angular PMF determined factor and ambient trace gas distributions based on wind speed and wind direction at the airport. It has been found that, the PMF determined factors had highest relative contributions when the winds originating from the west and southwest of the airport where runways 14R/32L and 18R/36L, as well as terminals T1, T2, T3, T4 and TS4, are located. Being embedded in a region with varying different sources including aircraft and airport terminal emissions, emission ratios of combustion tracers measured and angular correlation analysis based on wind direction and speed indicated that SO_2 and CO emissions are potentially determined by aircraft take off activities at 18L/36R runway located along the east and northeast of the sampling point where more than 50% of the take-off activity took place in the sampling period. Further origins of the organic aerosols measured at the Madrid-Barajas were identified towards a better understanding of emissions from an international airport and provide the chemical composition of particulate matter and gaseous pollutants in the vicinity of airport.

There are two previously reported significant ways to reduce aviation emissions at airports, improving efficiency of the processes emitting air pollutants such as electrification of airport taxiway operations (Salihu *et al.*, 2021), and switching to sustainable alternative fuels where applicable. Improved ground activities at airports such as electric aircraft towing system can potentially lead up to 82 % reduction in CO_2 emissions (van Baaren, 2019), while switching to SAF alone reduce Landing-takeoff cycle (LTO) emissions up to 70 % compared to fossil fuel (Schripp *et al.*, 2022). Further, SAF use for auxiliary power units (APU) also potentially reduce NO_x and CO_2

https://doi.org/10.5194/egusphere-2023-2197
Preprint. Discussion started: 6 October 2023

emissions by at least 5%. Therefore, improving energy efficiency of ground activities at airports and using SAF are recommended for policymakers to improve the overall air quality at airports.

Author contributions. **Saleh Alzahrani, Doğuşhan Kılıç, Michael Flynn, Paul I. Williams** and **James Allan** designed the project; **Saleh Alzahrani, Doğuşhan Kılıç, Michael Flynn** and **Paul I. Williams** performed the fieldwork; **Saleh Alzahrani** performed the data analysis, and wrote – original draft of the article; **Doğuşhan Kılıç** reviewed and edited the article; **Paul I. Williams** and **James Allan** supervised, reviewed and edited the article.

Competing interests. At least one of the (co-) authors is a member of the editorial board of Atmospheric Chemistry and Physics.

Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 814801.

References

Air transport statistics - Statistics Explained (europa.eu)

Amato, F., Moreno, T., Pandolfi, M., Querol, X., Alastuey, A., Delgado, A., Pedrero, M. and Cots, N., 2010. Concentrations, sources and geochemistry of airborne particulate matter at a major European airport. Journal of Environmental Monitoring, 12(4), pp.854-862.

Anderson, B.E., Beyersdorf, A.J., Hudgins, C.H., Plant, J.V., Thornhill, K.L., Winstead, E.L., Ziemba, L.D., Howard, R., Corporan, E., Miake-Lye, R.C. and Herndon, S.C., 2011. *Alternative aviation fuel experiment (AAFEX)* (No. NASA/TM-2011-217059).

Anderson, B.E., Chen, G. and Blake, D.R., 2006. Hydrocarbon emissions from a modern commercial airliner. *Atmospheric Environment*, *40*(19), pp.3601-3612.

Annex, I.C.A.O., 16. Environmental Protection. *Volume II Aircraft Engine Emissions*.

Bond, T.C., Streets, D.G., Yarber, K.F., Nelson, S.M., Woo, J.H. and Klimont, Z., 2004. A technology-based global inventory of black and organic carbon emissions from combustion. *Journal of Geophysical Research: Atmospheres*, *109*(D14).

Boldo, E., Medina, S., Le Tertre, A., Hurley, F., Mücke, H.G., Ballester, F., Aguilera, I. and Daniel Eilstein on behalf of the Apheis group, 2006. Apheis: Health impact assessment of long-term exposure to PM 2.5 in 23 European cities. *European journal of epidemiology*, *21*, pp.449-458.

Canagaratna, M.R., Jayne, J.T., Jimenez, J.L., Allan, J.D., Alfarra, M.R., Zhang, Q., Onasch, T.B., Drewnick, F., Coe, H., Middlebrook, A. and Delia, A., 2007. Chemical and microphysical characterization of ambient aerosols with the aerodyne aerosol mass spectrometer. *Mass spectrometry reviews*, *26*(2), pp.185-222.

Canonaco, F., Crippa, M., Slowik, J.G., Baltensperger, U. and Prévôt, A.S., 2013. SoFi, an IGOR-based interface for the efficient use of the generalized multilinear engine (ME-2) for the source apportionment: ME-2 application to aerosol mass spectrometer data. *Atmospheric Measurement Techniques*, *6*(12), pp.3649-3661.

Carslaw, D.C., Beevers, S.D., Ropkins, K. and Bell, M.C., 2006. Detecting and quantifying aircraft and other on-airport contributions to ambient nitrogen oxides in the vicinity of a large international airport. *Atmospheric Environment*, *40*(28), pp.5424-5434.

Carslaw, D.C. and Ropkins, K., 2012. Openair—an R package for air quality data analysis. *Environmental Modelling & Software*, *27*, pp.52-61.

https://doi.org/10.5194/egusphere-2023-2197
Preprint. Discussion started: 6 October 2023

Crilley, L.R., Bloss, W.J., Yin, J., Beddows, D.C., Harrison, R.M., Allan, J.D., Young, D.E., Flynn, M., Williams, P., Zotter, P. and Prévôt, A.S., 2015. Sources and contributions of wood smoke during winter in London: assessing local and regional influences. *Atmospheric chemistry and physics*, *15*(6), pp.3149-3171.

He, R.W., Shirmohammadi, F., Gerlofs-Nijland, M.E., Sioutas, C. and Cassee, F.R., 2018. Pro-inflammatory responses to PM0. 25 from airport and urban traffic emissions. *Science of the total environment*, *640*, pp.997-1003.

Herndon, S.C., Jayne, J.T., Lobo, P., Onasch, T.B., Fleming, G., Hagen, D.E., Whitefield, P.D. and Miake-Lye, R.C., 2008. Commercial aircraft engine emissions characterization of in-use aircraft at Hartsfield-Jackson Atlanta International Airport. *Environmental science & technology*, *42*(6), pp.1877-1883.

Helin, A., Niemi, J.V., Virkkula, A., Pirjola, L., Teinilä, K., Backman, J., Aurela, M., Saarikoski, S., Rönkkö, T., Asmi, E. and Timonen, H., 2018. Characteristics and source apportionment of black carbon in the Helsinki metropolitan area, Finland. *Atmospheric Environment*, *190*, pp.87-98.

Hu, S., Fruin, S., Kozawa, K., Mara, S., Winer, A.M. and Paulson, S.E., 2009. Aircraft emission impacts in a neighborhood adjacent to a general aviation airport in Southern California. *Environmental science & technology*, *43*(21), pp.8039-8045.

Hudda, N. and Fruin, S.A., 2016. International airport impacts to air quality: size and related properties of large increases in ultrafine particle number concentrations. *Environmental science & technology*, *50*(7), pp.3362-3370.

Hudda, N., Gould, T., Hartin, K., Larson, T.V. and Fruin, S.A., 2014. Emissions from an international airport increase particle number concentrations 4-fold at 10 km downwind. *Environmental science & technology*, *48*(12), pp.6628-6635.

Hudda, N., Simon, M.C., Zamore, W., Brugge, D. and Durant, J.L., 2016. Aviation emissions impact ambient ultrafine particle concentrations in the greater Boston area. *Environmental science & technology*, *50*(16), pp.8514-8521.

Jimenez, J.L., Canagaratna, M.R., Donahue, N.M., Prevot, A.S.H., Zhang, Q., Kroll, J.H., DeCarlo, P.F., Allan, J.D., Coe, H., Ng, N.L. and Aiken, A.C., 2009. Evolution of organic aerosols in the atmosphere. *science*, *326*(5959), pp.1525-1529.

Jonsdottir, H.R., Delaval, M., Leni, Z., Keller, A., Brem, B.T., Siegerist, F., Schönenberger, D., Durdina, L., Elser, M., Burtscher, H. and Liati, A., 2019. Non-volatile particle emissions from aircraft turbine engines at ground-idle induce oxidative stress in bronchial cells. *Communications biology*, *2*(1), p.90.

Kinsey, J.S., 2009. *Characterization of emissions from commercial aircraft engines during the Aircraft Particle Emissions eXperiment (APEX) 1 to 3*. Office of Research and Development, US Environmental Protection Agency.

Kinsey, J.S., Dong, Y., Williams, D.C. and Logan, R., 2010. Physical characterization of the fine particle emissions from commercial aircraft engines during the Aircraft Particle Emissions eXperiment (APEX) 1–3. *Atmospheric Environment*, *44*(17), pp.2147-2156.

Kinsey, J.S., Hays, M.D., Dong, Y., Williams, D.C. and Logan, R., 2011. Chemical characterization of the fine particle emissions from commercial aircraft engines during the Aircraft Particle Emissions eXperiment (APEX) 1 to 3. *Environmental science & technology*, *45*(8), pp.

Lee, D.S., Pitari, G., Grewe, V., Gierens, K., Penner, J.E., Petzold, A., Prather, M.J., Schumann, U., Bais, A., Berntsen, T. and Iachetti, D., 2010. Transport impacts on atmosphere and climate: Aviation. *Atmospheric environment*, *44*(37), pp.4678-4734.

Li, N., Hao, M., Phalen, R.F., Hinds, W.C. and Nel, A.E., 2003. Particulate air pollutants and asthma: a paradigm for the role of oxidative stress in PM-induced adverse health effects. *Clinical immunology*, *109*(3), pp.250-265.

https://doi.org/10.5194/egusphere-2023-2197
Preprint. Discussion started: 6 October 2023

Masiol, M. and Harrison, R.M., 2014. Aircraft engine exhaust emissions and other airport-related contributions to ambient air pollution: A review. *Atmospheric Environment*, *95*, pp.409-455.

Mazaheri, M., Johnson, G.R. and Morawska, L., 2011. An inventory of particle and gaseous emissions from large aircraft thrust engine operations at an airport. *Atmospheric Environment*, *45*(20), pp.3500-3507.

NIST Mass Spectrometry Data Center. (1990). Decane, US secretary of commerce. https://webbook.nist.gov/cgi/cbook.cgi?ID=C124185&Mask=200#Mass-Spec.

Onasch, T.B., Jayne, J.T., Herndon, S., Worsnop, D.R., Miake-Lye, R.C., Mortimer, I.P. and Anderson, B.E., 2009. Chemical properties of aircraft engine particulate exhaust emissions. *Journal of Propulsion and Power*, *25*(5), pp.1121-1137.
3415-3421.

Paatero, P., 1999. The multilinear engine—a table-driven, least squares program for solving multilinear problems, including the n-way parallel factor analysis model. *Journal of Computational and Graphical Statistics*, *8*(4), pp.854-888.

Paatero, P. and Tapper, U., 1994. Positive matrix factorization: A non-negative factor model with optimal utilization of error estimates of data values. *Environmetrics*, *5*(2), pp.111-126.

Petzold, A. and Schönlinner, M., 2004. Multi-angle absorption photometry—a new method for the measurement of aerosol light absorption and atmospheric black carbon. *Journal of Aerosol Science*, *35*(4), pp.421-441.

Pope III, C.A. and Dockery, D.W., 2006. Health effects of fine particulate air pollution: lines that connect. *Journal of the air & waste management association*, *56*(6), pp.709-742.

Reyes-Villegas, E., Green, D.C., Priestman, M., Canonaco, F., Coe, H., Prévôt, A.S. and Allan, J.D., 2016. Organic aerosol source apportionment in London 2013 with ME-2: exploring the solution space with annual and seasonal analysis. *Atmospheric Chemistry and Physics*, *16*(24), pp.15545-15559.

Reyes-Villegas, E., Priestley, M., Ting, Y.C., Haslett, S., Bannan, T., Le Breton, M., Williams, P.I., Bacak, A., Flynn, M.J., Coe, H. and Percival, C., 2018. Simultaneous aerosol mass spectrometry and chemical ionisation mass spectrometry measurements during a biomass burning event in the UK: insights into nitrate chemistry. *Atmospheric Chemistry and Physics*, *18*(6), pp.4093-4111.

Rissman, J., Arunachalam, S., Woody, M., West, J.J., BenDor, T. and Binkowski, F.S., 2013. A plume-in-grid approach to characterize air quality impacts of aircraft emissions at the Hartsfield–Jackson Atlanta International Airport. *Atmospheric Chemistry and Physics*, *13*(18), pp.9285-9302.

Salihu, A.L., Lloyd, S.M. and Akgunduz, A., 2021. Electrification of airport taxiway operations: A simulation framework for analyzing congestion and cost. Transportation Research Part D: Transport and Environment, 97, p.102962.

Schripp, T., Anderson, B.E., Bauder, U., Rauch, B., Corbin, J.C., Smallwood, G.J., Lobo, P., Crosbie, E.C., Shook, M.A., Miake-Lye, R.C. and Yu, Z., 2022. Aircraft engine particulate matter emissions from sustainable aviation fuels: Results from ground-based measurements during the NASA/DLR campaign ECLIF2/ND-MAX. Fuel, 325, p.124764.

Schwarze, P.E., Øvrevik, J., Låg, M., Refsnes, M., Nafstad, P., Hetland, R.B. and Dybing, E., 2006. Particulate matter properties and health effects: consistency of epidemiological and toxicological studies. *Human & experimental toxicology*, *25*(10), pp.559-579.

Smith, L.D., Allan, J., Coe, H., Reyes-Villegas, E., Johnson, M.P., Crayford, A., Durand, E. and Williams, P.I., 2022. Examining chemical composition of gas turbine-emitted organic aerosol using positive matrix factorisation (PMF). *Journal of Aerosol Science*, *159*, p.105869.

Stettler, M.E.J., Eastham, S. and Barrett, S.R.H., 2011. Air quality and public health impacts of UK airports. Part I: Emissions. *Atmospheric environment*, *45*(31), pp.5415-5424.

https://doi.org/10.5194/egusphere-2023-2197
Preprint. Discussion started: 6 October 2023

Timko, M.T., Albo, S.E., Onasch, T.B., Fortner, E.C., Yu, Z., Miake-Lye, R.C., Canagaratna, M.R., Ng, N.L. and Worsnop, D.R., 2014. Composition and sources of the organic particle emissions from aircraft engines. *Aerosol Science and Technology*, *48*(1), pp.61-73.

Timko, M.T., Onasch, T.B., Northway, M.J., Jayne, J.T., Canagaratna, M.R., Herndon, S.C., Wood, E.C., Miake-Lye, R.C. and Knighton, W.B., 2010. Gas turbine engine emissions—Part II: chemical properties of particulate matter.

Ulbrich, I.M., Canagaratna, M.R., Zhang, Q., Worsnop, D.R. and Jimenez, J.L., 2009. Interpretation of organic components from Positive Matrix Factorization of aerosol mass spectrometric data. *Atmospheric Chemistry and Physics*, *9*(9), pp.2891-2918.

Ungeheuer, F., Caudillo, L., Ditas, F., Simon, M., van Pinxteren, D., Kılıç, D., Rose, D., Jacobi, S., Kürten, A., Curtius, J. and Vogel, A.L., 2022. Nucleation of jet engine oil vapours is a large source of aviation-related ultrafine particles. *Communications Earth & Environment*, *3*(1), p.319.

van Baaren, E., 2019. The feasibility of a fully electric aircraft towing system.

Westerdahl, D., Fruin, S.A., Fine, P.L. and Sioutas, C., 2008. The Los Angeles International Airport as a source of ultrafine particles and other pollutants to nearby communities. *Atmospheric Environment*, *42*(13), pp.3143-3155.

Yang, X., Cheng, S., Lang, J., Xu, R. and Lv, Z., 2018. Characterization of aircraft emissions and air quality impacts of an international airport. *Journal of environmental sciences*, *72*, pp.198-207.

Yim, S.H., Stettler, M.E. and Barrett, S.R., 2013. Air quality and public health impacts of UK airports. Part II: Impacts and policy assessment. *Atmospheric environment*, *67*, pp.184-192.

Yu, K.N., Cheung, Y.P., Cheung, T. and Henry, R.C., 2004. Identifying the impact of large urban airports on local air quality by nonparametric regression. *Atmospheric Environment*, *38*(27), pp.4501-4507.

Yu, Z., Herndon, S.C., Ziemba, L.D., Timko, M.T., Liscinsky, D.S., Anderson, B.E. and Miake-Lye, R.C., 2012. Identification of lubrication oil in the particulate matter emissions from engine exhaust of in-service commercial aircraft. *Environmental science & technology*, *46*(17), pp.9630-9637.

Yu, Z., Liscinsky, D.S., Winstead, E.L., True, B.S., Timko, M.T., Bhargava, A., Herndon, S.C., Miake-Lye, R.C. and Anderson, B.E., 2010. Characterization of lubrication oil emissions from aircraft engines. *Environmental science & technology*, *44*(24), pp.9530-9534.

Yu, Z., Timko, M.T., Herndon, S.C., Richard, C., Beyersdorf, A.J., Ziemba, L.D., Winstead, E.L. and Anderson, B.E., 2019. Mode-specific, semi-volatile chemical composition of particulate matter emissions from a commercial gas turbine aircraft engine. *Atmospheric Environment*, *218*, p.116974.

Yunos, S.N.M.M., Ghafir, M.F.A. and Wahab, A.A., 2017, April. Aircraft LTO emissions regulations and implementations at European airports. In *AIP Conference Proceedings* (Vol. 1831, No. 1).

Zhang, Q., Jimenez, J.L., Canagaratna, M.R., Allan, J.D., Coe, H., Ulbrich, I., Alfarra, M.R., Takami, A., Middlebrook, A.M., Sun, Y.L. and Dzepina, K., 2007. Ubiquity and dominance of oxygenated species in organic aerosols in anthropogenically-influenced Northern Hemisphere midlatitudes. *Geophysical research letters*, *34*(13).

Zhu, Y., Fanning, E., Yu, R.C., Zhang, Q. and Froines, J.R., 2011. Aircraft emissions and local air quality impacts from takeoff activities at a large International Airport. *Atmospheric Environment*, *45*(36), pp.6526-6533.