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# Evaluation of aircraft emissions at London Heathrow Airport

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6	<b>Evaluation of Aircraft Emissions at London</b>
7	Heathrow Airport
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## 19 ABSTRACT

A study to monitor Ultrafine Particles (UFP) at Heathrow Airport was undertaken in the autumn of 20 2017. The campaign followed on from a similar study in 2016, which put UFP at the airport into 21 22 context with nearby measurements. The objective of the 2017 study was to undertake UFP monitoring at higher time resolution (60 second scans) and in a narrower particle size range (6 to 23 100 nm). High resolution data from the NOx, PM and Black Carbon analysers on site was also 24 collected during the survey. Measurements were made at the runway station, LHR2 to attempt to 25 characterise individual aircraft using the runway. Nucleation mode particles are again seen to 26 predominantly originate from the airport, with highest concentrations associated with departing 27 aircraft. While there is some correlation of nucleation particles with NOx and BC, these pollutants, 28 together with PM mass and Aitken mode particles, also show strong associations with winds from 29 off-airport directions. There is some evidence that BC emissions from landing aircraft are enriched 30 in UV-active BC (UVPM), most likely as a result of tyre abrasion upon landing. Comparison of 31 UFP measurements with the 2016 survey was not possible because of the differences in 32 configuration of the SMPS for the two surveys. This observation demonstrates the importance of 33 documenting SMPS configuration, to determine if comparison between published data is possible. 34 Analysis of the 1 minute measurement data with associated aircraft departure information was used 35 36 to group the data by aircraft type. Larger aircraft departing from the runway recorded higher measurements of nucleation particles and NOx compared to smaller aircraft, while emissions of BC, 37 UVPM and NO<sub>2</sub> appear to be dependent upon the age of the engine design, rather than the size of 38 the aircraft. 39

40 41

## 42 1. INTRODUCTION

- Heathrow Airport is the busiest two-runway airport in the world. In 2017, the airport handled over
  78.0 million passengers and approximately 471,000 aircraft movements
- 45 (https://www.heathrow.com/content/dam/heathrow/web/common/documents/company/investor/rep
- 46 orts-and-presentations/financial-results/2017/2017-FY-Heathrow-SP-results-release.pdf). The
- airport is located in a complex environment: bounded by the M25 and M4 motorways on two sides,and by the outskirts of London on a third side.
- 49

The history of AQ measurements at Heathrow Airport, together with review of UFP at airports and
the results of our UFP study at Heathrow Airport in 2016 are extensively discussed in Stacey (2019)
and Stacey et al (2020)

53

An increasing amount of research has been undertaken close to airports, to better understand the 54 nature of ultrafine particles (UFP) emitted from aircraft. The literature review by Stacey (2019) 55 collected the most relevant literature at the time into a single document. Prior research undertaken 56 57 and referenced in this review, together with a research study of UFP measurements undertaken at Heathrow Airport in 2016 by Stacey et al (2020), informs the direction of research and analysis 58 throughout this paper. More recently studies by, for example Henry et al (2019), Lopes et al 59 (2019), Bousiotis et al (2019) and Rivas et al (2020) have supported the work of others that UFP 60 from airports and aircraft can be observed many kilometres downwind of an airport. Fushimi et al 61 (2019) found that a significant proportion of UFP measured at Narita Airport consisted of unburned 62 jet lubrication oil. 63

64

Similarly, the impact of UFP on health has been increasingly studied in recent years. Bendtsten et
al (2019) reported that the UFP sampled at two airports in Denmark is comparable in toxicity to
UFP from diesel exhaust. Habre et al (2019) found observable health impacts in sensitive receptors

downwind of Los Angeles International Airport (LAX), while Wing et al (2020) also identified a
link between exposure to aircraft-related UFP and pre-term birth in the region of LAX

70

For the first time, a panel of experts (Cassee et al, White paper, 2019) has put forward a proposal to
regulate exposure to concentrations of UFP. In terms of mitigation, both Cassee et al (2019) and De
Jesus et al (2019) found that reducing emissions of PM<sub>2.5</sub> was not likely to have any significant
effect on measured concentrations of UFP.

75

The Stacey et al (2020) study showed that UFP concentrations at Heathrow in 2016 were clearly influenced by aircraft activity and wind direction. The smallest particles were associated with winds from the airfield, and the particle size distribution of the airport-derived airmass was clearly different to typical urban roadside, urban background and rural distributions. The study focussed on ensuring comparability with the reference monitoring stations, which report measurements every three minutes. At this time resolution, it is not possible to use the data to identify individual aircraft, which depart or arrive on average every 90 seconds at Heathrow.

83

A follow-up campaign was therefore devised to measure UFP, and where possible the other
pollutants at the monitoring station, at a faster time resolution to evaluate individual aircraft
emissions and the relationships between aircraft, UFP and other pollutants. This paper builds on the
2016 report and presents the results of the 2017 study.

88

# 89 **2. METHODS**

## 90 2.1 Monitoring Location

91 This measurement campaign was designed to undertake rapid measurements of UFP and the 92 conventional pollutants at Heathrow to further explore the local nature of these pollutants in the 93 context of aircraft movements at the airport.

- 94 The network of air quality monitoring stations at Heathrow Airport is presented in Figure 1:
- 95



Figure 1. Locations of Heathrow monitoring stations. Runway 27R, Runway 27L and Runway
 09R denote the three operating modes of the airport, indicating here the runway assigned for
 departing aircraft. Note that aircraft never depart in an easterly direction on the northern runway.

101 Because of the dominant south-westerly nature of the winds in the UK, the LHR2 monitoring

station is ideally positioned to measure aircraft exhaust plumes. This location was also one of the

103 two monitoring stations used in 2016 and fully described in Stacey et al (2020).

- 104
- 105

# 106 2.2 UFP Measurement Campaign

107 Measurement of UFP at the LHR2 monitoring station was undertaken between 4<sup>th</sup> October and 7<sup>th</sup>

108 November 2017.

- 110 The following equipment was used:
- Butanol based TSI Model 3776 CPCs (TSI inc., MN, USA) to count particle numbers (the
- 112 3776 is more effective at detecting smaller particles than previous TSI CPCs D50 2.5nm).

• TSI Model 3082 with long DMA (Model 3081) classifier and soft X-ray neutraliser.

114 Automatic on-board software correction was enabled for diffusive losses and multiple charge.

115 Analyser operation and data storage controlled by the Model 3082 running AIM v10.2.0.11.

116 Data was downloaded weekly from the 3082 to a USB stick for subsequent analysis.

117 The operating methodology of the TSI Scanning Mobility Particle Sizer (SMPS) and Condensation

118 Particle Counter (CPC) has been extensively described in literature, for example by Wiedensohler et

al. (2012) and Wiedensohler et al. (2018). The only difference from the recommendations of

120 Wiedensohler et al. (2012) was the absence of a dryer. This is considered advantageous due to

121 minimising diffusive losses of particles while having little effect upon the size distribution of

122 largely hydrophobic nanoparticles subject to a significant Kelvin effect.

The SMPS instrument was configured to sample in the range 6.38nm to 98.2nm, 64 channels per decade. Sampling was programmed to run for 1 minute, sweeping up in size for 45 seconds, and returning down for the remaining 15 seconds.

126 The instrument was set up to be operated continuously for the entire measurement campaign;

unattended automated operation 24 hours per day. Because of the proprietary nature of the TSI
software and only a short window of opportunity to deploy the analysers, remote communication to
the analysers was not undertaken. The monitoring station was visited weekly to ensure correct
operation and take remedial action if required.

131

132 Calibration of the CPC and SMPS followed identical procedures and used facilities described in

133 Stacey et al (2020) but within the narrower particle size range used for the 2017 survey.

134 The 6-100nm configuration of the SMPS in 2017 differs significantly from the setup used at

Heathrow in 2016 by Stacey et al (2020) and in the UK National Particles network. Both the

136 Heathrow 2016 and National Network configurations are described in the Stacey et al (2020) paper

and are not documented further here. Comparisons of the 2016 and 2017 datasets will be explored

- in the results, but will be significantly influenced by the differences in configurations used in 2016
- and 2017 and, to an extent, the differing meteorology.
- 140 The other analysers deployed at LHR2 are described fully in Stacey et al (2020), but were
- additionally configured to collect 1 minute average data.
- 142

#### 143 **2.3 Data Analysis**

- 144 The plots and analysis undertaken in this paper make extensive use of the R and R Studio programs
- 145 (R Foundation for Statistical Computing, Vienna, Austria, and R Studio Inc, MA, USA) and the
- 146 OpenAir suite of analysis tools (Carslaw and Ropkins, (2012))
- 147
- 148 In accordance with the processes defined in Stacey et al (2020) for the 2016 datasets, Nucleation
- 149 particles are defined as particles smaller than 25 nm, Aitken particles are defined as particles
- 150 between 26 and 100 nm.
- 151 Particle number concentrations are reported in units of particles /cm<sup>3</sup>, and are calculated from
- individual size bin data from the SMPS, with no decade adjustment applied.
- 153 Measurements from the black carbon aethalometers are reported using identical procedures as
- reported in Stacey et al (2020)
- 155

## 156 **2.5 Measurement Quality Assurance and Quality Control**

157 Processing of the data was undertaken using the same QA/QC procedures described in Stacey et al

158 (2020). While the Heathrow study UFP data reported here uses the same quality assurance and

- 159 quality control procedures used for the national network datasets and the 2016 study, the differences
- 160 in configurations in 2017 (including flow rates, size ranges, sample time, software), will have a
- significant impact on the ability to make direct comparison between the two surveys. These
- 162 differences will be discussed later.

- 163 For measurements of NO<sub>x</sub>, PM<sub>10</sub>, PM<sub>2.5</sub>, BC and meteorology, the measurements at Heathrow are
- 164 managed, collected and processed following guidance described in <u>https://uk-</u>
- air.defra.gov.uk/assets/documents/reports/cat09/1902040953\_All\_Networks\_QAQC\_Document\_20
- 166 <u>12</u> Issue2.pdf. Information about these analysers is also provided in the Supplemental
- 167 Information, Tables S1 and S2.
- 168

169 **3. RESULTS** 

# 170 **3.1 Overall Summary**

- 171 Timeseries data for the hourly measurements at LHR2 are presented in Figure 2 below. One minute
- data for all pollutants are available in the DOI, and are presented graphically in Supplemental
- 173 Information, Figure S1. Hourly averaged measurements of NO<sub>x</sub>, PM<sub>10</sub>, PM<sub>2.5</sub> and BC are also
- accessible through the <u>http://heathrowairwatch.org.uk</u> webpages. The 1 minute averaged data from
- these analysers will be used to explore associations and differences to typical ambient
- 176 environments.



Hourly timeseries at LHR 2, October / November 2017



183 It can be seen from Figure 2 that the nucleation concentrations appear to be weakly correlated with 184 NO<sub>2</sub> and BC (all data  $r^2$  0.2 to 0.3), but the relationship for nucleation particles is poor with PM<sub>10</sub> 185 and PM<sub>2.5</sub> (all data  $r^2$  less than 0.01)Concentrations of nucleation particles clearly undergo a diurnal 186 cycle and, as observed in 2016 (Stacey et al (2020)), increase coincident with periods when aircraft 187 are active. The average particle size distribution for the 2017 survey reaches a maximum number 188 concentration at 12.2 nm.

189 Diurnal plots are presented in the SI (SI figs S26 to S33). Concentrations of NOx, Nucleation and

190 Aitken particles follow the expected diurnal profiles, where highest concentrations are experienced

- between 06:00 and 21:00. In contrast, diurnal concentrations of PM, BC and UVPM are highest
- between the hours of 18:00 and 02:00, coinciding with traditional periods of domestic heating, and
- the increase in the evening due to the road traffic rush hour. The diurnal profiles for PM follow the

typical profile of regional monitoring (presented in the SI), suggesting that airport measurementsare strongly influenced by off-airport airmasses.

196

#### **3.2** Dependence of Airport Measurements on Meteorology

198

The meteorology for the 2017 survey was dominated by south westerly winds, ideal for assessing the contribution of the airport and aircraft emissions at the LHR2 monitoring station. The wind rose plot for the survey is presented in the SI, figure S34

Polar plots of the hourly average data are presented in the SI, figures S2 to S10. As with the 2016 202 survey, nucleation particles are almost exclusively associated with winds from the airport. Aitken 203 particles are strongly associated with winds from the airport, but there is also contribution from 204 205 easterly and northerly wind directions. NOx,  $PM_{10}$  and  $PM_{2.5}$  polar plots are very similar to those seen at other monitoring stations across the south east of England, and mostly not from the direction 206 of the airport, reflecting the diverse sources of these pollutants in the UK. The polar plots for BC 207 and UVPM show some influence from the airport, but also when winds are low and immediately 208 west of the station. There was a construction depot next to the monitoring station during the survey, 209 active between 23:00 and 04:00, and it is likely that this has influenced the data. For the purposes 210 of aircraft analysis, this period is not included in analysis in any case. Imagery of the construction 211 depot is presented in the SI, figure S11 212

- 213
- 214
- 215

#### **3.3** Relationship Between Pollutants

Following exact time synchronisation of all measurement datasets, bivariate regression analysis was undertaken using the polarPlot function in openAir. This analysis was used to identify which wind directions were associated with the closest correlation between pollutants. These plots are provided in the SI, figures S12 to S25.

- The plots show very strong ( $r^2$  greater than 0.8) correlation between Nucleation and Aitken particles from the direction of the airport, much weaker when winds are from northerly directions. The weak correlation ( $r^2$  less than 0.4) between Nucleation and Aitken particles from the north clearly indicates that nucleation particles mostly originate from the airfield. Nucleation particles from the
- indicates that nucleation particles mostly originate from the airfield. Nucleation particles from t airport are also closely correlated with BC ( $r^2$  above 0.8).
- Nucleation particles from the airport show some correlation with UVPM and NOx ( $r^2$  between 0.5
- and 0.9), but correlation is weak ( $r^2$  less than 0.4) for Nucleation particles with either PM<sub>10</sub> or PM<sub>2.5</sub>.
- 228  $PM_{10}$  and  $PM_{2.5}$  correlation with NOx is mostly weak (r<sup>2</sup> less than 0.5) for most wind directions,

though there are clusters of good correlation ( $r^2$  above 0.8) to the north and one to the south that

could be associated with the nearby runway.  $PM_{10}$  and  $PM_{2.5}$  correlations with UVPM (r<sup>2</sup> above

231 0.8) are strongly associated with some airport wind directions and speeds, as well as from directions

north of the monitoring station, suggesting a multitude of sources contributing to PM and UVPM in

the area. The correlation immediately to the south closely mirrors the PM/NOx correlation, further

suggesting the influence of the runway as a contributor to local measurements.

235

NOx and BC correlation is good to strong ( $r^2$  between 0.6 and 1.0) for most wind directions except for the NW sector. Correlation between NOx and UVPM is strong ( $r^2$  above 0.8) for wind directions associated with the airport.

239

# 240 **3.4** Dependence of Measurements on Airport Operation

As previously stated, Heathrow operate the two runways in a rotating system when aircraft depart and arrive in a westerly direction. During any typical day, aircraft land on runway 27R for half the day, before swapping and landing on runway 27L. Aircraft depart on the other runway, allowing complete independence of departure and arrival schedules. From a monitoring perspective, this is very useful, because it raises the possibility to assess emissions from departing and arriving aircraft.

It needs to be remembered that the measurements at the monitoring station will be impacted by 246 cooling, dilution and interaction with other sources, but this is mitigated to some extent by the 247 proximity of the station to the runway and the absence of any other sources between the aircraft and 248 249 the monitoring station. In addition, especially for gaseous and mass-based PM measurements, while the background concentrations will contribute to the reported measurements, their 250 251 contributions are not removed from the datasets. This has been considered during the analysis. Aircraft movement information for the 2017 survey was again provided by Heathrow Airport 252 Limited. 253

254

The 2016 survey found that average concentrations of Nucleation particles was highest when

aircraft were departing closest to the monitoring station.

The table below provides average concentrations measured at the airport in October / November
2017 in various operating modes:

259

Pollutant / Operation	Overall	Depart 27R	Depart 27L	Depart 09R	Overnight
*	(902 hours)	(320 hours)	(308 hours)	(45 hours)	(229 hours)
	(,	(,	(,	(	(,
Nucleation, # / cm <sup>3</sup>	1813	3625	1328	422	141
Aitken , # / $cm^3$	205	317	191	127	81
BC, $\mu g/m^3$	3.22	3.61	2.34	4.47	3.61
UVPM, $\mu g/m^3$	0.71	0.85	0.49	0.58	0.83
$PM_{10}, \mu g/m^3$	15.1	14.4	13.5	28.4	15.5
$PM_{2.5}, \mu g/m^3$	10.0	9.7	8.9	18.6	10.2
NOx, ppb	52.9	76.5	39.2	71.5	33.4
NO, ppb	32.6	50.1	20.6	48.8	20.1
NO <sub>2</sub> , ppb	20.3	26.4	18.7	22.7	13.2

260

**Table 1** – average concentrations in different airport operating modes.

261 The table clearly shows that:

262	•	Highest particle numbers are associated with aircraft departing from runway 27R, closest to
263		the monitoring station. On average, Nucleation particle concentrations are 3 times higher
264		than those seen for aircraft landing on runway 27R (departing on 27L), ~8.5 times higher
265		than operations in easterly winds (departing on 09R) and 25 times higher than when the
266		airport is closed overnight.
267	•	For Aitken particles, the differences are less marked: when aircraft are departing on 27R,
268		average concentrations are 1.7 times higher than departures on 27L, 2.5 times higher than
269		departures on 09R and 3.9 times higher than overnight concentrations. Additionally,
270		concentrations of Aitken particles show a significant baseline that appears to be independent
271		of airport operating mode, confirming that emissions of Aitken particles from the airport are
272		produced in far smaller quantities when compared to emissions of Nucleation particles.
273	•	PM concentrations are highest during easterly winds (departing on 09R). This is certainly
274		the influence of longer range transport of PM from London and beyond.
275	•	BC concentrations are also highest during easterly winds, but average concentrations are
276		higher for aircraft departing on 27R compared to landing on 27R. This is also true for
277		UVPM.
278	•	UVPM concentrations are elevated overnight, confirming that domestic heating is a likely
279		additional source in the area.
280	•	Average NOx, NO and NO <sub>2</sub> concentrations are all higher when aircraft depart on 27R
281		compared to landing on 27R (departing on 27L). But high average NOx and NO
282		concentrations are also recorded during easterly winds, reflecting the influence of emissions
283		from London on these local measurements.
284	The o	bservation that departing aircraft emit higher numbers of UFP compared to arriving aircraft
285	appea	rs to contrast with work by other researchers, eg. Hudda et al (2017), Shirmohammadi et al
286	(2017	), which suggest that arriving aircraft have a significant effect on UFP concentrations directly
287	under	the flight path. However, other studies, including Keuken et al (2015) have shown that

elevated UFP concentrations can be attributed to airports even 40km from the airport and not under
flight paths. It is therefore possible that ground level dispersion of UFP emissions from aircraft
movements has not yet been fully considered in modelled and measured approaches to the
assessment of UFP from aircraft and further investigation of the possible impact mechanisms is
warranted.

293

# 294 **3.5** Examination of Fine Temporal Resolution Data

The monitoring station at LHR2 is 170m from the centre of the northern runway. Under favourable meteorology, plumes from aircraft departing and landing impact on the monitoring station, raising the possibility that these plumes can be further analysed and characterised by, for example, aircraft type, engine type, aircraft landing and aircraft departing.

299

300 On average (https://www.heathrow.com/file\_source/Company/Static/PDF/Investorcentre/Heathrow-

301 (SP)-FY2016-results-release-(FINAL).pdf), an aircraft departs from the airport every 90 seconds

between 06:00 and 23:00 every day. The SMPS/CPC configuration at LHR2 was set to provide a

full particle size sweep every minute, allowing the possibility to investigate whether to uniquely

304 assign a single measurement to an individual aircraft. Some structure in the PN measurements can

be observed which bears excellent correlation to the runway operations. The plot in Figure 3

306 presents the stacked timeseries collected on 20 October.

307

1 minute timeseries at LHR 2, 20 October 2017





### Figure 3. Stack timeseries plot, LHR2, 20 October

On this day, aircraft were landing on 27R during the morning period, and departing from 27R in the afternoon period. The elevated Nucleation particle count during departures is very clear in this plot and mirrors the observations seen in the 2016 survey. The plot also shows very clear correlation of NOx, BC and UVPM with particle number concentrations, lower for arriving aircraft and higher for departing aircraft – as would be expected for the different thrust settings in these two modes of engine operation.

Correlation of the above pollutants is less obvious for  $PM_{10}$  and  $PM_{2.5}$ , which do not follow the abrupt change in scale when the aircraft operating mode changes. The level of detail seen in the 1 minute data allows some unexpected observations to be made. The plot in Figure 4 shows the stacked timeseries for 16 October:

1 minute timeseries at LHR 2, 16 October 2017



**Figure 4.** Stack timeseries plot, LHR2, 16 October

Aircraft movements on 16 October followed the same pattern as 20 October and the trends betweenpollutants is, by and large, similar. Closer inspection reveals some subtle differences:

328

329

• PM<sub>10</sub> and PM<sub>2.5</sub> concentrations are higher during the morning arrival mode than the afternoon departure mode.

BC and UVPM concentrations do not follow each other at all throughout the airport 330 operating day. Prior to 06:00, the agreement between them is reasonable, though the effect 331 of non-aircraft sources (e.g. overnight domestic heating) is observable in the data. UVPM 332 concentrations are high between 09:00 and 15:00 (during arrivals), compared to 333 concentrations after 15:00. In contrast, BC concentrations between 09:00 and 15:00 are 334 335 lower than measurements after 15:00. On examination of the meteorology between 09:00 and 15:00, recorded wind directions were between 170 and 220 degrees. This is the sector 336 where air sampling captures the point where the majority of aircraft touchdown on the 337

runway, leading to the possibility that tyre smoke from landing aircraft was transported from the runway and measured at the station during this period. Tyre smoke from landing aircraft is a blue-grey colour and likely to be in the fine particle range, as the tyres are subjected to great stress from the acceleration and weight of the aircraft. The correlation between  $PM_{2.5}$ and UVPM, together with the absence of correlation with NOx and Nucleation particles, associated with exhaust emissions, further supports this observation.

- Winds from 0:00 to 06:00 originated from the north east and east of the monitoring station,
   suggesting off-airport emissions contributed to the elevated levels of NOx, BC and UVPM
   during this period. The NOx, BC and UVPM measurements at LHR2 are very similar to
   measurements made at other monitoring stations in the area.
- 348

The SMPS/CPC setup provides detailed information about the PSD every minute. This detail is not necessary for analysis, as the breakdown into nucleation and Aitken particle number concentrations demonstrates how the particle size distribution is dominated by fine particles. For completeness, an animation of the 1 minute PSD data from 20 October is provided in SI Animation S1. This animation clearly shows three distinct modes:

#### • Period when aircraft are not operating (0:00 to 06:00 and 23:00 to 0:00)

- Period where aircraft are landing (06:00 to 14:00)
- Period where aircraft are departing (14:00 to 23:00)

The animation also shows just how dependent the measurements are on aircraft movements. There are many periods of both high emissions, associated with aircraft, and relatively "quiet" periods, coinciding with reduced aircraft activity. This is the first time that we are aware of that airport UFP measurements have been reported in this way, clearly illustrating the nature and effect of the aircraft activity.

362

#### 363 **3.6** Correlation of UFP with aircraft movements

As part of normal airport operation, Heathrow Airport Limited keep a log of all aircraft ground movements. Records of aircraft type, time of departure or arrival and the relevant runway used were provided at 1 minute resolution. This allows analysis of Nucleation mode particles to be closely associated with exhaust plumes by tying together aircraft location, wind speed and direction, time taken for the plume to arrive at the measurement station and the associated pollution data. By knowing what aircraft is being measured, clustering of Nucleation particle concentrations by aircraft type is also possible.

For the purposes of this investigation, only aircraft departing on 27R were examined, and only
when winds were from the 105 to 265 degree sector – i.e. when the exhaust plume would be
transported to the monitoring station. Reviewing the timeseries data for the entire survey, there
were a selection of days when concentrations of Nucleation particles were highest, providing the
strongest potential to assign peak concentrations to individual aircraft. The comparison was
therefore further restricted to include only departures on 9-16, 19-21, 23 and 31 October 2017.
During this time, 5127 aircraft departed from Runway 27R, clustered into the following groups:

A :	Number of	Number of aircraft	Percentage of total
Aircraft type	aircraft	successfully identified	successfully identified
Airbus A31x / A32x series	2408	1188	49%
Airbus A33x series	191	113	59%
Airbus A34x series	72	52	72%
Airbus A35x series	42	21	50%
Airbus A380 series	315	200	63%
Boeing 737 series	137	69	50%
Boeing 747 series	308	202	66%
Boeing 757 series	39	15	38%
Boeing 767 series	307	196	64%
Boeing 777 series	732	477	66%
Boeing 787 series	442	274	62%
Others	134	70	52%

Total	5127	2877	56%

Table 2 – Departing aircraft on Runway 27R, separated by type, on selected days in October 2017.
"successfully identified" represents the number of aircraft where measured nucleation
concentrations were elevated above the prevailing background concentrations at the expected
arrival time of the plume at the monitoring station.

- 383 Initial review of the assignment of peaks revealed that a large number of departures were poorly
- identified by the analysers. A higher proportion of heavier aircraft, with an expected higher fuel use
- during takeoff, are successfully identified when compared to lighter aircraft (for example 72% of all
- A340 aircraft were identified, vs 49% of all A31x/A32x). By way of example of the problem of
- identification, Figure 5 shows Nucleation particle concentrations over a one hour period on one day.



388

Figure 5 – Nucleation concentrations recorded for aircraft departures, 13-14:00 15 October 2017.
 The aircraft type is labelled at the top of each bar, and colour coded according to the legend.

- 392 It is clear from this plot that a significant number of nucleation peaks are very low when compared
- to other similar aircraft. There are a number of possible reasons for this:
- The departure time of the aircraft is reported at the start of the minute the aircraft "throttles
- 395 up". It was not possible to determine the exact position of the aircraft on the runway, so
- assumptions are made about when the emission plume will arrive at the monitoring station.

- High time resolution meteorological data was not available for this survey. All calculations for plume transportation were made using 15 minute averaged wind speed and direction data
   The dataset has not been screened for rainfall. A proportion of plumes will have been negatively impacted during periods of rainfall, but high resolution rainfall data was not available to identify and filter out these periods.
- The 1 minute scan of the SMPS from 6 to 100 nm means that if the exhaust plume arrived at
   the monitoring station midway through the scan, it is possible that the SMPS would miss the
   Nucleation particles completely from a departing aircraft.
- It is also possible that, when wind direction was closer to 260 degrees, that the plume from a departing aircraft would be detectable for a longer period, due to the increased distance from the monitoring station, leading to the possibility that the SMPS would record a single aircraft plume over multiple minutes.
- 409 Because of the number of mis-assigned plumes, the data were further screened by rejecting
- 410 identifications when Nucleation particle number concentrations were lower than 4000/cm<sup>3</sup>. Using
- this restriction, 44% of the departures were removed from the analysis. The table below summarises
- 412 the results from these screened identifications.
- 413

Aircraft type	# Aircraft assessed	Nucleation particles, #/cm <sup>3</sup> / RSD, %	BC, ug/m <sup>3</sup>	UVPM, ug/m <sup>3</sup>	NO, ppb	NO <sub>2</sub> , ppb	PM <sub>10</sub> , ug/m <sup>3</sup>	PM <sub>2.5</sub> , ug/m <sup>3</sup>
Airbus A31x / A32x series	1188	8060 / 47%	4.18	0.80	42.1	27.9	13.1	8.5
Airbus A33x series	113	11438 / 59%	3.87	0.64	85.0	41.8	12.4	8.0
Airbus A34x series	52	10859 / 60%	4.50	0.51	91.0	31.2	12.4	8.0
Airbus A35x series	21	12266 / 45%	3.34	0.54	99.7	39.9	11.4	7.0
Airbus A380 series	199	13578 / 64%	3.98	0.66	107.9	34.7	13.2	8.3
Boeing 737 series	69	7719 / 46%	3.57	0.73	39.4	24.8	14.3	9.2
Boeing 747 series	202	12734 / 63%	4.12	0.72	95.6	40.0	13.0	8.1

Boeing 757	15	7063 /	4.80	0.67	70.9	32.3	13.9	8.9
series		45%						
Boeing 767	196	10438 /	4.59	0.79	84.0	38.6	12.7	8.4
series		57%						
Boeing 777	477	12422 /	3.56	0.69	112.3	38.3	12.7	8.3
series		56%						
Boeing 787	274	12406 /	3.14	0.64	84.1	35.1	12.3	7.9
series		56%						
Others	70	8078 /	3.31	0.72	36.2	26.0	12.9	8.6
Others		47%						
All departures	2876	10266	3.94	0.73	71.9	33.0	12.9	8.4

414 **Table 3** – Summary of average concentrations, separated by aircraft type, screened for Nucleation particle

415 measurements greater than 4000 particles  $/ \text{ cm}^3$ . The relative standard deviation (RSD) for nucleation

416 particles is presented to demonstrate the wide variation in the measurements recorded.

### 417 The Nucleation particle number data are further assessed in the box and whisker plot in Figure 6:



418

Figure 6 – Box and whisker plot, separating nucleation measurements by individual aircraft type.
Average concentrations are represented by a X, median by a line within the box. The box upper and
lower limits represent the 25<sup>th</sup> and 75<sup>th</sup> percentiles while the whiskers present the 0 and 100%
boundaries. Note that the lower whisker ignores data screened by rejecting all results below 4000
particles/cm<sup>3</sup>. Outliers are represented by individual dots.

424 Bearing in mind the varying sample sizes for each aircraft type, the average data in the above table

425 and figure confirms the following:

• Smaller aircraft emit fewer nucleation particles than larger aircraft

• Total NOx concentrations are highest from largest aircraft

NO<sub>2</sub> concentrations follow a similar pattern to NOx – larger aircraft generally emit higher
 concentrations than smaller aircraft, though it is likely that the newer fleet of heavy aircraft
 have lower NO<sub>2</sub> emissions – measured NO<sub>2</sub> from Boeing 747 aircraft is higher than Airbus
 A380 aircraft, for example. More investigation is required to get a fuller understanding of
 this observation.

- There is no clear trend in the BC data. Average BC emissions from the Boeing 787 were the
  lowest recorded for any aircraft type, suggesting that the newer design of this engine may be
  better for these emissions.
- There is no clear trend in the UVPM data, though average measurements appear to be lower
  for newer aircraft types Boeing 787 vs Boeing 767 for example.
- Measurements of PM<sub>10</sub> and PM<sub>2.5</sub> appear to be completely independent of aircraft type.
   Average PM<sub>10</sub> concentrations recorded during departures of Boeing 747, Airbus A380 and
   31x/32x aircraft are essentially identical. This further confirms that background mass
   concentrations of PM dominate measurements any additional contribution from aircraft is
   not likely to be significant.

Further investigation of the nucleation particle count data for each aircraft group was undertaken, using a simple correction to normalise the measurements with respect to wind speed. The data were examined before and after correction, using both the relationship between relative standard deviations within aircraft type and exploring the ratio of average concentrations between aircraft types. Unfortunately, a systematic improvement in the relative standard deviation of each clustered group was not observed, suggesting that the relationship between emissions from aircraft and measured downwind concentrations is more complex than a simple adjustment for one parameter.

450

# 451 **3.7** Comparison of 2017 particle size distribution with 2016 dataset

452	A similar study to investigate UFP at the airport was undertaken at Heathrow in the autumn of 2016
453	by Stacey et al (2020), in direct comparison with other monitoring in the south east of England.
454	The 2016 study configured the TSI SMPS/CPC identically to the comparator monitoring stations,
455	the 2017 study investigated a smaller particle range at a faster time resolution to identify individual
456	aircraft UFP contribution.
457	There were significant differences identified in the particle distributions and counts between the two
458	datasets, which were a direct consequence of the differences in how the analyser was configured for
459	each campaign. As a result, direct comparison between the 2016 and 2017 data is not possible; this
460	is discussed further in the SI.
461	

# 463 **4.** CONCLUSIONS

An extensive campaign to monitor UFP at London Heathrow Airport was undertaken in the autumn of 2017. The primary objective was to examine high temporal resolution data to investigate the relationship between individual aircraft and measured concentrations of UFP, PM<sub>10</sub>, PM<sub>2.5</sub>, NOx and BC.

The SMPS analyser was specifically configured for fast response (1 minute scans) and within a
much smaller size range (6-100 nm particles) than in our 2016 campaign. This change in
configuration caused a shift in measurements, both in magnitude and peak particle size, meaning

that comparison with historic and current UFP data in the UK was impossible.

472 This study, within 170 metres of a busy runway, shows that nucleation mode particles

473 predominantly originate from the airport, with highest concentrations associated with departing

474 aircraft. This observation is in contrast with some other research, which suggests that UFP

475 concentrations downwind of airports is dominated by aircraft emissions being transported to ground476 level by wing tip vortices from arriving aircraft.

There is some correlation of nucleation particles with NOx and BC, and these pollutants, togetherwith PM and Aitken particles, also show strong associations with winds from off-airport directions,

are not associated with nucleation particles. There is some evidence that BC emissions from landing

480 aircraft is higher in UV-active BC, most likely as a result of tyre abrasion upon landing.

481 Analysis of the 1 minute measurement data with associated aircraft departure information was used482 to group the data by aircraft type. Larger aircraft departing from the runway recorded higher

measurements of nucleation particles and NOx compared to smaller aircraft, but emissions of BC,

484 UVPM and  $NO_2$  appear to be more dependent upon the age of the engine design, rather than the

485 size of the aircraft.

486

#### 487 DATA AVAILABILITY

- 488 Data supporting this publication are openly available from the UBIRA eData repository at
- 489 <u>https://doi.org/10.25500/00000535</u>
- 490

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# 494 **CRediT author statement**

- 495 Brian Stacey: Conceptualisation, methodology, software, validation, formal analysis,
- 496 investigation, resources, data curation, writing original draft, writing review and editing,
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# 501 **REFERENCES**

- Andersson, J., Wedekind, B., Hall, D., Stradling, R., Barnes, C. and Wilson, G. (2000).
- 504 DETR/SMMT/CONCAWE Particle Research Programme: Sampling and Measurement
   505 Experiences. Conference Paper, doi: 10.4271/2000-01-2850.
- 506
- Bendtsen, K.M., Brostrøm, A., Koivisto, A.J., Koponen, I., Berthing T., Bertram, N., Kling, K.I.,
  Dal Maso, M., Kangasniemi, O., Poikkimäki, M., Loeschner, K., Clausen, P.A., Wolff, H., Jensen,
  K.A., Saber, A.T., and Vogel, U., Airport emission particles: exposure characterization and toxicity
  following intratracheal instillation in mice. *Part Fibre Toxicol* 16, 23 (2019).
- 511 https://doi.org/10.1186/s12989-019-0305-5
- 512
  513 Bousiotis, D., Dall'Osto, M., Beddows, D.C.S., Pope, F.D., and Harrison, R.M., 2019. Analysis of
  514 new particle formation (NPF) events at nearby rural, urban background and urban roadside sites,
- 515 Atmos. Chem. Phys., 19, 5679–5694, <u>https://doi.org/10.5194/acp-19-5679-2019</u>
- 516
  517 Carslaw, D.C. and Ropkins, K., 2012. *openair* An R package for air quality data analysis,
  518 Environmental Modelling and Software, Environ. Model. & Softw., 27-28, 52-61,
- 519 https://dx.doi.org/10.1016/j.envsoft.2011.09.008
- 520
- de Jesus, A.L., 1, Rahman, M.M., Mazaheri, M., Thompson, H., Knibbs, L.D., Jeong, C., Evans, G.,
- Nei, W., Ding, A., Qiao, L., Li, L., Portin, H., Niemi, J.V., Timonen, H., Luoma, K, Petäjä, T.,
- 523 Kulmala, M., Kowalski, M., Peters, A., Cyrys, J., Ferrero, L., Manigrasso, M., Avino, P., Buonano,
- 524 G., Reche, C., Querol, X., Beddows, D., Harrison, R.M., Sowlat, M.H., Sioutas, C. and Morawska,
- 525 L., 2019. Ultrafine particles and PM2.5 in the air of cities around the world: Are they
- representative of each other?, Environment International, 129, 118-135,
- 527 <u>https://doi.org/10.1016/j.envint.2019.05.021</u>

- Fanning, E., Yu, R.C., Lu, R.and Froines, J., 2007. Monitoring and modeling of ultrafine particles
  and black carbon at the Los Angeles International Airport, ARB contract number 04-325,
- 531 <u>https://ww3.arb.ca.gov/research/apr/past/04-325.pdf</u>
- 532533 Fleuti, E., Maraini, S., Bieri, L. and Fierz, M., Ultrafine Particle Measurements at Zurich Airport,
- 534 University of Applied Sciences and Arts Northwestern Switzerland FHNW,
- 535 <u>file:///C:/Users/hardinmt/Downloads/2017-03\_Zurich-Airport\_UFP\_Study%20(1).pdf</u>
- Health Effects Institute, 2013. HEI Review Panel on Ultrafine Particles. Understanding the Health
- 537 Effects of Ambient Ultrafine Particles, HEI Perspectives 3, Health Effects Institute, Boston MA.
- 538 <u>https://www.healtheffects.org/system/files/Perspectives3.pdf</u>
   539
- Fushimi, A., Saitoh, K., Fujitani, Y. and Takegawa, N., 2019. Identification of jet lubrication oil as
  a major component of aircraft exhaust nanoparticles, Atmos. Chem. Phys, 19, 6389-6399,
  <u>https://doi.org/10.5194/acp-19-6389-2019</u>
- Habre, R., Zhou, H., Eckel, S.P., Enebish, T., Fruin, S., Bastain, T., Rappaport, E., Gilliland, F.,
  Short-term effects of airport-associated ultrafine particle exposure on lung function and
  inflammation in adults with asthma. Environ Int. 2018;118:48-59. doi:10.1016/j.envint.2018.05.031
- Henry, R.C., Moham, S. and Yadzani, S., 2019. Estimating potential air quality impact of airports
  on children attending the surrounding schools, Atmos. Env. 212, 128-135,
  <u>https://doi.org/10.1016/j.atmosenv.2019.05.046</u>
- 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, Environ. Sci. Technol., 50,
  3362-3370, <u>https://dx.doi.org/10.1021/acs.est.5b05313</u>
- Keuken, M.P., Moerman, M., Zandveld, P., Henzing, J.S. and Hoek, G., 2015. Total and sizeresolved particle number and black carbon concentrations in urban areas near Schiphol airport (the
  Netherlands), Atmos. Environ., 104, 132-142, <u>http://dx.doi.org/10.1016/j.atmosenv.2015.01.015</u>
- Lopes, M., Russo, A., Monjardino, J., Gouveia, C., Ferreira, F., 2019. Monitoring of ultrafine
  particles in the surrounding urban area of a civilian airport, Atmospheric Pollution Research, 10,
  1454-1463, <u>https://doi.org/10.1016/j.apr.2019.04.002</u>
- Masiol, M., Harrison, R.M., Vu, T.V. and Beddows, D.C.S., 2017. Sources of sub-micrometre
  particles near a major international airport, Atmos. Chem. Phys., 17, 12379-12403,
  <u>https://doi.org/10.5194/acp-17-12379-2017</u>
- 567
- Morawska, L., Wierzbicka, A., Buonanno, G., Cyrys, J., Schnelle-Kreis, J., Kowalski, M., Riediker,
  M., Birmili, W., Querol, X., Cassee, F., Yildirim, A., Elder, A., Yu, I.J., Ovrevik, J., Hougaard, K.,
- 570 Loft, S., Schmid, O., Stöger, T., Peters, A., and Lucht, S., 2019. Ambient ultrafine particles:
- evidence for policy makers. A report prepared by the 'Thinking outside the box' team.
  <u>https://www.researchgate.net/publication/337111816\_Ambient\_ultrafine\_particles\_evidence\_for\_p</u>
  olicy\_makers\_A\_report\_prepared\_by\_the 'Thinking\_outside\_the\_box' team
- 574
  575 Peters, J., Berghmans, P., Van Laer, J. and Frijns, E., 2016. UFP- en BC-metingen rondom de
- 578

- Rivas, I., Beddows, D.C.S., Amato, F., Green, D.C., Järvi, L., Hueglin, C., Reche C., Timonen, H.,
  Fuller, G.W., Niemi, J.V., Pérez, N., Aurela, M., Hopke, P.K., Alastuey, A., Kulmala, M., Harrison,
  R.M., Querol, X. and Kelly, F.J., 2020. Source apportionment of particle number size distribution
  in urban background and traffic stations in four European cities, Environment International, 135,
  105345, <u>https://doi.org/10.1016/j.envint.2019.105345</u>
- Shirmohammadi, F., Sowlat, M.H., Hasheminassab, S., Saffari, A., Ban-Weiss, G. and Sioutas, C.,
  2017. Emission rates of particle number, mass and black carbon by the Los Angeles International
  Airport (LAX) and its impact on air quality in Los Angeles, Atmos. Environ., 151, 82-93,
  https://dx.doi.org/10.1016/j.atmosenv.2016.12.005
- 589
- Stacey, B., 2019. Measurement of ultrafine particles at airports: A review, Atmos.Environ., 198, 463-477, <u>https://dx.doi.org/10.1016/j.atmosenv.2018.10.041</u>
- Stacey, B., Harrison, R.M. and Pope, F., 2020. Evaluation of ultrafine particle concentrations and
  size distributions at London Heathrow Airport, Atmos. Environ, 222, 117148,
  https://doi.org/10.1016/j.atmosenv.2019.117148
- 596

- 597 Takegawa, N., Murashima, Y., Fushimi, A., Misawa, K., Fujitani, Y., Saitoh, K., and Sakurai, H.,
- 2020. Characteristics of sub-10 nm particle emissions from in-use commercial aircraft observed at
  Narita International Airport, Atmos. Chem. Phys. Discuss. <u>https://doi.org/10.5194/acp-2020-395</u>, in
  review, 2020
- 601
- Wiedensohler, A., Wiesner, A., Weinhold, K., Birmili, W., Hermann, M., Merkel, M., Müller, T.,
  Pfeifer, S., Schmidt, A., Tuch, T., Velarde, F., Quincey, P., Seeger, S.and Nowak, A., 2018.
  Mobility particle size spectrometers: Calibration procedures and measurement uncertainties,
  Aerosol Sci. Technol., 52, 146-164, https://dx.doi.org/10.1080/02786826.2017.1387229
- 605 Aerosol Sci. Technol., 52, 146-164, <u>https://dx.doi.org/10.1080/02786826.2017.1387229</u> 606
- 607 Wiedensohler, A., Birmili, W., Nowak, A., Sonntag, A., Weinhold, K., Merkel, M., Wehner, B.,
- Tuch, T., Pfeifer, S., Fiebig, M., Fjäraa, A.M., Asmi, E., Sellegri, K., Depuy, R., Venzac, H.,
- Villani, P., Laj, P., Aalto, P., Ogren, J.A., Swietlicki, E., Williams, P., Roldin, P., Quincey, P.,
- Hüglin, C., Fierz-Schmidhauser, R., Gysel, M., Weingartner, E., Riccobono, F., Santos, S.,
- Grüning, C., Faloon, K., Beddows, D., Harrison, R., Monahan, C., Jennings, S.G., O'Dowd, C.D.,
- Marinoni, A., Horn, H.-G., Keck, L., Jiang, J., Scheckman, J., McMurry, P.H., Deng, Z., Zhao,
- 613 C.S., Moerman, M., Henzing, B., de Leeuw, G., Löschau, G. and Bastian, S., 2012. Mobility
- 614 particle size spectrometers: harmonization of technical standards and data structure to facilitate high
- 615 quality long-term observations of atmospheric particle number size distributions, Atmos. Meas.
- 616 Tech., 5, 657-685, <u>www.atmos-meas-tech.net/5/657/2012</u>/ <u>https://dx.doi.org/10.5194/amt-5-657-</u> 617 <u>2012</u>
- 618
- 619 Wing, S.E., Larson, T.V., Hudda, N., Boonyarattaphan, S., Fruin, S., and Ritz, B, 2020. Preterm
- birth among infants exposed to *in utero* ultrafine particles from aircraft emissions. Environmental
- 621 Health Perspectives, 128(4), <u>https://doi.org/10.1289/EHP5732</u>