

## Authors' comments (final response) to the referees' comments and the other short comments

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Title: Identification of jet lubrication oil as major component of aircraft exhaust nanoparticles

Authors: Akihiro Fushimi, et al.

Thank you very much for your constructive and valuable comments on our manuscript. We have fully taken them into account in revising our manuscript as detailed below (Our response is shown [in blue](#)). The revised contents in the revised manuscript are also shown [in blue](#).

### **RC1: Anonymous Referee #1**

*RC1: 'Review: Identification of jet lubrication oil as major component of aircraft exhaust nanoparticles',  
Anonymous Referee #1, 25 Feb 2019*

#### **General comments**

*(Referee #1 comment)* Fushimi et al. present a study on the chemical analysis of nanoparticles in aircraft engine exhaust. They identify jet lubrication oil as a major component of particles < 30 nm. The size resolved sampling using a multi-stage cascade impactor took place near the Narita International airport. Chemical analysis of the samples used a thermal desorption unit coupled to gas chromatography /mass spectrometry. The authors designed the study with necessary caution, in terms of duplicate sampling, dilution of the sampling flow for measurements of particle number concentration, analyzing nighttime (airport non-flight hours) vs daytime samples and analyzing reference jet fuel and lubrication oils. The usually challenging task of chemical analysis of nanoparticles (limited mass) is overcome in this case by high particle number concentrations.

*(Author's response)* Thank you very much for your positive comments.

*(Referee #1 comment)* The measured particle number concentration brings me to my main point of concern regarding this paper: although, one might expect high particle number concentration near an airport, so far I have not seen ambient number concentrations of  $2.5 \times 10^7 \text{ cm}^{-3}$  (Figure S3). The authors should comment on the reason of these high numbers, and should point out the differences to other studies: e.g. Hudda et al. observed max.  $1.5 \times 10^5 \text{ cm}^{-3}$  within 3 km of LAX airport.

*(Author's response)* (1) We have rechecked the data (total number concentration shown in original Fig. S3) and found those data was incorrect.

*(Author's changes in manuscript)* We have corrected the data and replaced the figure (Fig. 2). Now, total number concentration became 1/16 of the original values, and the maximum concentration is about  $1.7 \times 10^6 \text{ cm}^{-3}$ .

We added the following explanation. "The total number concentrations at our measurement site is higher than the maximum value ( $1.5 \times 10^5 \text{ particles cm}^{-3}$ ) measured within 3 km of Los Angeles International (LAX) Airport (Hudda et al., 2014). It seems reasonable because our measurement site is much closer to the runway (i.e. 140 m). In fact, Zhu et al. (2011) reported higher total particle number

concentrations (i.e.  $>1 \times 10^7$  particles  $\text{cm}^{-3}$ ) during takeoffs at the blast fence of LAX airport.” (P6, L28-31)

Accordingly, we added the following reference.

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

(Referee #1 comment) Also, it would be helpful to show a longer time series of particle number measurements additionally to Figure S3 (which is only one hour). This might shed light into certain conditions that favor the buildup of such extremely high nanoparticle number concentrations. For such a time series graph a log y-axis might be helpful in order to evaluate the urban background particle number concentrations – if these numbers are reasonable, the measured numbers at Narita Intl. airport during operation hours would appear more plausible.

(Author’s response) We agree with the reviewer.

(Author’s changes in manuscript) We added a figure of the one-month time series total number concentrations and size distribution of particles. (Fig. S2) Accordingly, we added related explanation about the figure. “One-month time series total number concentrations and size distribution of particles is shown in Fig. S2. Total particle number concentrations during operation hours (6:00–23:00) were remarkably larger than non-operational hours (23:00–6:00). Also, there was no noticeable enhancement of nanoparticles during non-operational hours.” (P6, L24-27)

(Referee #1 comment) Apart from this point, the study appears well designed and the chemical analysis using GC/MS is solid. The main conclusion – identification of lubrication oil - is robust, since comparison by retention time, m/z and EI-fragmentation spectra agree well with pure jet lubrication oil products.

(Author’s response) Thank you very much for your positive comments.

#### **Minor/technical comments:**

(Referee #1 comment) p.1 l.28: Please comment on the formation of soot under idling vs. low- and high-thrust.

(Author’s response) We agree.

(Author’s changes in manuscript) We added some explanation about low thrust, idling, and high thrust conditions shown below. “low engine thrust (e.g. idle and taxi modes)” and “high engine thrust (e.g. take-off and climb)” (P2, L1).

(Referee #1 comment) p.3 l.7-10: Did you calculate/estimate the inlet line losses of the small particles?

(Author’s response) Yes.

(Author’s changes in manuscript) We added the following sentence. “For the SMPS, the penetration efficiency through the sampling tube was estimated to be >70% approximately above 10 nm based on the theoretical formulae of Gormley and Kennedy (1949).” (P3, L17-19).

(Referee #1 comment) p.3. l.25: Did the manufacturer recommend the backup filters used (two different ones)? Can the differences of the back-up filters alter flow rates and thus cut-off sizes?

(Author’s response) The default filter substrates for the back-up of the samplers (NanoMoudill, MSP) are glass fiber filter and quartz fiber filter.

(Author's changes in manuscript) We added the following explanation. "Using different substrates of the backup filters do not alter the flow rates." (P4, L6)

(Referee #1 comment) p. 3 l. 28: A nitrocellulose filter installed underneath the PC filter? Does this have an effect on the distance between nozzle and impaction plate?

(Author's response) A nitrocellulose filter was installed underneath the PC filter.

(Author's changes in manuscript) We replaced the word "under" to "underneath" (P4, L3). When a nitrocellulose filter was installed underneath the PC filter, the distance between nozzle and impaction plate change slightly. However, the effect to the change in cut-off size seems negligible because of the results we got. To explain this, we added following description in the manuscript. "on cellulose filters" (P4, L16)

(Referee #1 comment) p.4 l.1: These numbers are slightly different from the specs of the manufacturer. Did you measure cut-off sizes? If yes, how?

(Author's response) We did not measure the cut-off sizes. The cut-off sizes of each sampler (NanoMoudill, MSP) are calibrated and reported with each sampler by the manufacture.

(Author's changes in manuscript) We added the following explanation. ", calibrated and reported by the manufacture," (P4, L8).

(Referee #1 comment) p.4 l.19 The experimental section should describe the procedure of the gravimetric analysis in the main text, since this is extremely challenging for small size fractions.

(Author's response) We agree.

(Author's changes in manuscript) According to the comments from you and the Referee #2, we moved most information originally written in the supplement, including the method to obtain particle mass (original Supplement, Section 1.1), to the main body of the manuscript.

(Referee #1 comment) p.5 l.19: OC is roughly 2/3, and only during day. There is also 15-20% sulfur in one sample, and another nighttime sample is 100% "other elements". Hence, the statement that nanoparticles comprise "mainly organic carbon" is not correct.

(Author's response) The original sentence was not correct. The explanation was intended to be only for "Daytime" samples not for "Nighttime samples".

(Author's changes in manuscript) We added "daytime" in the sentence (P8, L28). For the daytime samples, organic carbon is the primary components. So, we did not change the other explanation.

## **RC2: Anonymous Referee #2**

*RC2: 'Review of Fushimi et al.', Anonymous Referee #2, 06 Mar 2019*

### **General comments**

(Referee #1 comment) The paper by Fushimi et al. presents an investigation of the chemical composition of ultrafine particles measured close to a runway of the Narita International Airport, Japan. Several studies have already shown that large amounts of particles smaller than 30 nm are emitted by aircrafts. However, hardly anything is known about their chemical composition. Since these particles have only little mass, it is very difficult to investigate their composition. The chemical composition, however, is important to know for estimating how relevant aircraft emissions are for public health and whether they have an impact on weather or climate. Knowing where exactly these particles originate would also give the opportunity to find solutions for reducing their emissions. The authors find that the organic compounds of the particles measured near the runway are dominated by nearly intact forms of jet engine lubrication oil. Knowing this can help to develop techniques for controlling oil emissions, which could greatly reduce aircraft exhaust particles.

The subject of this paper is relevant for ACP. Overall, the experimental data are presented well and sound. I recommend publication of this paper after the authors address my comments.

(Author's response) Thank you very much for your positive comments.

(Referee #2 comment) It is known that aircraft emissions largely differ for changing jet engine conditions (e.g. Masiol and Harrison, 2014). The largest amount of particles may not necessarily be emitted while take-off (high thrust). Instead, particle emissions can be also very high while taxiing or just while running the APU. From the map it looks like the measurement site could not only receive the particle emissions from take-off or landing. Since the taxi track and the terminal area are just behind the runway, the measured particles could also well be dominated by other jet engine conditions. The authors need to discuss how much their results on particle composition may depend on these different engine conditions.

(Author's response) This is a very important point and should be evaluated in the future.

(Author's changes in manuscript) We added the following explanation at the "Conclusions and implications" chapter. "We believe ambient measurements, like shown in this paper, can provide complementary insights into aircraft emissions which are not obtained from engine exhaust measurements. However, our ambient particulate samples may have affected by emissions from wide variety of jet engines, operating conditions (e.g. take-off, landing, taxiing and idling), maintenance conditions, and other sources (e.g. auxiliary power units and ground service equipments) (Stettler et al., 2011; Yu et al., 2012; Masiol and Harrison, 2014). The chemical composition of nanoparticles is also the average of those variety of emissions, although take-off and landing seems to have greater impact because the measurement site is near the runway. Those emissions should be separately evaluated in the future." (P10, L10-16).

(Referee #2 comment) To my point of view, this is important with regard to the conclusion that is drawn – I think one cannot be sure that the lubricant oil particles are also emitted to a reasonable amount in the upper troposphere, so it is questionable whether they "can potentially affect the radiative balance of the atmosphere".

(Author's response) As suggested by the referee, it is bit uncertain that the lubrication-oil-dominated nanoparticles are actually emitted from aircraft in the upper troposphere. However, the sentence in the original manuscript was intended to describe possible importance of aircraft PM emission in the upper troposphere, which is apart from its chemical composition.

(Author's changes in manuscript) Therefore, we did not change the words here. (P10, L9)

### **Specific comments**

(Referee #2 comment) 1) What was the wind direction and wind speed during each measurement? Was the air transported from the runway to the measurement site for the entire measurement period?

(Author's changes in manuscript) We added the wind roses and the data of wind speed during each sampling period in Fig. S2. We added the following sentence "Although the air was not necessarily transported from the runway to the measurement site for the entire sampling period for the daytime samples, remarkable enhancement of nanoparticles was observed multiple days in every daytime sampling period." (P7, L21-23).

(Referee #2 comment) 2) I would strongly recommend shifting the appendix into the main text because it is important information.

(Author's response) We agree.

(Author's changes in manuscript) We moved all the text and references in the original supplement to the main body of the manuscript (Sections 2.5, 2.6, 2.7, 3.1, and 3.2). Original Figs. S2 and S4 (now Figs. S1 and S3), and newly added figure and table (Fig. S2 and Table S1) were kept in the Supplement.

(Referee #2 comment) 3) Fig. 1: How do the authors define a "plume"? Can the peaks in number concentration be attributed to specific take-offs or landing aircrafts? What is the fraction of "plume" to "no-plume" events?

(Author's response) Regarding original Fig.1 (now Fig.3), we chose the "plume event" during an increasing event of number concentrations (total number concentrations were in the range of  $6.8 \times 10^5 - 1.3 \times 10^6$  particles  $\text{cm}^{-3}$ ) which has typical particle size distribution of plume events. We chose the "no-plume event" which has low and stable (like a baseline) total number concentrations ( $1.1 - 1.6 \times 10^4$  particles  $\text{cm}^{-3}$ ). Both events shown here have same duration (19 seconds). If we take the original Fig. S3 (Fig. 2 in the revised manuscript. 11:00-12:00 on February 15) as an example, the ratio of the time duration of plume event and non-plume event is about 3:1.

(Author's changes in manuscript) We added the following explanation "The peak concentrations of total particle number ( $6.8 \times 10^5 - 1.3 \times 10^6$  particles  $\text{cm}^{-3}$ ) during the plume event (indicated in Fig. 2) are about two orders of magnitude higher than the baseline concentrations ( $1.1 - 1.6 \times 10^4$  particles  $\text{cm}^{-3}$ ) during the no-plume event." in the manuscript (P6, L19-22).

Accordingly, in Fig.2, we indicated the periods for "plume event" and "no-plume event" of Fig.3.

We also added the wind vectors and information of take-off/landing in Fig.2. We added the following explanation "Judging from synchronized increase of  $\text{CO}_2$  (data is not shown in this paper) and the reasonable time-delay (20–200 seconds approximately) between aircraft take-off/landing and increase of particle number concentration, it seems that most peaks of particle number concentrations can be attributed to specific take-offs or landings of aircraft fleets." in the manuscript (P6, L22-24).

Please also see our response to your general comments written above.

### **Technical comments**

(Referee #2 comment) 1) p 1, l 14, "A new particulate: : ": This sentence is without any context..

(Author's response) We agree.

(Author's changes in manuscript) We added the following sentence. "Therefore, research needs to characterize aircraft exhaust particles have been increasing." (P1, L17-18).

(Referee #2 comment) 2) p 6, l 4, "The mass chromatograms: : ": This sentence makes more sense to shift a few lines above, e.g., to p 5, l 21..

(Author's response) We agree.

(Author's changes in manuscript) The sentence was moved to the place where the referee suggested. (P9, L1-2).

(Referee #2 comment) 3) Fig. 1: It does not say here what the dotted line means..

(Author's response) It was bit hard to find the explanation about this since it was originally written in the supplement.

(Author's changes in manuscript) We have moved most information in the original supplement to the main body of the manuscript. Accordingly, the following explanation about the referee's suggestion was also moved to the main text. "However, the EEPS can show an artifact peak at approximately 10 nm with polydisperse particles, which is not usually observed in the case of the SMPS (Fujitani et al., 2012). Therefore, we treat the EEPS data below 10 nm as supporting information and indicate it using dashed lines in this paper." (P6, L14-16).

(Referee #2 comment) 4) Fig. 2: I find the scale of the y-axis somehow weird. Should it not range from zero to 2.5e6 for every single subplot?.

(Author's response) We agree.

(Author's changes in manuscript) In the figure, we added the baseline at zero signal. We also added y-scale for every single subplot. (Fig.6).

### **Reference**

(from the Referee #2) Masiol, M. and Harrison, R. M. (2014): Aircraft engine exhaust emissions and other airport-related contributions to ambient air pollution: A review, *Atm. Environ.*, 95, 409-455, <https://doi.org/10.1016/j.atmosenv.2014.05.070>

***SC1: 'Aviation lubrication oil emissions', Dr. Zhenhong Yu, 14 Feb 2019***

(SC1-1) Designs of the venting of lubrication oil systems for different aircraft engines can vary dramatically. Some engines vent oil system excess air to the bottom of the nacelle into ambient air, while some other engines vent directly into the engine combustion exhaust at high temperature. Thus, according to the previous studies, the contribution from lubrication oil to aircraft organic PM emissions for different engines could vary from 5% to almost 100%. Providing a detailed description of the aircraft fleet as well as the associated engine types could be very helpful for the readers to understand and evaluate the obtained measurement results.

(Author's response) We agree.

(Author's changes in manuscript) We added a table which show the summary of aircraft models used in the Runway A of Narita International Airport, Japan during the measurement period (Table S1).

Accordingly, the following explanation was added. "Summary of aircraft models used in the Runway A of Narita International Airport during our measurement period is shown in Table S1." (P2, L27-29)

(SC1-2) Engine operational conditions such as engine power could have significant influences on lubrication oil emissions. Impacts of PM emissions from aircraft on local air quality are normally evaluated during the landing and take-off (LTO) cycles. Given the locations of sampling at the airport and wind directions, an estimate of the contribution of each stage during the LTO cycle (taxi, takeoff, and landing may affect different sampling locations) to the oil emissions would be helpful.

(Author's response) This is a very important point and should be evaluated in the future.

(Author's changes in manuscript) We added the following explanation at the "Conclusions and implications" chapter. "We believe ambient measurements, like shown in this paper, can provide complementary insights into aircraft emissions which are not obtained from engine exhaust measurements. However, our ambient particulate samples may have affected by emissions from wide variety of jet engines, operating conditions (e.g. take-off, landing, taxiing and idling), maintenance conditions, and other sources (e.g. auxiliary power units and ground service equipments) (Stettler et al., 2011; Yu et al., 2012; Masiol and Harrison, 2014). The chemical composition of nanoparticles is also the average of those variety of emissions, although take-off and landing seems to have great impact because the measurement site is near the runway. Those emissions should be separately evaluated in the future." (P10, L10-16).

(SC1-3) Oil emissions could also be associated with engine maintenance. One of the challenges of evaluating aviation PM emissions is the lack of information on engine maintenance, which results in a large discrepancy in emission measurements even on the same type of the aircraft engines. Could the authors comment on this issue?

(Author's response) We do not have information about the engine maintenance so far.

(Author's changes in manuscript) We have added the explanation about the possible impact of maintenance condition in the manuscript as indicated in our response to your previous comment (SC1-2).

### ***Other revision***

(Author's response) We have added the following references according to the revision indicated above.

- Agrawal, H., Malloy, Q. G. J., Welch, W. A., Miller, J. W., and Cocker, D. R.: In-use gaseous and particulate matter emissions from a modern ocean going container vessel, *Atmos. Environ.*, 42, 5504-5510, 10.1016/j.atmosenv.2008.02.053, 2008.
- Kinsey, J.S., 2009. Characterization of Emissions from Commercial Aircraft Engines during the Aircraft Particle Emissions EXperiment (APEX) 1 to 3, EPA-600/R-09/130. United States Environmental Protection Agency, National Risk Management Research Laboratory, Research Triangle Park, NC.



# Identification of jet lubrication oil as major component of aircraft exhaust nanoparticles

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**Abstract.** Jet engine aircraft are ubiquitous and significant sources of atmospheric nanoparticles. Using size-resolved  
10 particulate samples collected near a runway of the Narita International Airport, Japan, we clearly demonstrate that organic compounds in the ambient nanoparticles (diameter: <30 nm) were dominated by nearly intact forms of jet engine lubrication oil. This finding provides direct evidence for the importance of unburned lubrication oil as a source of aircraft exhaust nanoparticles and also has an implication for their environmental impacts near airports and in the upper troposphere.

## 1 Introduction

15 Jet engine aircraft are a significant source of atmospheric nanoparticles and exist ubiquitously from ground level to the upper troposphere (Masiol and Harrison, 2014). A new particulate emission standard for turbofan and turbojet aircraft engines will come into effect from 2020 (International Civil Aviation Organization, 2017). [Therefore, research needs to characterize aircraft exhaust particles have been increasing.](#) Previous studies have shown that the impacts of aircraft on the distribution of nanoparticles in ambient air may range over a horizontal scale of approximately 16 km near airports (Hudda et al., 2014).  
20 Nanoparticles can penetrate deep into the human respiratory tract and may have adverse effects on human health (Oberdorster et al., 2000; Biswas and Wu, 2005). The nanoparticles in diesel vehicle exhaust comprise mainly of organic compounds with relatively high saturation vapor pressures (alkanes, alkenes, etc.), and their lifetimes may be shorter than those of submicron particles owing to their evaporation and coagulation (Fushimi et al., 2008; Harrison et al., 2016). To  
25 understand the mechanisms of formation of nanoparticles emitted from jet engines and their physical/chemical transformation in ambient air, it is important to determine the size distribution and chemical composition of nanoparticles emitted from in-use commercial aircraft under real-world conditions.

Previous studies have suggested that aircraft exhaust nanoparticles mainly comprise volatile particles. For example, the fraction of particles that completely evaporate below 300 °C are approximately 70–95%, and the number concentrations below 20 nm was found to decrease with an increasing ambient temperature (Wey et al., 2006). Bulk-level chemical analyses  
30 of aircraft exhaust particles showed that the particle compositions were dominated by organic compounds under low engine

thrust (e.g. idle and taxi modes) conditions and elemental carbon under high engine thrust (e.g. take-off and climb) conditions (Agrawal et al., 2008; Presto et al., 2011; Masiol and Harrison, 2014; Yu et al., 2017). This feature is contradictory to the volatility of aircraft exhaust nanoparticles. Sulfur compounds originating from jet fuels are also known to be the major components of aircraft exhaust particles (Masiol and Harrison, 2014; Yu et al., 2017). Particle emission factors show a strong dependence on the contents of sulfur and aromatics in jet fuel (Wey et al., 2006; Masiol and Harrison, 2014). On the other hand, some qualitative markers of jet engine lubrication oil were commonly found in aircraft exhaust particles (Timko et al., 2010; Yu et al., 2012). The contribution of lubrication oil to the total organic mass may range from 5% to 100% (Timko et al., 2010; Yu et al., 2012). While such previous studies have provided useful insights into the characteristics of aircraft exhaust particles, little is known regarding the origin and detailed chemical composition of size-resolved particles and especially nanoparticles (Kinsey, 2009; Presto et al., 2011; Kinsey et al., 2011; Masiol and Harrison, 2014).

The purpose of this study is to determine the size-resolved chemical composition of particles emitted from jet engine aircraft during take-off and landing in real-world conditions, and to estimate the contribution of jet fuel and lubrication oil to the nanoparticle mass. We have therefore collected particulate samples from an area near a runway at the Narita International Airport, Japan, during the daytime and nighttime using low-pressure cascade impactors. We used thermal-desorption gas chromatography mass spectrometry (TD-GC/MS) to identify the chemical composition of nanoparticles having diameters smaller than approximately 30 nm originating from real-world aircraft emissions, which is unprecedented.

## 2 Methods

### 2.1 Jet fuels and lubrication oils

To investigate the emission sources of the nanoparticles in aircraft exhausts, we obtained two Jet A1 fuels and two jet engine lubrication oils (Mobil Jet Oil II and Mobil Jet Oil 254, ExxonMobil, Irving, TX, USA) from Ishinokoyu Co. Ltd. (Mitaka, Tokyo, Japan). The Mobil Jet Oil II has a market share of 49% (Winder and Balouet, 2002), and the Mobil Jet Oil 254 is a newer generation oil.

### 2.2 Measurement site

Field measurements were conducted at a distance of 140 m west of runway A of the Narita (Tokyo) International Airport, Japan in winter (February 5–26, 2018, Fig. 1). The instruments used for obtaining the particle number size distributions and size-resolved particulate samplers were installed in a container. The airport has two runways. The runways A and B had an average of 401 and 290 flights per day, respectively, in 2017. Aircraft operations are allowed from 6:00 to 23:00. [Summary of aircraft models used in the Runway A of Narita International Airport during our measurement period is shown in Table S1.](#)

## 2.3 Particle number size distribution

The size distributions of the particle number concentration were measured every 1 s using the engine exhaust particle sizer (EEPS, Model 3090, D = 0.006–0.560  $\mu\text{m}$ , TSI, Shoreview, MN, USA; flow rate: 10 L  $\text{min}^{-1}$ ) during the entire measurement period. A copper tube (inside diameter: 10 mm, and length: 2 m), electrically conductive tubes (inside diameter: 6.35 and 9.53 mm, total length: 1 m; Part 3001788, TSI), and a glass manifold (inside diameter: 40 mm, total length: 600 mm) were used to transport the ambient air at a ground height of 3 m to the EEPS. To avoid particle deposition onto the sampling tubes and to increase the response speed, an extra pump (flow rate: 30 L  $\text{min}^{-1}$ ) was used to vacuum the air inside the glass manifold.

The size distributions of the particle number were also measured every 5 min using a scanning mobility particle sizer (SMPS, Model 3936, D = 15–660 nm, TSI, Shoreview, MN, USA), which consists of an electrostatic classifier (Model 3080), differential mobility analyzer (DMA, Model 3081), and a condensation particle counter (CPC, Model 3022A). Ambient air was aspirated from the roof of the container through a stainless-steel tube (inner diameter: 10 mm, length: approximately 3 m, inlet height: approximately 3 m above ground level) and was split into the main sample flow (approximately 0.8 L  $\text{min}^{-1}$ ) and bypass flow (approximately 20 L  $\text{min}^{-1}$ ). The bypass flow was used to reduce the possible loss of nanoparticles due to Brownian diffusion. The main sample flow was diluted with particle-free air (approximately 2 L  $\text{min}^{-1}$ ) and further split into the individual sample flows for the SMPS (approximately 0.3 L  $\text{min}^{-1}$ ) and other CPCs (approximately 2.5 L  $\text{min}^{-1}$ ). We used the dilution flow to reduce the effects of particle coincidence in the CPCs at higher concentrations. For the SMPS, the penetration efficiency through the sampling tube was estimated to be >70% approximately above 10 nm based on the theoretical formulae of Gormley and Kennedy (1949).

## 2.4 Sampling

Size-resolved particles in the ambient air at a height of approximately 3 m from the ground were collected using two low-pressure cascade impactors (NanoMoudi II, Model 125B, MSP, Shoreview, MN, USA; flow rate: 10.2 L  $\text{min}^{-1}$ ) simultaneously. To distinguish the effect of aircraft emissions, the samples were collected during the daytime (during aircrafts operation hours) and nighttime (during non-operation hours). Three daytime (7:00–22:00) samples were collected from 16:24 on February 9, 2018 to 13:09 on February 13, 2018 (duration = 56.8 h, sample #1), from 17:33 on February 13, 2018 to 9:37 on February 17, 2018—except for 13:30–16:45 on February 15, 2018 (duration = 48.8 h, sample #2)—and from February 19 to February 20, 2018 (duration = 30.0 h, sample #3). One nighttime (0:00–6:00) sample was collected during February 22–26, 2018 (duration = 30.0 h, sample #4).

For one of the two NanoMoudi II impactors, a gold (Au) foil (diameter: 47 mm, Mitsubishi Materials, Tokyo, Japan; “NanoMoudi II-Au”, hereafter) was used as the collection substrate for the impaction stage, and a quartz-fiber filter (diameter: 47 mm, 2500QAT-UP, Pall, East Hills, NY, USA) was used as the substrate for the backup filter. In the other NanoMoudi II, a polycarbonate membrane filter (Nuclepore; pore size: 0.05  $\mu\text{m}$ ; diameter: 47 mm; Whatman, GE

Healthcare UK Ltd., Buckinghamshire, UK; “NanoMoudi II-PC,” hereafter) was used as the collection substrate for the impaction stage. At each impaction stage, a nitrocellulose membrane filter (AAWP04700, pore size: 0.8  $\mu\text{m}$ ; diameter: 47 mm; Merck Millipore, Billerica, MA, USA) was set underneath the PC filter. A polytetrafluoroethylene with non-woven fabric polyethylene/polyethylene terephthalate membrane filter (TFH-47; diameter: 47 mm, Horiba, Kyoto, Japan, for samples #1 and #2) or a quartz-fiber filter (diameter: 47 mm, 2500QAT-UP, Pall, for samples #3 and #4) was used as the substrate for the backup filter. Using different substrates of the backup filters do not alter the flow rates. Using NanoMoudi II, the particles were separated into 14 size fractions. For the NanoMoudi II-Au, for example, the equivalent cut off aerodynamic diameters at a 50% efficiency (D50) of the impaction stages, calibrated and reported by the manufacture, were as follows: 0.010, 0.018, 0.032, 0.057, 0.105, 0.170, 0.290, 0.560, 1.00, 1.80, 3.10, 6.20, and 9.90  $\mu\text{m}$ . Au foils were rinsed with acetone (dioxin analytical grade, Wako Pure Chemical Industries, Osaka, Japan) before use. A copper tube (inside diameter: 10 mm, length: 3 m) was used as the sampling line. Before each sampling, the impactor nozzles and the support rings of the NanoMoudi II were cleaned using acetone and blown off with an air-duster.

The NanoMoudi II-Au samples were used for particle-mass weighing, elemental/organic carbon (EC/OC) analysis, and organic analysis. The NanoMoudi II-PC samples were used for elemental analysis. The NanoMoudi II with aluminum foil as a collection substrate can be used to collect particles with a reasonable size distribution, and the aluminum foil and PC filters on cellulose filters have comparable collection efficiencies (Fujitani et al., 2006). Therefore, we assumed that the NanoMoudi II-Au and NanoMoudi II-PC collected particles with reasonable size distributions, and their size distributions were comparable with each other. In this paper, the data for the backup filters are not presented because their collection characteristics (especially adsorption of gaseous compounds) are remarkably different from those of the impaction substrates.

## 2.5 Particle mass

The particle masses of NanoMoudi II-Au and NanoMoudi II-PC samples were determined from the differences between the weights of the collection substrates before and after the sampling. For the NanoMoudi II-PC samples, only PC filters were weighed after eliminating static electricity using an ion balancer (TAS-182 NWM, Trinc Corp., Shizuoka, Japan). The substrates were weighed with a microbalance (readability 0.1  $\mu\text{g}$ , UMX 2, Mettler-Toledo, Columbus, OH, USA) in a chamber (CHAM-1000, Horiba) in which the temperature and relative humidity were controlled at 21.5  $^{\circ}\text{C}$  and 35%, respectively. Each sample was weighed twice, and the obtained results were averaged. If the difference between two recorded weights exceeded 0.5  $\mu\text{g}$  in the case of the Au samples or 2.0  $\mu\text{g}$  in the case of the PC samples, the sample was re-weighed. The samples were not conditioned before the weighing because Au foils and PC filters have low hygroscopicity.

## 2.6 EC/OC

The EC, OC, and total carbon (TC) in the NanoMoudi II-Au samples were determined by using a thermal/optical carbon analyzer (DRI Model 2001 Carbon Analyzer; Desert Research Institute, Las Vegas, NV, USA) (Chow et al., 1993). Three-eighths of each Au-foil sample cut in a fan shape was analyzed after the outside of the deposit area (diameter: 28 mm) had

been cut off. The samples were analyzed using the IMPROVE protocol (OC<sub>1</sub>: 120 °C; OC<sub>2</sub>: 250 °C; OC<sub>3</sub>: 450 °C; OC<sub>4</sub>: 550 °C [in a 100% He atmosphere]; EC<sub>1</sub>: 550 °C; EC<sub>2</sub>: 700 °C; EC<sub>3</sub>: 800 °C [in a 2% O<sub>2</sub>/98% He atmosphere] (Chow et al., 2001)). The pyrolysis of the OC during analysis was not corrected because adequate correction using laser light is not possible with Au-foil samples.

## 5 2.7 Elements

The elemental compositions of the NanoMoudi II-PC samples were determined using particle-induced X-ray emission (PIXE) analysis at the Nishina Memorial Cyclotron Center of the Japan Radioisotope Association in Iwate, Japan. The target elements were Na, Mg, Al, Si, P, S, Cl, K, Ca, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Se, Br, Sr, Y, Zr, Nb, Mo, Hg, and Pb. The NanoMoudi II-PC samples were mounted on a Mylar target frame and bombarded with 2.9-MeV protons from a small  
10 cyclotron (Sera et al., 1992). The beam current, accumulated charge, and typical measuring time were 40–60 nA, 20–58 µC, and 10–12 min, respectively. The X-ray spectra thus obtained were analyzed using the SAPIX program (Sera et al., 1992). A quantitative analysis of the elemental values was performed using the Nuclepore-Br method (Sera et al., 1997). Blank filters were analyzed in all the procedures. The accuracy of the PIXE analysis was confirmed based on the National Institute of Standards and Technology (NIST) standard reference materials (Saitoh and Sera, 2005).

## 15 2.8 Organic composition

The organic compounds in the NanoMoudi II-Au samples were analyzed using thermal desorption gas chromatography/mass spectrometry (TD-GC/MS), which is sensitive and suitable for trace-level particulate samples (Fushimi et al., 2011). A thermal desorption unit (TDU; Gerstel GmbH & Co. KG, Mülheim an der Ruhr, Germany), a cooled injection system as a GC inlet (CIS 4; Gerstel), 6890 GC (Agilent Technologies, Palo Alto, CA, USA), and a double-focusing magnetic sector  
20 mass spectrometer (JMS-700K, JEOL, Tokyo, Japan) were used. For the GC columns, a DB-5MS (length: 30 m, internal diameter: 0.25 mm, film thickness: 0.25 µm; Agilent Technologies, Palo Alto, CA, USA) was used.

The NanoMoudi II-Au samples were cut into a fan shape (1/8–3/8 of 28 mm Φ, PM mass per sample: 1–20 µg) and were placed in a glass liner (length: 60 mm, outside diameter: 6 mm, inside diameter: 5 mm, Gerstel). The samples were transferred into the TDU and 1 µL of the internal standard mixture of <sup>13</sup>C-labeled polycyclic aromatic hydrocarbons  
25 (approximately 0.5 µg mL<sup>-1</sup> for each compound; US EPA 16 PAH cocktail, Cambridge Isotope Laboratories (CIL), Andover, MA, USA) and deuterium *n*-alkane mixtures (10.7 µg mL<sup>-1</sup> of C<sub>24</sub>D<sub>50</sub> *n*-alkane and 11.0 µg mL<sup>-1</sup> of C<sub>30</sub>D<sub>62</sub> *n*-alkane) were injected onto the surface of the samples using an autosampler (MPS-TEX, Gerstel). The samples were then thermally desorbed using the TDU; the temperature was increased from 30 °C (held for 0.5 min) to 350 °C (held for 3 min) at 50 °C  
min<sup>-1</sup>, using a helium desorption flow at 50 mL min<sup>-1</sup> in splitless mode. The interface temperature was maintained at 350 °C.  
30 During desorption at the TDU, the desorbed compounds were focused at 0 °C on a quartz wool inside the glass liner (inside diameter: 2 mm) in the CIS 4 for subsequent GC/MS analysis. The CIS 4 was then programmed to increase the temperature from 0 °C (held for 0.75 min) to 150 °C at 960 °C min<sup>-1</sup> and from 150 °C to 350 °C (held for 3 min) at 720 °C min<sup>-1</sup> to

inject focused compounds into the GC column. The injection was performed in splitless mode with a 3-min splitless time. The GC oven was programmed to increase the temperature from 40 °C (held for 3 min) to 150 °C at 20 °C min<sup>-1</sup> and to 320 °C at 10 °C min<sup>-1</sup> (held for 15 min). Helium was used as a carrier gas at 2.5 mL min<sup>-1</sup> in a constant flow mode. The temperature of the transfer line between the GC and MS was 320 °C. The samples were ionized using the electron ionization method (ionizing voltage: 70 V, ionizing current: 600 μA, ion source temperature: 260 °C). The MS was operated in scan mode ( $m/z$  35–400) with a mass resolution of 1000 to obtain comprehensive information regarding the organic compounds in the particulate samples. The accelerating voltage was 10.0 kV, and the detector voltage was 0.40 kV. The Jet A1 fuels and the jet lubrication oils were diluted by approximately 1000 times with *n*-hexane (dioxin analytical grade, Wako Pure Chemical Industries) and then analyzed with TD-GC/MS under the same condition as the particulate samples.

## 3 Results and discussion

### 3.1 Particle number size distribution

In our parallel measurements at the measurement site, the size distribution and concentrations measured using the EEPS agreed well with those measured using the SMPS for particles larger than 15 nm. A typical example is shown in Fig. S1. However, the EEPS can show an artifact peak at approximately 10 nm with polydisperse particles, which is not usually observed in the case of the SMPS (Fujitani et al., 2012). Therefore, we treat the EEPS data below 10 nm as supporting information and indicate it using dashed lines in this paper.

From the measurements obtained using the EEPS, ~~total particle number concentrations remarkably increased up to more than  $1 \times 10^6$  particles cm<sup>-3</sup> substantial number concentrations of nanoparticles were observed~~ consistently when an aircraft took off or landed while wind (northerly or easterly winds) was blowing from the runway to the measurement site (Fig. 2). The peak concentrations of total particle number ( $6.8 \times 10^5 - 1.3 \times 10^6$  particles cm<sup>-3</sup>) during the plume event (indicated in Fig. 2) are about two orders of magnitude higher than the baseline concentrations ( $1.1-1.6 \times 10^4$  particles cm<sup>-3</sup>) during the no-plume event. Judging from synchronized increase of CO<sub>2</sub> (data is not shown in this paper) and the reasonable time-delay (20–200 seconds approximately) between aircraft take-off/landing and increase of particle number concentration, it seems that most peaks of particle number concentrations can be attributed to specific take-offs or landings of aircraft fleets. One-month time series total number concentrations and size distribution of particles is shown in Fig. S2. Total particle number concentrations during operation hours (6:00–23:00) were remarkably larger than non-operational hours (23:00–6:00). Also, there was no noticeable enhancement of nanoparticles during non-operational hours.

The total number concentrations at our measurement site is higher than the maximum value ( $1.5 \times 10^5$  particles cm<sup>-3</sup>) measured within 3 km of Los Angeles International (LAX) Airport (Hudda et al., 2014). It seems reasonable because our measurement site is much closer to the runway (i.e. 140 m). In fact, Zhu et al. (2011) reported higher total particle number concentrations (i.e.  $>1 \times 10^7$  particles cm<sup>-3</sup>) during takeoffs at the blast fence of LAX airport. The total particle number

concentrations at our measurement site often exceeded  $1 \times 10^6$  particles  $\text{cm}^{-3}$ , which is higher than the average concentrations at a roadside with a large amount of heavy-duty diesel vehicles in Kawasaki, Japan in winter 2011 ( $1.2 \times 10^5$  particles  $\text{cm}^{-3}$  (Fujitani et al., 2012)). When the aircraft exhaust plume approached the measurement site, the modal diameters were approximately 10 nm or smaller, which is smaller than those of diesel vehicle exhaust particles (Fushimi et al., 2011).

- 5 Typical examples of the size distributions of particle number concentrations measured with an engine exhaust particle sizer (EEPS) are shown in Fig. 3A. When the aircraft exhaust plumes were transported from the runway to the measurement site during take-off or landing, large enhancements of nucleation-mode particles were observed. When the aircraft exhaust plume approached the measurement site, the modal diameters were approximately 10 nm or smaller, which is smaller than those of diesel vehicle exhaust particles (Fushimi et al., 2011). The modal diameters were approximately 10 nm or smaller (see the supplement). In contrast, without the aircraft exhaust plumes, nucleation-mode particles were not observed. The number size distributions at 40–500 nm with aircraft exhaust plumes did not show a significant difference as compared to those without aircraft exhaust plumes. The mass size distributions, as estimated from the measured number concentrations while assuming a density of  $1.0 \text{ g cm}^{-3}$ , showed significant enhancements in the nucleation mode and a slight increase in the accumulation mode (Fig. 3B). These results clearly indicate that nanoparticles of diameters  $<30 \text{ nm}$  contribute to the major fraction of aircraft exhaust particle mass.
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The size distributions of particle number concentrations averaged during the sampling periods are shown in Fig. S3 (A). During the daytime sampling periods, the modal diameters were approximately 10 nm or smaller. In contrast, during the nighttime sampling period, the modal diameter was 34 nm, and the peak concentrations observed ( $1.1 \times 10^4$  particles  $\text{cm}^{-3}$ ) were lower than those observed during the daytime ( $8.8\text{--}21 \times 10^4$  particles  $\text{cm}^{-3}$ ) by one order of magnitude. These results clearly show that aircraft emissions greatly affect the atmosphere at our sampling site during the daytime sampling periods. Although the air was not necessarily transported from the runway to the measurement site for the entire sampling period for the daytime samples, remarkable enhancement of nanoparticles was observed multiple days in every daytime sampling period. We estimated the particle mass concentrations from the measured number concentrations while assuming a density of  $1.0 \text{ g cm}^{-3}$  (Fig. S3 (B, C)). At the nanoparticle size range (stage 11–13), the particle mass concentrations during the daytime were several times those observed during the nighttime. This suggests that aircraft emissions also greatly affect the nanoparticle samples (stage 11–13) during the daytime on mass basis.

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### 3.2 Particle mass and chemical components

The mass concentrations of the particles, OC, EC, sulfur and other elements are shown in Fig. 4 by particle size. Generally, particle mass concentrations showed bimodal distributions with fine mode (diameter:  $0.11\text{--}0.56 \text{ }\mu\text{m}$ ) and coarse mode ( $1.0\text{--}9.9 \text{ }\mu\text{m}$ ). The concentrations of the total particle mass were  $9.7\text{--}13.4 \text{ }\mu\text{g m}^{-3}$  during the daytime and  $10.7 \text{ }\mu\text{g m}^{-3}$  during the nighttime. At the nanoparticle stage (S11–S13, diameter:  $10\text{--}57 \text{ nm}$ ),  $4\text{--}10 \text{ }\mu\text{g}$  of the particulate samples per stage were

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collected, which was assumed to be sufficient for the chemical analyses. The size distributions of particle mass concentrations of NanoMoudi II-AU and NanoMoudi II-PC agreed reasonably with each other.

The OC showed not only a fine mode at 0.11–1.0  $\mu\text{m}$  but also a nucleation mode at 18–57 nm for the daytime samples #1 and #2. The sulfur also showed a bimodal distribution with a nucleation mode at 10–32 nm and a fine mode in all the daytime samples. In contrast, the EC showed a monomodal distribution with a modal diameter of 0.11–0.56  $\mu\text{m}$ .

In this study, inorganic salts such as nitrate and ammonium were not measured. Thus, large percentages of the particulate mass remained unidentified, especially in the fine and coarse modes. On the other hand, in the nanoparticle size range, NanoMoudi II may have positive artifact on the particulate mass because more than half of the particulate mass often remains unidentified with the measured OC, EC, ions, and elements even in the case of vehicle exhaust particles, of which the major components are supposed to be carbonaceous (Fushimi et al., 2011; Fushimi et al., 2016). In addition, the particle mass concentration at each stage in the nanoparticle size range was approximately 1.4–10 times those estimated from the number concentrations measured using the EEPS (Figs. S3C and 4). Therefore, we assumed that the general chemical characteristics of the nanoparticles can be explained based on the measured components.

The proportions of OC, EC, sulfur, and other elements are shown in Fig. 5 by particle size. For the daytime samples #1 and #2, the EC percentages were high (up to >40%) at approximately 0.057–0.29  $\mu\text{m}$  (stage 8–10). In contrast, the smaller particles in the nanoparticle size range comprised larger percentages of OC. The OC proportions were approximately 60–80% in the nanoparticles (10–32 nm) of the daytime samples #1 and #2. The sulfur and the sum of the other elements comprised approximately <10% and 10–30%, respectively, in the nanoparticles (10–32 nm) of the daytime samples #1 and #2. These results suggest that the nanoparticles emitted from a wide variety of in-use commercial aircraft with high thrusts mainly consist of OC. This is interesting and important because there has been some inconsistency between the volatility of the nanoparticles and the composition of the bulk particles in previous studies. However, if aircraft exhaust nanoparticles primarily comprise OC, the higher volatility appears to be reasonable. The OC proportions can be larger (EC proportions can be smaller) if the pyrolysis that occurs during the carbon analysis is corrected. Furthermore, the masses of the organic materials are generally 1.2–3.1 times that of the OC (Bae et al., 2006), and sulfur and other elements often exist as organic or inorganic compounds. Therefore, the proportion of organic materials, sulfur compounds, and other organic/inorganic elements would be larger than that presented in this paper.

### 3.3 Organic composition of size-resolved particles

A chemical analysis of the daytime size-resolved ambient particles suggests that nanoparticles having diameters of 10–32 nm (S12 and S13 of the impactor stages) mainly comprise organic carbon (see supplement for details). We thus focus on the chemical characteristics of organic compounds for this size range, in comparison with those of jet fuels and jet lubrication oils.



The mass chromatograms ( $m/z$  85) of size-resolved particles collected during the daytime (7:00–22:00, aircraft operation hours) and nighttime (0:00–6:00, non-operation hours), a jet lubrication oil, and a Jet A1 fuel are shown in Fig. 6. A series of  $n$ -alkanes was detected in the mass chromatograms ( $m/z$  85, an indicator of hydrocarbons) of Jet A1 fuels (Fig. 6). The carbon numbers of these  $n$ -alkanes were in the range of C<sub>11</sub>–C<sub>18</sub>, with the largest peak for C<sub>14</sub>. Interestingly, “humps” (baseline elevations) in the mass chromatograms at  $m/z$  85—which is often detected in mineral-oil-based lubricants commonly used for automobiles—were not detected in jet lubrication oils (Mobil Jet Oil II and Mobil Jet Oil 254). Instead, approximately 25 distinct peaks (likely fatty acid esters of pentaerythritol) were detected at the retention time of approximately 21–29 min (corresponding to molecular weights of approximately 380–530) from two jet lubrication oils (Fig. 6). This is considered to be reasonable because the base stocks of jet lubrication oils are essentially a mixture of C<sub>5</sub>–C<sub>10</sub> fatty acid esters of pentaerythritol (Timko et al., 2010; Yu et al., 2012). Furthermore, three compound groups (N-phenyl-1-naphthylamine, alkylated diphenyl amines, and tricresyl phosphate) were detected, which are reported as toxic substances in the material safety data sheet of lubrication oils. These three compound groups and fatty acid esters can be used as good markers for jet lubrication oil or jet exhaust because they are not usually contained in mineral-oil-based lubricants. In fact, these markers for jet lubrication oil were not detected from a mineral-oil-based lubricant for diesel vehicles with our TD-GC/MS analysis.  $n$ -Alkanes were not detected from two jet lubrication oils.

~~The mass chromatograms ( $m/z$  85) of size-resolved particles collected during the daytime (7:00–22:00, aircraft operation hours) and nighttime (0:00–6:00, non-operation hours), a jet lubrication oil, and a Jet A1 fuel are shown in Fig. 2.~~ The daytime nanoparticle samples (S13: 10–18 nm, S12: 18–32 nm, and S11: 32–57 nm) clearly show the presence of oil-marker peaks at a retention time of approximately 21–27 min (likely fatty acid esters of pentaerythritol). The intensity ratios of these peaks at 22.3 min or later were very similar to those of a jet lubrication oil (Fig. 7). However, the intensities of the peaks at 22.3 min or earlier in the case of the daytime samples were lower than those of a jet lubrication oil. This may be due to the partial evaporation of more volatile compounds in the atmosphere, which was found to be the case for diesel exhaust nanoparticles in roadside atmospheres (Fushimi et al., 2008; Harrison et al., 2016). The mass spectra of peaks at 21–27 min in nanoparticles collected during the daytime were very similar to that of a jet lubrication oil (an example is shown in Fig. 8). In contrast, the oil-marker peaks were very small in larger particles collected during the daytime (e.g., S9: 105–170 nm or S7: 290–560 nm) and were not detected in nanoparticles collected during the nighttime (Fig. 6). The other marker compounds for jet lubrication oil mentioned above were also detected in the daytime nanoparticle samples but not in the nighttime samples. C<sub>22</sub>–C<sub>33</sub>  $n$ -alkanes were detected in the daytime S9 and S7 samples but were weak or not detected in nanoparticles.

## 4 Conclusions and implications

From the aforementioned results, we conclude that approximately half the organic compounds in the <30-nm particles detectable using TD-GC/MS can be attributed to nearly intact forms of jet lubrication oil. This has not been identified in

previous studies. Jet lubrication oil is released into the atmosphere through a centrifugal breather vent, located in bypass air flow, as a droplet smaller than approximately 1  $\mu\text{m}$  or as vapor (Timko et al., 2010). The vented lubrication oil may be mixed with hot combustion gas at the exhaust area or in the atmosphere.

Our findings have an important implication for environmental issues from the ground level to the upper troposphere. The development of superior technologies for controlling oil emissions (e.g., through a breather vent) may greatly reduce aircraft exhaust nanoparticles. A reduction in the oil contributions would be beneficial in mitigating the health risk caused by aircraft exhaust nanoparticles as jet lubrication oils contain some toxic materials. Furthermore, a detailed knowledge of aircraft emissions is also required for improving our understanding of the origin and fate of ambient particles in the upper troposphere, which can potentially affect the radiative balance of the atmosphere (Righi et al., 2016).

We believe ambient measurements, like shown in this paper, can provide complementary insights into aircraft emissions which are not obtained from engine exhaust measurements. However, our ambient particulate samples may have affected by emissions from wide variety of jet engines, operating conditions (e.g. take-off, landing, taxiing and idling), maintenance conditions, and other sources (e.g. auxiliary power units and ground service equipments) (Stettler et al., 2011; Yu et al., 2012; Masiol and Harrison, 2014). The chemical composition of nanoparticles is also the average of those variety of emissions, although take-off and landing seems to have great impact because the measurement site is near the runway. Those emissions should be separately evaluated in the future.

### **Data availability**

For the data shown in this paper, please contact the corresponding author via email (fushimi.akihiro@nies.go.jp).

### **Supplement**

The supplement related to this article is available online at: <https://doi.org/.....>

### **Author contributions**

AF contributed to conceptualization, validation, investigation, resources, data curation, original manuscript draft preparation, manuscript review and editing, visualization, and supervision. KS contributed to conceptualization, validation, investigation, resources, data curation, and manuscript review and editing. YF contributed to validation, investigation, resources, data curation, and manuscript review and editing. NT contributed to conceptualization, validation, investigation, data curation, manuscript review and editing, supervision, project administration, and funding acquisition.

## Competing interests

The authors declare no competing interests.

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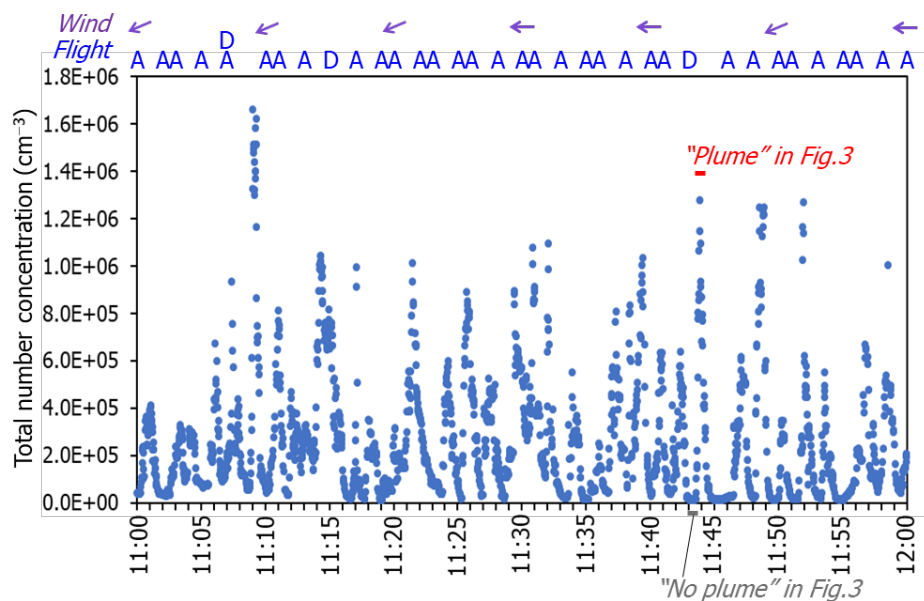
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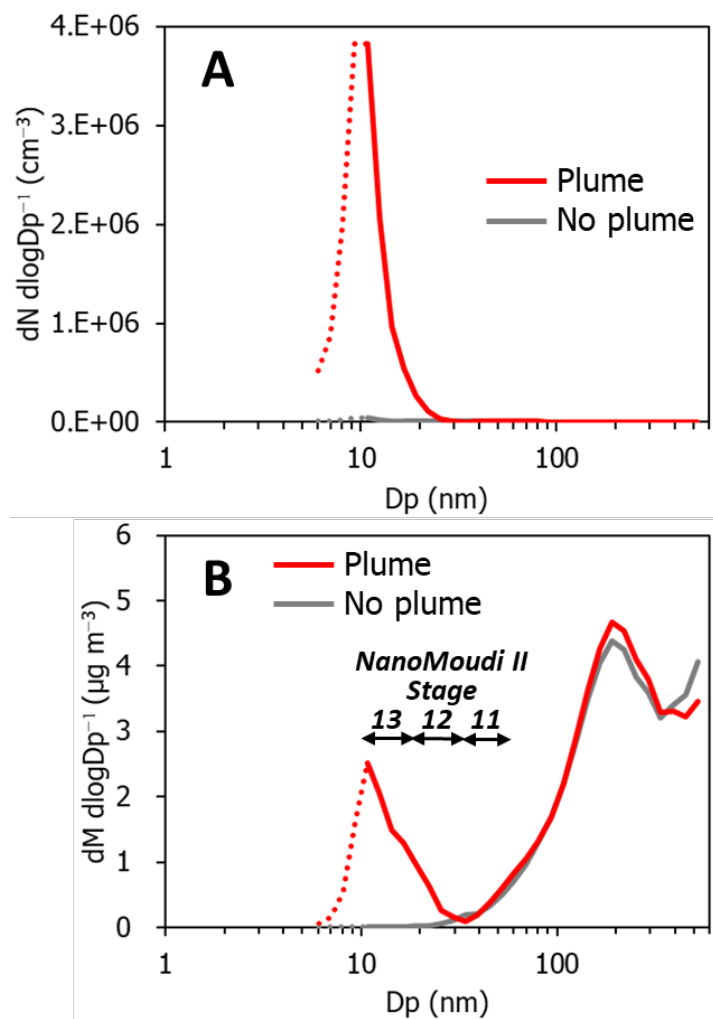
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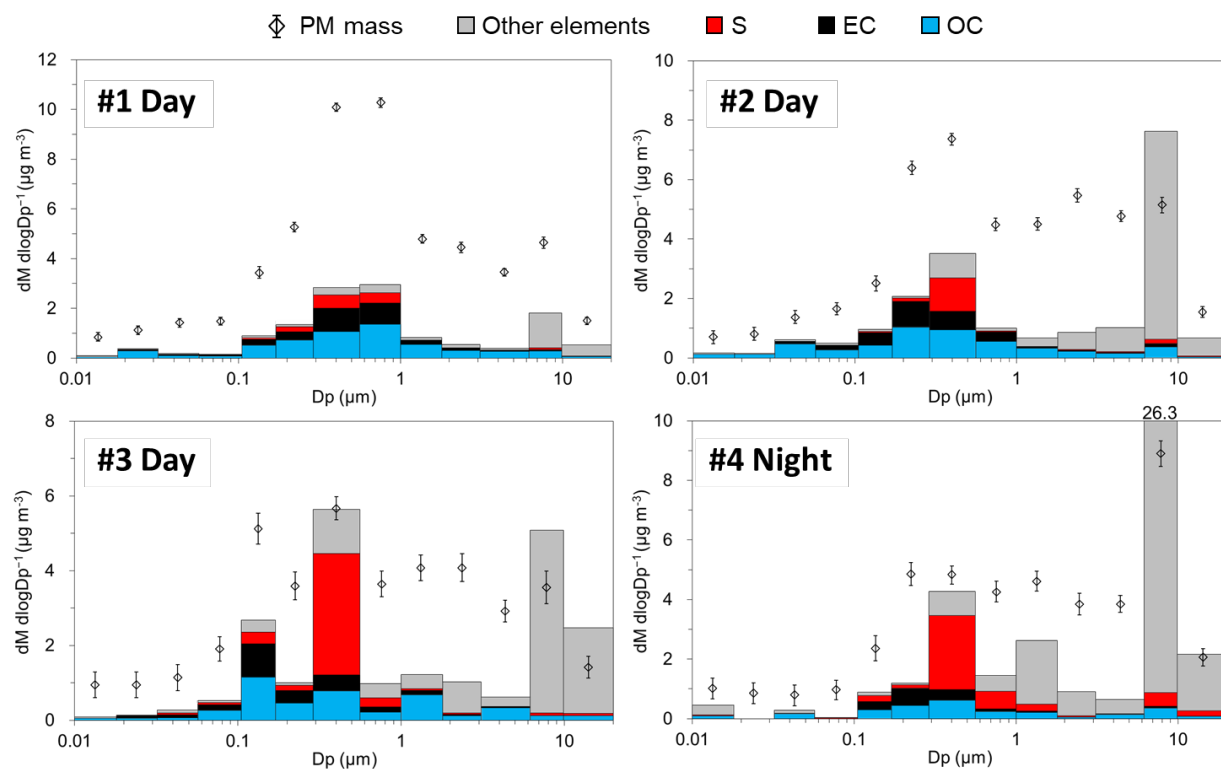
**Figure 1.** Map of the measurement site.



**Figure 2.** Time series total number concentrations of particles measured using the EEPS between 11:00–12:00 on February 15, 2018. One-second data is shown. The words "D" and "A" indicate departure and arrival times of aircraft fleets, respectively reported by Narita International Airport. The time periods of the "Plume" and the "No plume" events shown in Fig. 3 are shown as bars. Wind directions measured at the measurement site are shown in arrows. Wind speed was  $3.2\text{--}4.8\text{ m s}^{-1}$  in this one hour.

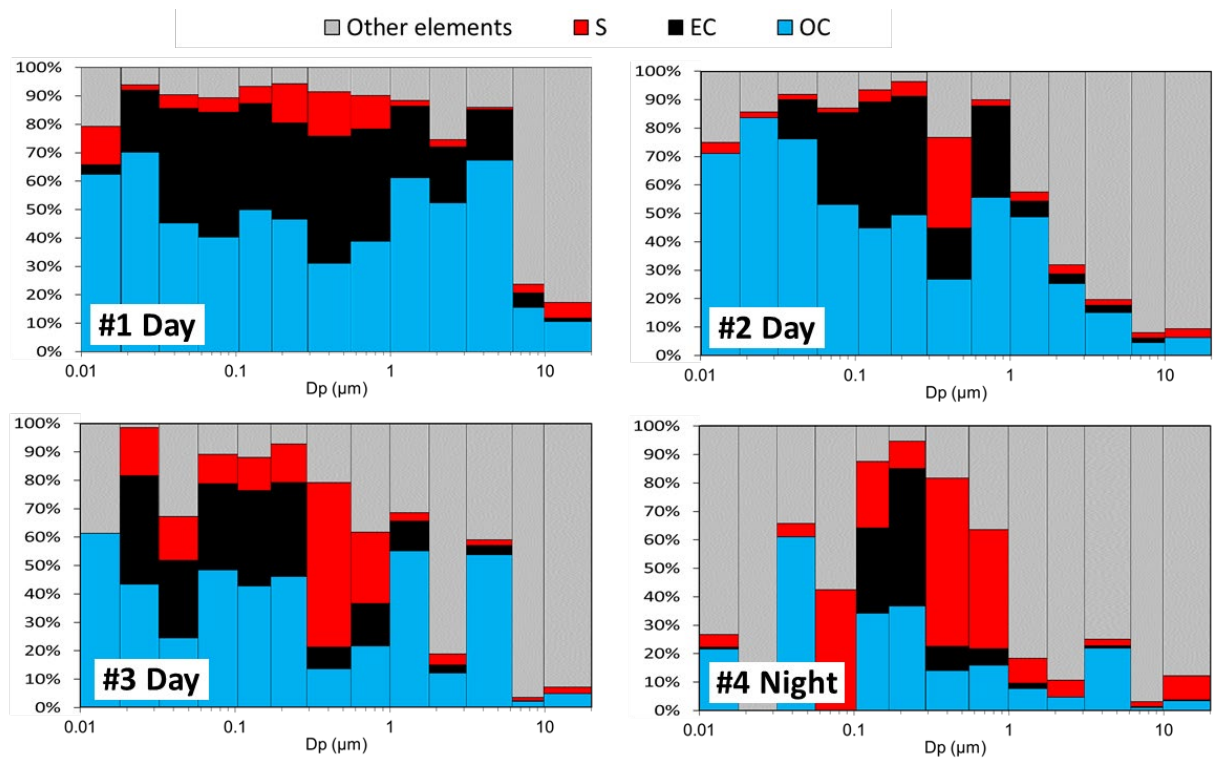


**Figure 3.** Size distributions of particle concentrations with and without aircraft exhaust plumes. (A) Particle number concentrations. (B) Estimated particle mass concentrations. The averaging times are approximately 20 s for both events. The measurement periods were 11:43:42–11:44:01 on February 15, 2018 and 11:43:11–11:43:30 on February 15, 2018 for the “plume” and “no plume” events, respectively indicated in Fig. 2.

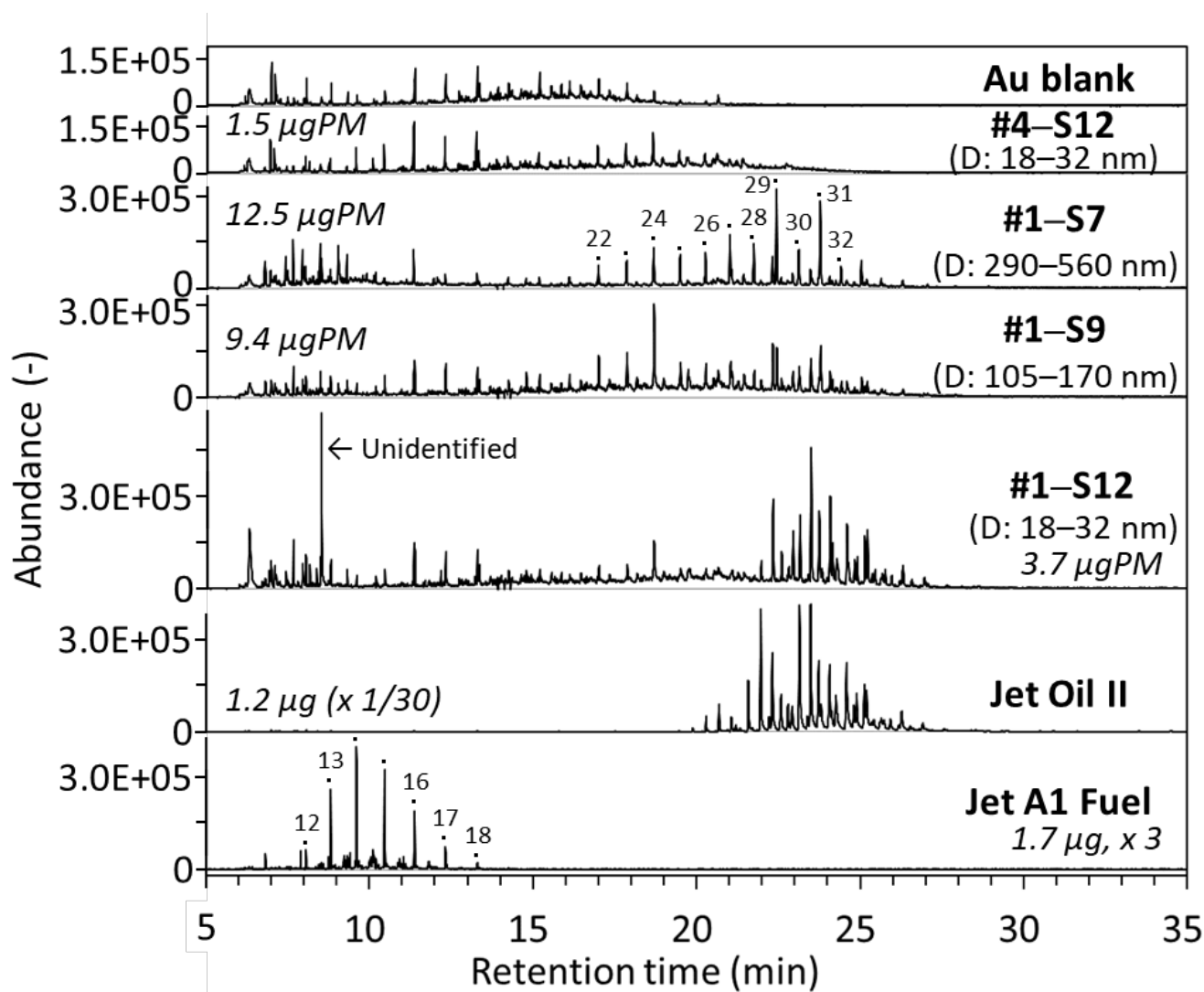


**Figure 4.** Mass concentrations of particles, OC, EC, sulfur, and other elements by particle size. The data of sulfur and other elements were adjusted so that the particulate masses of the NanoMoudi II-PC samples at each stage are equal to that of the NanoMoudi II-Au samples.

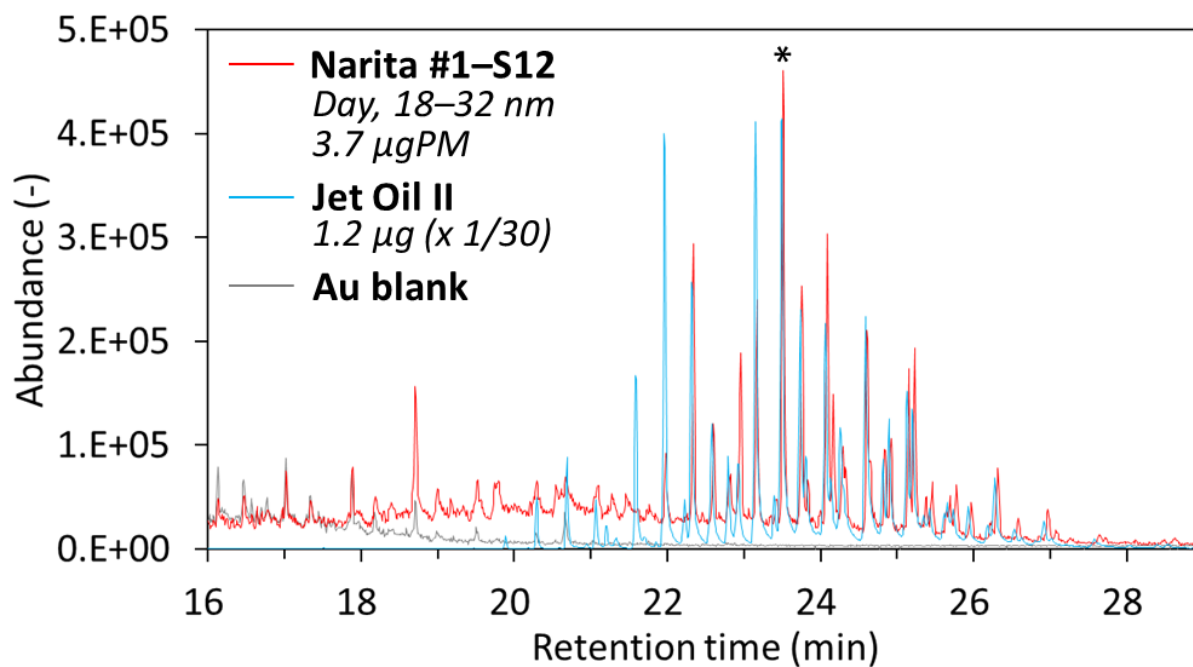




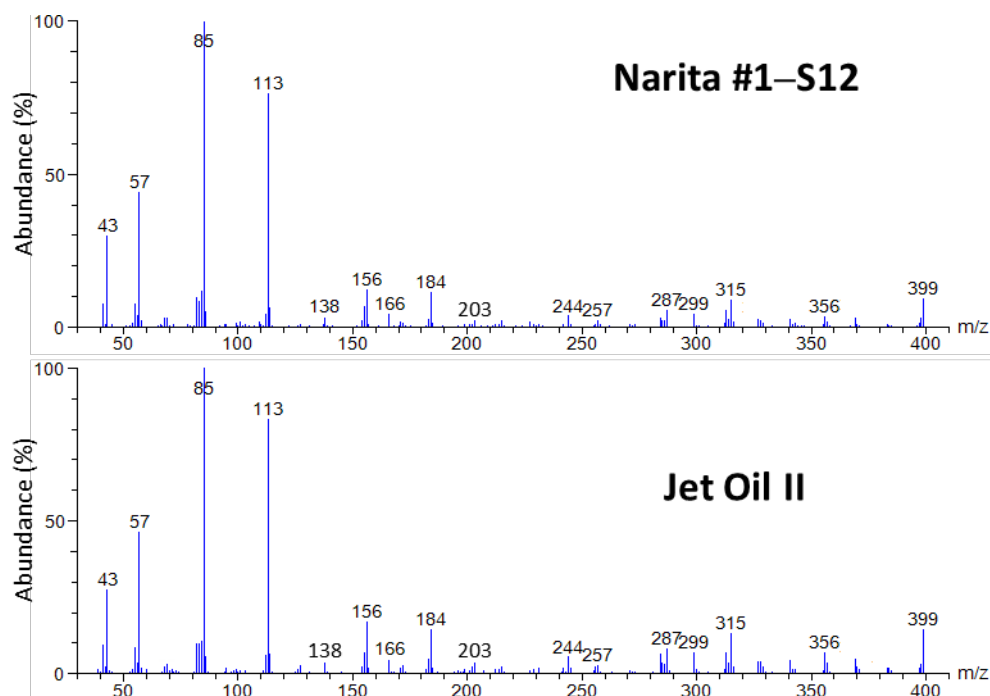
**Figure 5.** Proportions of OC, EC, sulfur, and other elements by particle size.



**Figure 6.** Mass chromatograms ( $m/z$  85) of size-resolved ambient particles collected during the daytime (sample #1, February 9–13, 2018) and nighttime (sample #4, February 22–26, 2018) at the Narita International Airport. Mass chromatograms of Jet Oil II, Jet A1 fuel, and Au-foil blank are also shown for comparison. The mass values (in  $\mu\text{g}$ ) presented in the plots indicate the mass of the samples that were analyzed using TD-GC/MS. The carbon numbers of  $n$ -alkanes are shown in the chromatograms of the S7 particles and Jet A1 fuel.



**Figure 7.** Mass chromatograms ( $m/z$  85) of a nanoparticle sample collected during the daytime (sample #1, February 9–13, 2018; S12, diameter: 18–32 nm) at the Narita International Airport, Jet Oil II, and Au-foil blank. The mass spectra of the peaks at 23.51 min of Narita #1–S12 sample and Jet Oil II with an asterisk are shown in Fig. 8.



**Figure 8.** Mass spectra of a nanoparticle sample collected during the daytime at the Narita International Airport (sample #1, February 9–13, 2018; S12, diameter: 18–32 nm) and Jet Oil II at 23.51 min of the TD-GC/MS chromatograms. The chromatographic peaks are indicated in Fig. 7. The instrument background spectrum was subtracted for the Narita #1–S12 sample.

*Supplement of*

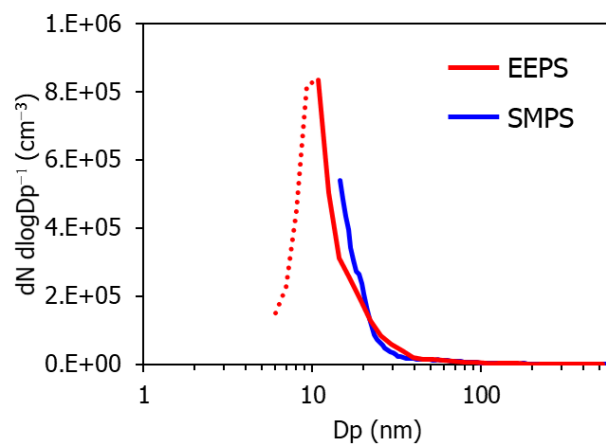
**Identification of jet lubrication oil as major component of aircraft exhaust nanoparticles**

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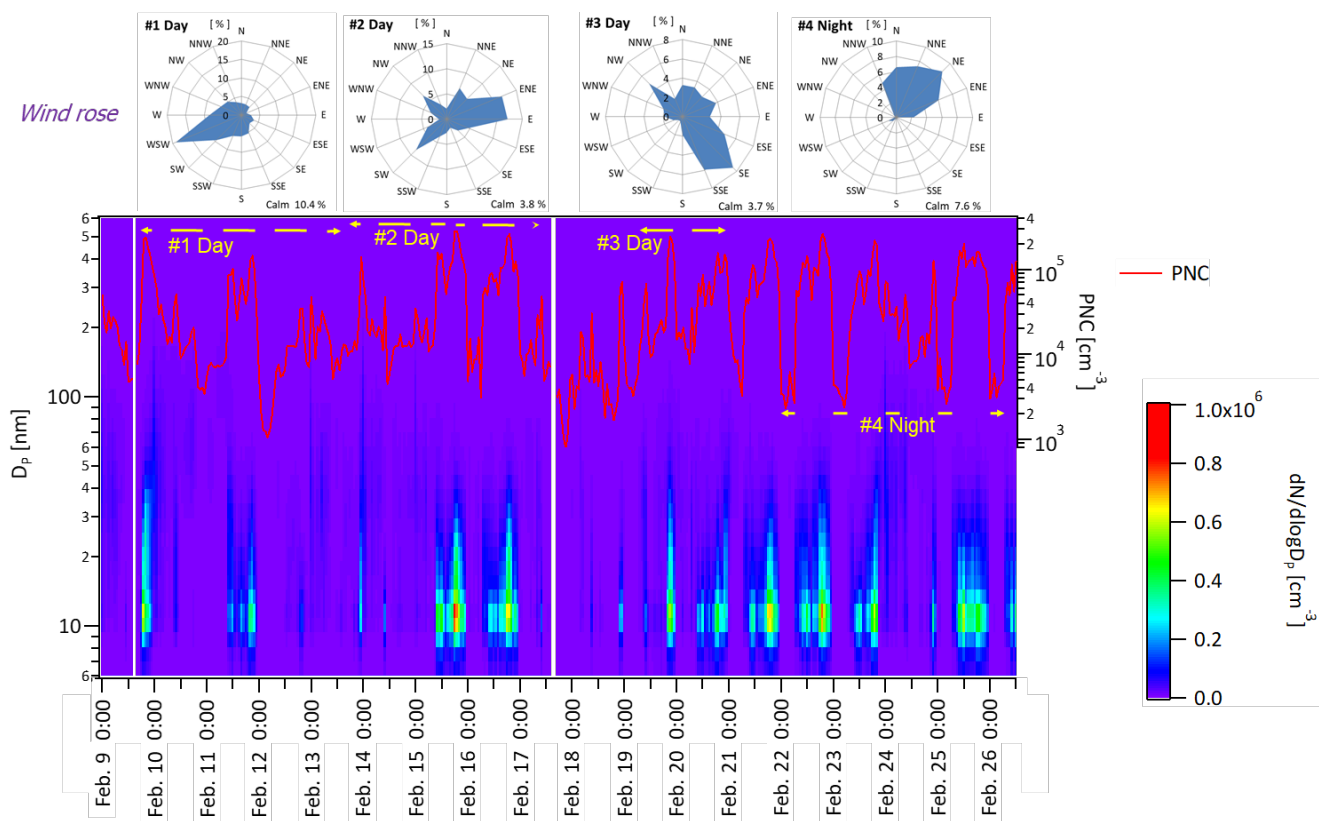
5 *Correspondence to:* Akihiro Fushimi (fushimi.akihiro@nies.go.jp)

**Table S1.** Summary of aircraft models used in the Runway A of Narita International Airport, Japan in February 5-26, 2018.

Rank	Number of flights	Model
1	1,159	A320
2	1,094	B763
3	741	B738
4	739	B788
5	711	B77W
6	707	B789
7	559	A333
8	478	B772
9	390	A321
10	243	B748
11	211	B77L
12	172	B744
13	122	A20N
14	122	A388
15	115	A332
16	96	A359
17	90	DH8D
18	79	B773
19	67	A343
20	50	B739
21	43	B735
22	35	MD11
23	25	B752
24	22	A306
25	14	CRJ7
25	14	GLF5
27	8	GLF4
28	7	SU95
29	5	CL60
29	5	GLF6
31	4	B737
32	3	F2TH
32	3	GLEX
32	3	LJ45
35	2	C56X
35	2	E35L
35	2	FA7X
35	2	GALX
39	1	C25C
39	1	C680
39	1	F900
39	1	G280
39	1	GL5T
Total	8,149	

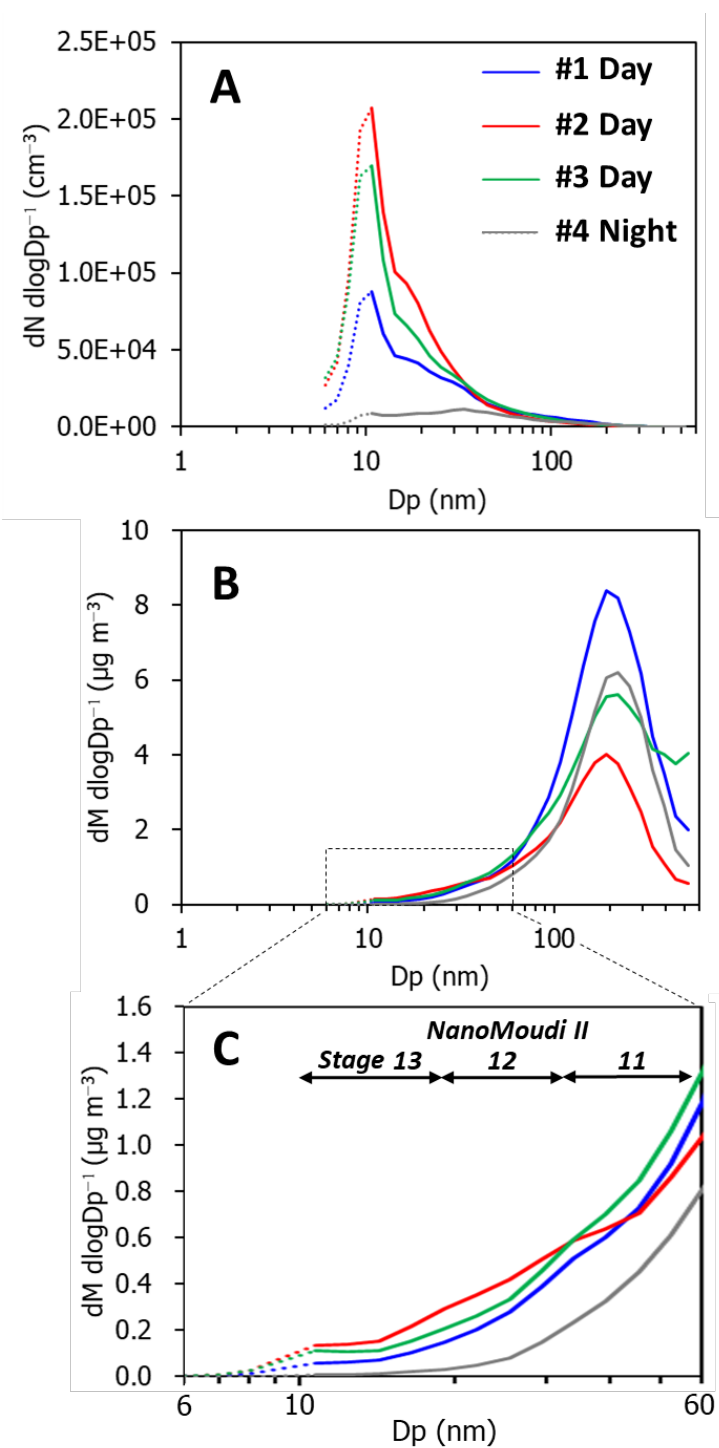


**Figure S1.** Size distributions of particle number concentrations measured using EEPS and SMPS. Data averaged over 1 h between 11:00–12:00 on February 15, 2018 are shown.



**Figure S2.** One-month time series total particle number concentrations (PNC) and size distribution of particles measured using the EEPS in February 9–26, 2018. One-hour averaged data measured with EEPS is shown. The sampling periods and their wind roses at the measurement site are shown. The averages and the ranges (minimum – maximum) of the wind speeds during the sampling periods were 2.2 (0–9.2) m s<sup>-1</sup> (#1 Daytime), 2.9 (0–7.2) m s<sup>-1</sup> (#2 Daytime), 2.4 (0–6.9) m s<sup>-1</sup> (#3 Daytime), and 2.9 (0–6.1) m s<sup>-1</sup> (#4 Nighttime). The Runway A is in a northerly or easterly direction from our measurement site.





**Figure S3.** Size distributions of particle number concentrations measured using the EEPS averaged during the sampling periods (A). (B, C) Estimated size distributions of particle mass concentrations.