



D1.1 nvPM and vPM physicochemical characteristics from ground-based measurements

WP1: Contrail ice nucleation in the low soot regime

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D1.1: nvPM and vPM physicochemical characteristics from ground-based measurements

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About the document

This document describes the work conducted within A4Climate task 1.1 - vPM from aviation: Characterise the contribution of unburnt kerosene, lubrication oil and sulfate to the total PM emissions from the overall aviation fleet .

It is an accompanying document that describes the origin and preliminary analysis of the data set of the A4Climate airport campaign, which was conducted from March to May 2026. The dataset itself can be accessed via a digital object identifier.

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Nature of the deliverable ¹

DATA

¹ Deliverable types:

R: document, report (excluding periodic and final reports).

DEM: demonstrator, pilot, prototype, plan designs.

DEC: websites, patent filings, press and media actions, videos, etc.

OTHER: software, technical diagrams, etc.



Dissemination level

PU	Public, fully open. e.g., website	X
SEN	Sensitive, limited under the conditions of the Grant Agreement	
CL	Classified information under the Commission Decision No2015/444	

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Abbreviations

vPM	volatile particulate matter
nvPM	non-volatile particulate matter
DOI	Digital object identifier
UFP	Ultrafine particles (particles smaller than 100 nm)
SMPS	Scanning mobility particle sizer
TD	Thermodenuder



Executive summary

The objectives of deliverable 1.1 in the A4CLIMATE's WP1 is to quantify the ratio of non-volatile particulate matter (nvPM) to volatile particulate matter (vPM), and chemically characterize the vPM composition from aviation emissions. Therefore, A4CLIMATE conducted an extensive measurement campaign downwind Frankfurt Airport from March to May 2026, involving state-of-the-art instrumentation in a laboratory container. The involved partners successfully recorded particle size distribution, chemical composition and performed a volatility-based separation of submicron particles. A special focus was on ultrafine particles, these are particles smaller than 100 nm, as this size class is typically being emitted at high number concentrations from aviation engines. A novel approach of this campaign was the online analysis of lubrication oil tracers. These oils, being emitted solely from jet engines, allow the identification of events in which the particles unambiguously contain emissions from aircraft engines. Based on the events, the partners are now able to analyze the volatile fraction of particles from aviation, the content of lubrication oil and sulfate, during the high-aviation-contribution periods. In addition, we measured black carbon (soot), and the gases sulfur dioxide and carbon dioxide. Further (and beyond the original proposed objectives of A4Climate), we continuously measured the ice nucleating ability of the particles during the campaign by a portable ice nucleation chamber (PINEAir), which was deployed for the first time downwind a large airport. Some of the data are final and are published openly accessible on Zenodo. Further data that requires a more sophisticated analysis, such as the analysis of unburnt kerosene, which will be uploaded to the same data repository under the same digital object identifier with a follow-up version number.

1. Introduction

Aviation-induced cirrus clouds change the natural global cloudiness and thereby create an imbalance between incoming shortwave radiation and outgoing infrared radiation, resulting in global warming (Kärcher, 2018). Although, they are short-lived, the continuous formation of contrails and contrail cirrus results in a global annual mean net radiative forcing (RF) of 62.1 mW m^{-2} for the year 2019 (Teoh et al., 2024). Over Europe and North America, where dense air traffic meets frequent occurrence of ISSRs, contrails cause a significant net RF of up to 876 mW m^{-2} and 414 mW m^{-2} annual mean, respectively (Teoh et al., 2024). There is consensus on the warming effect of contrails, which is why the aviation industry investigates mitigation strategies that specifically target contrail formation. Recent in-flight observations behind a modern lean-burn engine reveal that contrails are still forming at low soot emission levels, despite three orders of magnitude reduction of the emission index of nvPM during cruise (Voigt et al., 2026). Hence, not accounting for volatile PM (vPM) in contrail modelling may underestimate ice formation, especially in the “soot-poor” regime at low ambient temperatures (Ponsonby et al., 2025), as sulphate and organic aerosols emitted by the engine take over the role of condensation nuclei for contrail formation (Yu et al., 2024).

Hence, aviation vPM emissions need to be characterised on the molecular level to understand where the particle emissions are coming from. While the emission of sulphate is directly dependent on the fuel sulphur content (FSC), and organic emissions from fuel largely depend on the combustion efficiency, also lubrication oil, being independent of the fuel composition, is emitted from jet engines (Yu et al., 2012; Fushimi et al., 2019; Ungeheuer et al., 2021). In a laboratory study, Ponsonby et al. (2024) have shown that pure lubrication oil particles can serve as contrail ice-forming particles. Unfortunately, it is to acknowledge that the emissions of lubrication oil and other semi-volatile organics from aircraft engines have been completely overlooked by the European aviation industry's roadmap strategy toward clean and climate-neutral aviation (NLR, 2025). The ICAO acknowledges that no emission indices and no other information on the effect of engine lubricants are available and therefore cause uncertainties in PM emissions from aviation (ICAO, 2020). Decker et al. (2024) estimate an upper limit emission index (EI) of lubrication oil of 110 mg/kg fuel , which is one order of magnitude higher than the EI of soot, but largely uncertain as it is solely based on lubrication oil consumption.

Here, we deployed novel aerosol instrumentation downwind Frankfurt Airport, Germany, for online measurements of the chemical composition and microphysical properties of particles from aviation. It is to acknowledge that these emissions represent only the ground airport activity. Nevertheless, with a unique measurement setup targeting chemical composition and microphysical properties, the A4CLIMATE dataset D1.1 reveals new insights on the composition of volatile particulate matter from aviation. This document intends to provide an overview of the measured parameters and highlights the main findings of the airport campaign. It is to mention that the data are openly available, meanwhile they are currently further analyzed by the consortium with potential future publications.

2. Methods

2.1. Campaign overview

The A4Climate campaign at Frankfurt Airport took place between 17 March and 12 May 2026 and was designed to characterise aviation-related emissions in the vicinity of a large international airport. Measurements were conducted from the GUF mobile laboratory container, which was deployed near Terminal 2 in coordination with the airport operator, Fraport (50°03'09.4" N, 8°35'09.7" E). The container was equipped with more than ten instruments for measurements of gas- and particle phase composition and aerosol physicochemical properties.

Sampling was performed via three inlet lines. One inlet line was dedicated to gas-phase measurements, whereas two additional inlet lines were fitted with PM1 and PM2.5 size-selective pre-separators, respectively, for aerosol measurements. This inlet configuration allowed simultaneous measurements of gaseous and particulate pollutants related to airport operations.



Figure 1. Deployment of the GUF laboratory container in March 2026 at Frankfurt Airport Terminal 2 and a view of the inside of the container after instrumentation setup.

Meteorological conditions during the campaign included several periods of northeasterly winds, during which the measurement site was influenced primarily by air masses advected from Frankfurt city rather than from the airport (Fig. 2). These periods were therefore considered representative of urban background conditions with negligible direct influence from aviation emissions and were used to distinguish airport-related emission signatures from general urban pollution. Conversely, periods with wind from the airport were associated with elevated aviation tracer signals, indicating direct influence from airport operations and allowing detailed analysis using the complete measurement setup.

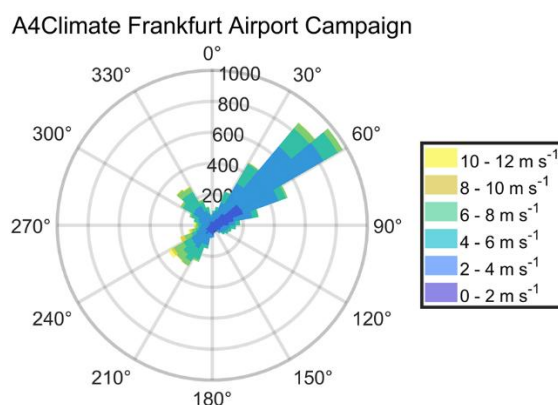


Figure 2. Wind rose showing the distribution of wind direction and wind speed during the campaign period (17 March 2026–12 May 2026). Meteorological data were obtained from the Deutscher Wetterdienst (DWD) station at Frankfurt Airport (station code: 1420). Wind sector from the airport is south-west.

2.2. Particle phase instrumentation

2.2.1. Online-Orbitrap mass spectrometer (DBDI-Orbitrap-MS)

Real-time molecular characterization of aerosol composition was performed using a high-resolution mass spectrometer (Orbitrap Exploris120, Thermo Fisher Scientific) coupled with a Soft Ionization by Chemical Reaction In Transfer (SICRIT) ion source (Plasmion GmbH). The ambient air was sampled through a charcoal denuder to remove the gas phase, a heating section to evaporate aerosol particles, and introduced into the SICRIT ion source where the evaporated compounds are ionized by dielectric barrier discharge ionization (DBDI). The resulting ions were then transmitted into the Orbitrap analyzer, where mass spectra were obtained by detecting the oscillation frequencies of the ions. This process generates a high mass resolution and sub-ppm mass accuracy for molecular formula assignment.

2.2.2. Aerosol mass spectrometer (C-ToF-AMS)

A compact time-of-flight aerosol mass spectrometer (C-ToF-AMS) was used to measure the chemical composition of non-refractory submicron aerosol particles (Drewnick et al., 2005). Particles were focused into a narrow beam, flash-vaporized by a heated surface vaporizer (~650 °C), and the resulting vapors were ionized by electron impact (at 70 eV). The ions were then analyzed by time-of-flight mass spectrometry to quantify the major aerosol components: organics, sulfate, nitrate, ammonium, and chloride. Furthermore, possible marker ions for lubrication oil will be evaluated and tested against results from the Orbitrap measurements.

2.2.3. Single particle mass spectrometer (ALABAMA)

The ALABAMA (aircraft-based laser ablation aerosol mass spectrometer) was used to measure the size and chemical composition of individual aerosol particles in real time. Particles were detected optically, sized from their transit time between two lasers, and subsequently ionized by a laser, generating both positive and negative ions of single particles. Mass spectra of both polarities were simultaneously acquired by a bipolar time of flight mass spectrometer. Detailed instrumental description are reported by Brands et al. (2011) and Clemen et al. (2020).

2.2.4. Thermodenuder / scanning mobility particle sizer (TD-SMPS)

To measure total and non-volatile particle number concentrations, a condensation particle counter (CPC; Grimm 5.410) with a time resolution of 1 Hz and a lower cut-off diameter of 4 nm was combined with a thermodenuder operated at 350 °C. The system was connected to the PM1 inlet and was used to measure either the total particle number concentration or, downstream of the thermodenuder, the non-volatile particle fraction. In addition, particle number size distributions between 5.5 and 350 nm were measured at the PM1 inlet using a universal-scanning mobility particle sizer (Model 3938; TSI).

2.2.5. Thermodenuder / Partector (TD-Partector)

Particle size distributions were additionally measured from 2026-04-08 to 2026-05-13 by AERAS (Aircraft Emission Reporting & Analysis System), a system with a patent pending designed by DLR-VT to characterize aircraft emissions. The system was operated at the container gas-phase inlet. Here, particle measurements were performed with two Partector 2 Pro units (naneos), one equipped with a Catalytic Core (Catalytic Instruments) to measure total and non-volatile particle size distributions between 10 and 300 nm simultaneously over 8 channels, with a time resolution of 6

seconds. A size-dependent particle loss correction was applied to the Partector 2 Pro operating behind the Catalytic Core.

2.2.6. Multi-Angle Absorption Photometer (MAAP)

The Multi-Angle Absorption Photometer (MAAP) was used to measure aerosol light absorption and derive equivalent black carbon (eBC) mass concentrations in near real time. Particles were collected on a filter tape, and aerosol absorption was determined from simultaneous measurements of light transmission and backscattering at multiple angles. This multi-angle approach reduces artifacts caused by particle scattering and filter loading compared with simpler filter-based absorption methods. eBC concentrations were calculated using the instrument's standard mass absorption coefficient.

2.2.7. Portable Ice Nucleation Chamber (PINEAir)

An aircraft-version of the Portable Ice Nucleation Experiment (PINEAir) was deployed in the container to study ice nucleation processes and to measure INP concentrations under conditions pertinent for both mixed-phase and cirrus clouds, with temperatures from about -10 to about -50 °C (Möhler et al., 2021). The focus was on nucleation in the cirrus cloud regime. PINEAir is a cloud expansion chamber which avoids frost formation on the cold walls and thereby omits frost fragmentation and related background ice signals during the operation. The deployment of PINEAir at Frankfurt Airport was the first deployment of this new instrument in the exhaust plume of a large international airport.

2.3. Gas phase instrumentation

In addition to the comprehensive set of aerosol instrumentation, the two trace gases carbon dioxide (CO_2) and sulfur dioxide (SO_2) were measured. At the container gas phase inlet, a LI-COR LI-840 system was operated to measure CO_2 in real time at a temporal resolution of 1 s. The measurement principle is based on non-dispersive infrared absorption. At the same inlet, SO_2 was measured with a 43iQ Sulfur Dioxide Analyzer (Thermo Scientific) at a temporal resolution of 60 s. This analyzer uses pulsed fluorescence technology and was calibrated in-house using an ACTRIS reference gas.

3. Preliminary results

During A4CLIMATE airport campaign, the real-time measurements of comprehensive aerosol characterization downwind Germany's largest airport, Frankfurt Airport, was achieved. The measurements involved particle size spectrometers for physico-chemical characterization (size and number) with thermodenuders for determination of the volatile fraction, and multiple online mass spectrometers for chemical analysis at a high time resolution. The physicochemical information on particle size and volatility down to 10 nm was achieved by two systems: (1) the DLR-IPA setup involving differential mobility analyzers and condensation particle counters with and without a thermodenuder, and (2) the DLR-VT setup involving the Partector particle counter with and without catalytic stripper, resolving the transient events with a time resolution of 6 seconds.

Regarding chemical characterization of the transient airport plumes, we successfully measured the unambiguous lubrication oil as aviation markers in real time. The jet oil intensity is converted into a mass concentration based on the instrument's calibration at the field site. Analysis of the field data of all online mass spectrometers and the PINEAir ice nucleation counter is currently ongoing. Preliminary analysis indicates several events during the campaign of a clear airport signature with ultrafine particle concentrations exceeding the WHO high-number concentration value of $10\,000\text{ cm}^{-3}$ (24 hours average) and $20\,000\text{ cm}^{-3}$ (1 hour average).

3.1. Total particle concentration and volatile fraction

Particle number size distribution was measured throughout the campaign to characterize the physical properties of the aerosol population, providing a basis for further analysis. Figure 3 shows the particle size–time series (right), together with a pollution rose for the total particle number 10–20 nm size fraction (tPN10-20) as a function of wind direction and speed (left). Particle number concentration in the 10–50 nm range rises sharply during several episodes throughout the campaign. The pollution rose shows that the highest tPN10-20 concentrations are associated with wind directions from the airport sector linking these ultrafine particles to aviation activity.

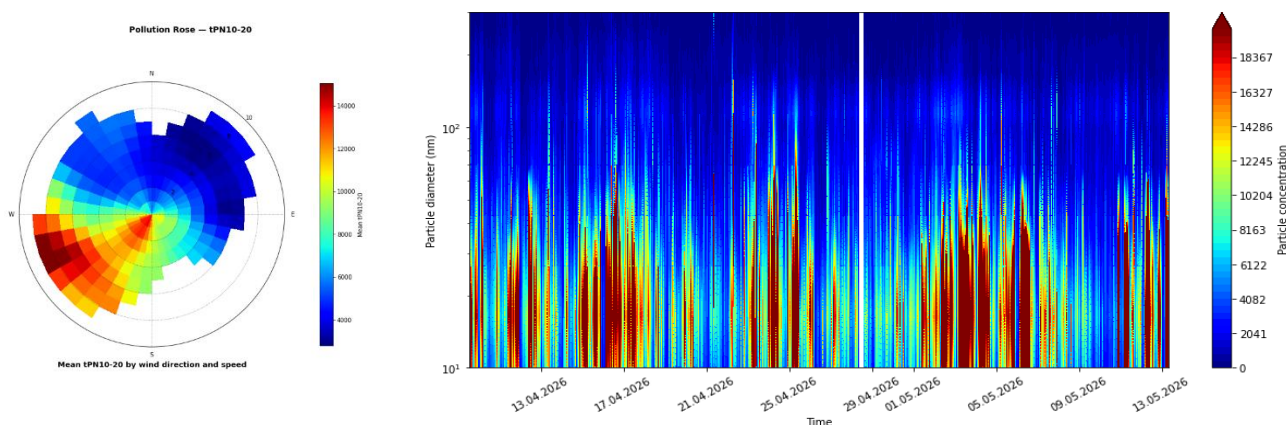
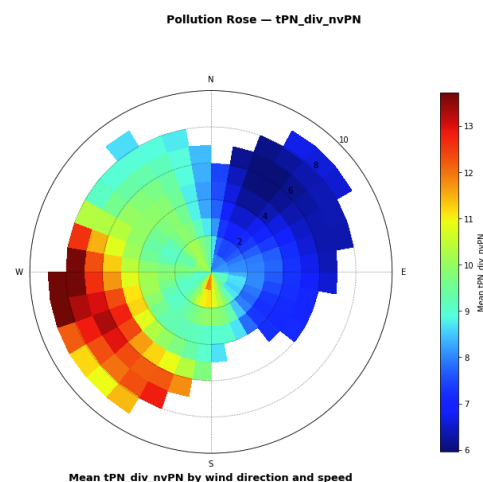


Figure 3. Wind rose showing the distribution of wind direction and wind speed during the campaign period (17 March 2026–12 May 2026). Meteorological data were obtained from the Deutscher Wetterdienst (DWD) station at Frankfurt Airport (station code: 1420). Wind sector from the airport is south-west. Partector data from DLR-VT.



The mean ratio of mean ratio of total particles (tPN) over the number of non-volatile particles (nvPN) (see Figure 4) indicates a clear enhancement of volatile particles stemming from airport emissions, with ~8% (1/13) being of non-volatile character, while that ratio from the urban background (north east) shows that ~17% of the total particles is of non-volatile character (1/6). Also the north-west direction indicates a larger fraction of volatile particles, which is likely close to the rural fraction of 10%.

Figure 4. Pollution wind rose showing the mean ratio of total particles (tPN) over the number of non-volatile particles (nvPN) based on the Partector measurements. Meteorological data were obtained from the Deutscher Wetterdienst (DWD) station at Frankfurt Airport (station code: 1420). Wind sector from the airport is south-west. Partector data from DLR-VT.

The analysis of the complementary setup with TD-SMPS is currently ongoing and will be added to the A4Climate database once the data are processed and finalized.

3.2. Jet Oil time series as a marker for aviation emissions

Figure 5 shows the time series of the eight jet oil tracer compounds measured during the full campaign period, from 2 April to 13 May 2026, at Frankfurt Airport. The time series shows that jet oil detection consistently corresponds with wind direction from the airport sector, between approximately 150° and 240°. Moreover, the fluctuation in intensity is closely related to airport operating hours, which further explains this pattern. The most intense signal period occurred at the

beginning of the campaign, from 3 to 7 April, coinciding with the higher wind speeds recorded within the airport sector. This is consistent with efficient short-range transport of freshly emitted plume material. Conversely, in several episodes when the wind direction rotates away from the airport sector, tracer intensity collapses to baseline. The pattern of this individual episode further supports the tracers are site specific which originated from fresh local aviation emissions. Further analysis of the time series of jet oil indicates that the occurrence of jet oil is highly correlated with the high number concentration of ultrafine particles in the size range < 40 nm.

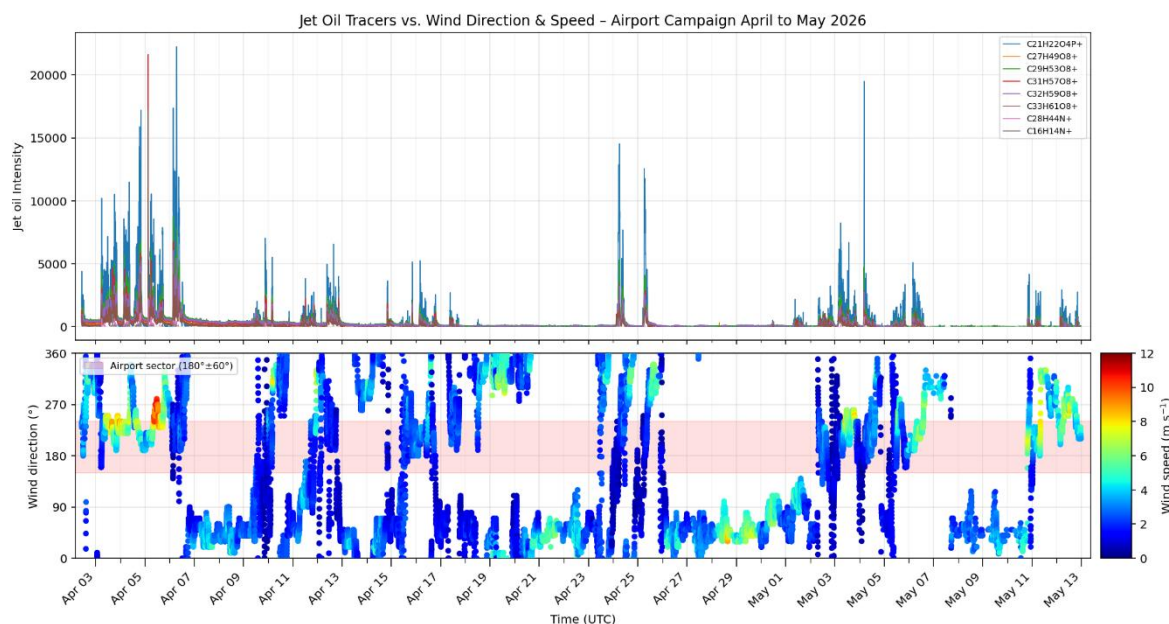


Figure 5. Time series of jet oil tracers (pentaerythritol esters and additives) as intensity. Intensity will be translated into mass concentration based on the campaign calibration files. The occurrence of the jet oil tracers is highly correlated with the wind sector from the airport indicated by the horizontal bar in the lower panel. Meteorological data were obtained from the Deutscher Wetterdienst (DWD) station at Frankfurt Airport (station code: 1420).

3.3. Trace gas time series and correlation to airport emissions

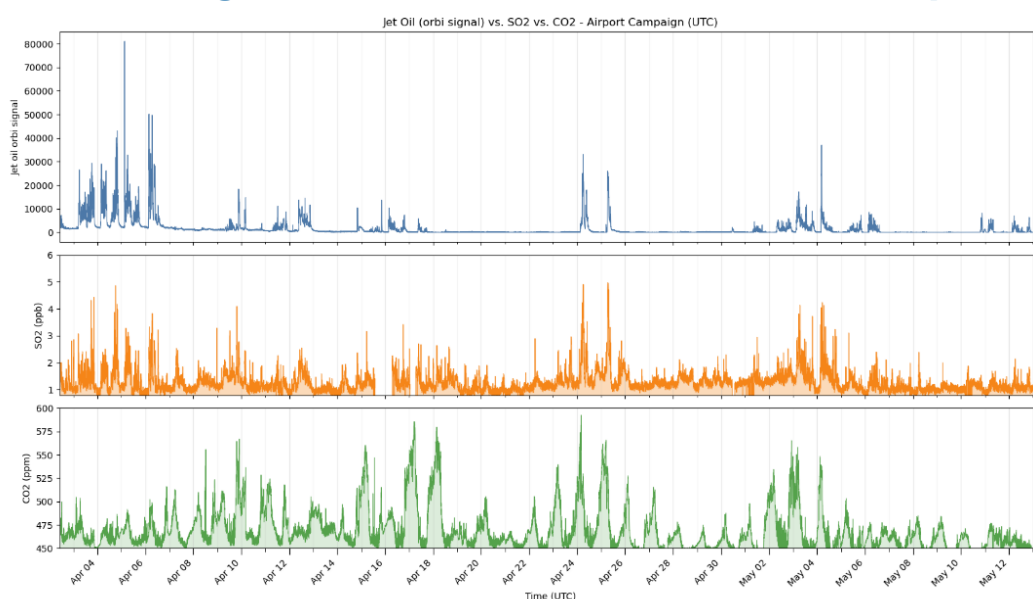


Figure 6. Preliminary time series of the jet oil signal, SO_2 and CO_2 recorded at Frankfurt Airport over the full campaign period. SO_2 mixing ratio shows a moderate correlation to the occurrence of jet oil markers in the particles, indicating the same emission source. The CO_2 mixing ratio does not show a similar pattern, as is likely driven by other combustion sources and atmospheric boundary layer variability.

Figure 6 compares the jet oil signal with two additional trace gases recorded throughout the campaign to place the jet oil tracers in the context of other combustion-related emissions. SO₂ is closely linked to aircraft engine emissions, as it forms from the oxidation of sulfur contained in jet fuel during combustion. Comparing its time series with that of jet oil therefore offers a further way of assessing their common source. The two records show a broadly similar pattern, with SO₂ peaks coinciding with several jet oil episodes (e.g. 24–26 April), consistent with both parameters originating from aircraft engine activity. The SO₂ was coming from fuel combustion, and jet oil from unburned lubrication oil vented through the engine or the oil breather. Some additional structure in the SO₂ record is not mirrored in the jet oil signal which suggests a minor contribution from other local combustion sources. CO₂, by contrast, reflects a much broader range of anthropogenic activity, including road traffic and other urban emissions in the surrounding area as well as boundary layer dynamics.

4. Data availability

4.1. Data repository

All data recorded during the A4Climate airport campaign are open accessible under the following version DOI [10.5281/zenodo.22027361](https://doi.org/10.5281/zenodo.22027361) and shall be cited as follows:

Vogel, A. L., Ahmad, M. N., & Ungeheuer, F. (2026). A4CLIMATE Frankfurt airport campaign (Version v1) [Dataset]. Zenodo. <https://doi.org/10.5281/zenodo.22027362>

Due to ongoing analysis not all instrumental data of the campaign are in a final state for upload (August 2026) but will be added to the same version doi in the following months.

4.2. Current A4CLIMATE airport campaign data

The current data present in the data repository are listed under table 1, as of August 2026.

Table 1. Campaign data available as open access.

File Name	Institution	Description
A4Climate_JetOil_ambient_final.csv	GUF	Ambient jet oil mass concentration (ng/m ³), derived from the summed Orbitrap signal of 8 tracer compounds via JetOil calibration against SMPS-derived mass
A4Climate_Orbitrap_H2SO4_rawdata.csv	GUF	Raw, uncalibrated HSO ₄ ⁻ ion signal (counts) from the Orbitrap Exploris 120 (negative mode)
A4Climate_Orbitrap_JetOil-intensity_rawdata.csv	GUF	Raw, summed Orbitrap signal intensity (counts) of the 8 jet oil tracer compounds, prior to mass conversion.
A4Climate_SMPS_PNSD_final.csv	GUF	Ambient particle number size distribution (dN, 7.17–537.61 nm, 241 bins)
A4Climate_Licor_CO2-H2O_final.txt	MPIC	CO ₂ (ppm) and H ₂ O (ppt) from a LI-COR LI-840A NDIR gas analyser, with cell temperature/pressure and absorption diagnostics; uncorrected.
A4Climate_MAAP_eBC_final.dat	MPIC	Equivalent black carbon (EBC, ng/m ³) and aerosol absorption coefficient (Sigma _{ap} , m ⁻¹) from a Multi-Angle Absorption Photometer (MAAP); UTC, uncorrected
A4Climate_OPC_PNSD_final.csv	MPIC	Particle number concentration across 31 size channels (0.25–40 µm) from a Grimm SkyOPC optical particle counter; quality-controlled.

A4Climate_Partector_nvPN.csv	DLR VT	Non-volatile particle number concentration, binned (10–300 nm), from Partector2Pro after Catalytic Stripper
A4Climate_Partector_nvPSD.csv	DLR VT	Non-volatile particle size distribution, full-resolution log-spaced bins (10–300 nm)
A4Climate_Partector_tPN.csv	DLR VT	Total (volatile + non-volatile) particle number concentration, binned (10–300 nm)
A4Climate_Partector_tPSD.csv	DLR VT	Total particle size distribution, full-resolution log-spaced bins (10–300 nm), direct sample
A4Climate_MA200_BC.csv	DLR VT	Black carbon (BC) concentration

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