PSI Center for Energy and Environmental Sciences

Measurements of Ultrafine particles and chemical traces from aviation emissions near the Zürich airport

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[2] AWEL, Amt für Abfall, Wasser, Energie und Luft, 8090 Zürich, Switzerland
[a]now at: NOAA CSL & Cooperative Institute for Research in Environmental Sciences (CIRES), Boulder, CO, USA

ETH Nanoparticles Conference , June 16th 2025

Stadt Kloten

Kanton Zürich Baudirektion Amt für Abfall, Wasser, Energie und Luft

SR Technics

Contact : sarah.tinorua@psi.ch

Aircraft engines emissions : Major impacts on climate and health

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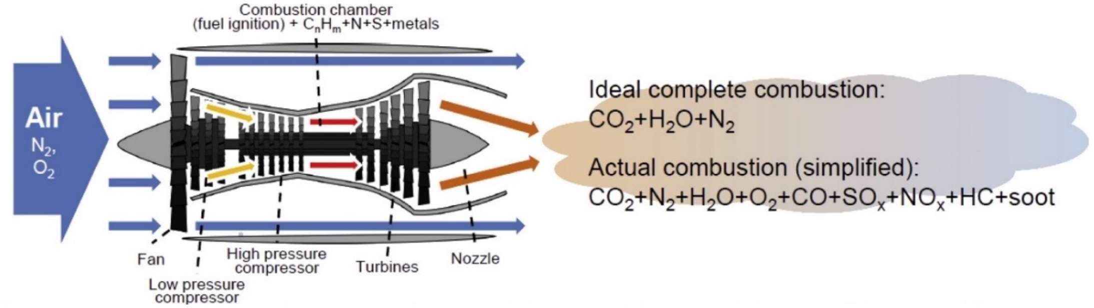
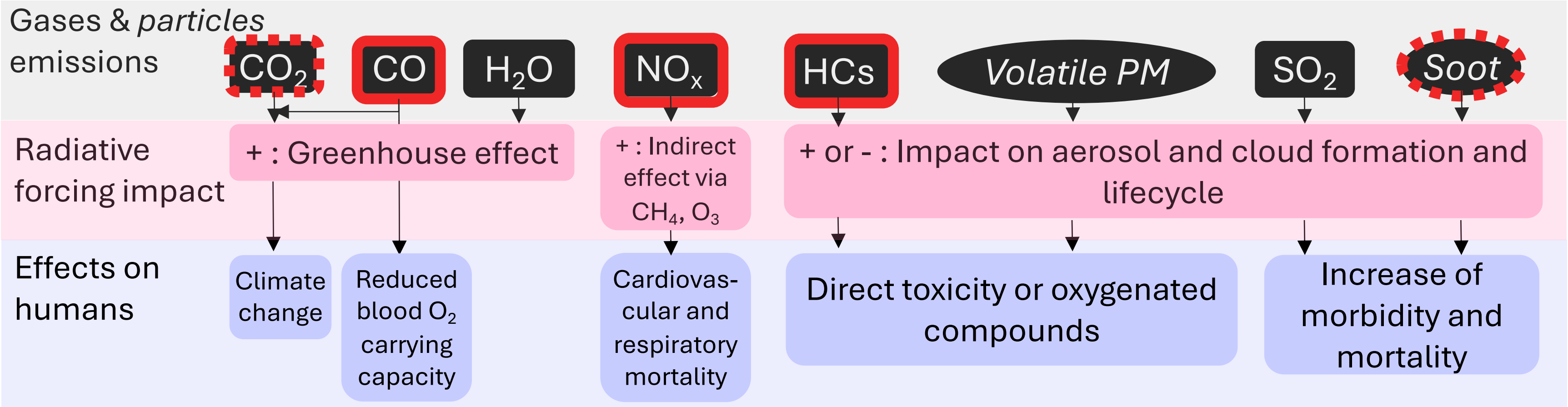
What is emitted :



Internationally regulated

Recently regulated by the International Civil Aviation Organization (ICAO)[3]



Adapted from Lee et al. 2009[1] and Masiol et al. 2014[2]

[1] Lee, D. S., et al. 2009, *43*(22), 3520–3537.

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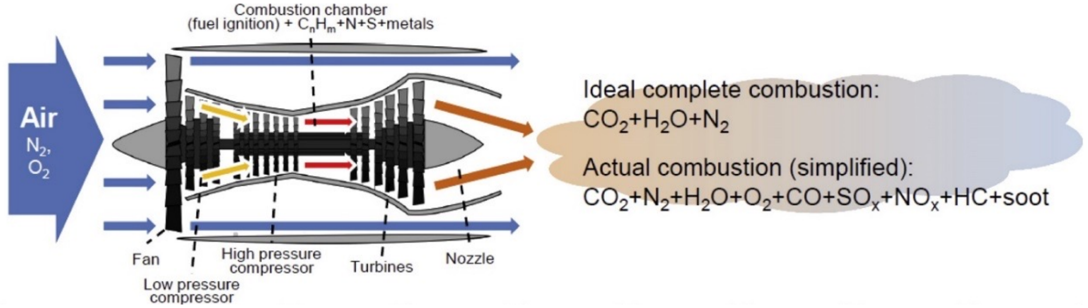

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Gases & *particles* emissions: CO_2 | CO | H_2O | NO_x | HCs | *Volatile PM* | SO_2 | *Soot*

Radiative forcing impact:
- + : Greenhouse effect
- + : Indirect effect via CH_4, O_3
- + or - : Impact on aerosol and cloud formation and lifecycle

Effects on humans:
- Climate change
- Reduced blood O_2 carrying capacity
- Cardiovas-cular and respiratory mortality
- Direct toxicity or oxygenated compounds
- Increase of morbidity and mortality

Adapted from Lee et al. 2009[1] and Masiol et al. 2014[2]

In 2024 the **global passenger traffic** was ~**9.5 billion (301/sec), +10.4%** compared to 2023

→ Number of passengers expected to double **by 2042**[4]

[1] Lee, D. S., et al. 2009, *43*(22), 3520–3537.

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[3]*Emissions Certification Policy and Guidance* | *Federal Aviation Administration*. (accessed 2024-06-29).

[4]*JOINT ACI WORLD-ICAO PASSENGER TRAFFIC REPORT, TRENDS, AND OUTLOOK* | *Airports Council International*. (accessed 2025-02-24).

Aviation emissions are a major contributor to UFPs concentrations

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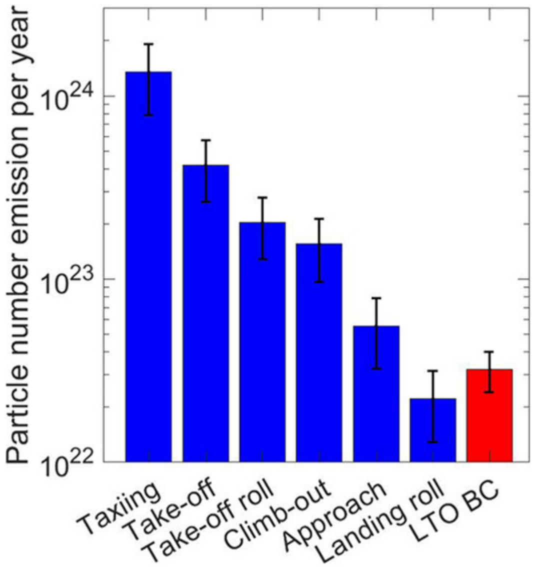
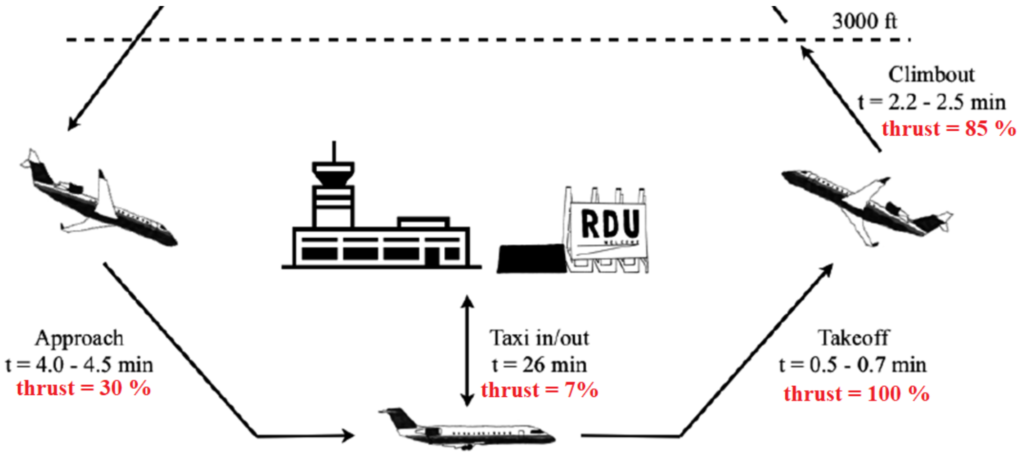


Total particle number emissions at Zurich Airport (3)

Landing & Take-off cycle (LTO)



- At the engine exit plane, **Particulate Matter** (PM) is dominated by **non-volatile PM (nvPM)** from fuel combustion + **volatile PM** from nucleation, e.g. induced by jet engine oil vapors
- Mostly **Ultrafine Particles, UFPs** (D<100nm), with a median diameter between 15-95 nm[1]

  → small **size** = greater health impact
- High **UFPs concentrations** reported around airports

  → Affect the local population + airport workers[2]
- **UFPs concentration** and **size** are **depending on the engine thrust but not only** ! (ageing processes, environmental conditions, …)

[1]Stacey, B. Atmos. Environ. 2019, 198, 463–477
[2]Bendtsen et al. Environ. Health 2021, 20, 10
[3]Zhang, X. et al., Environ. Science & Tech. 2020, 54, 22

APPROPRIATE investigation: *Aviation Plume PROPeRtIes AT point of Exposure* **: 4 main objectives**

Characterise Gas & PM emissions

Identify Aviation emission tracer

Quantify nvPM contribution to total PM

Understand aviation plume evolution

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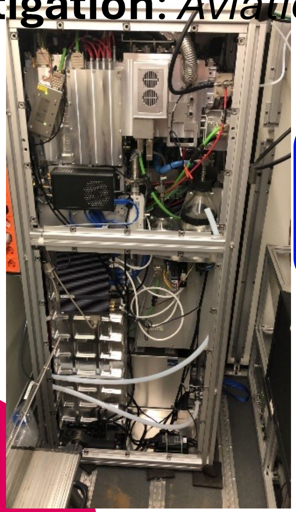

1) Lab measurements of engine lubrication oils & fuel

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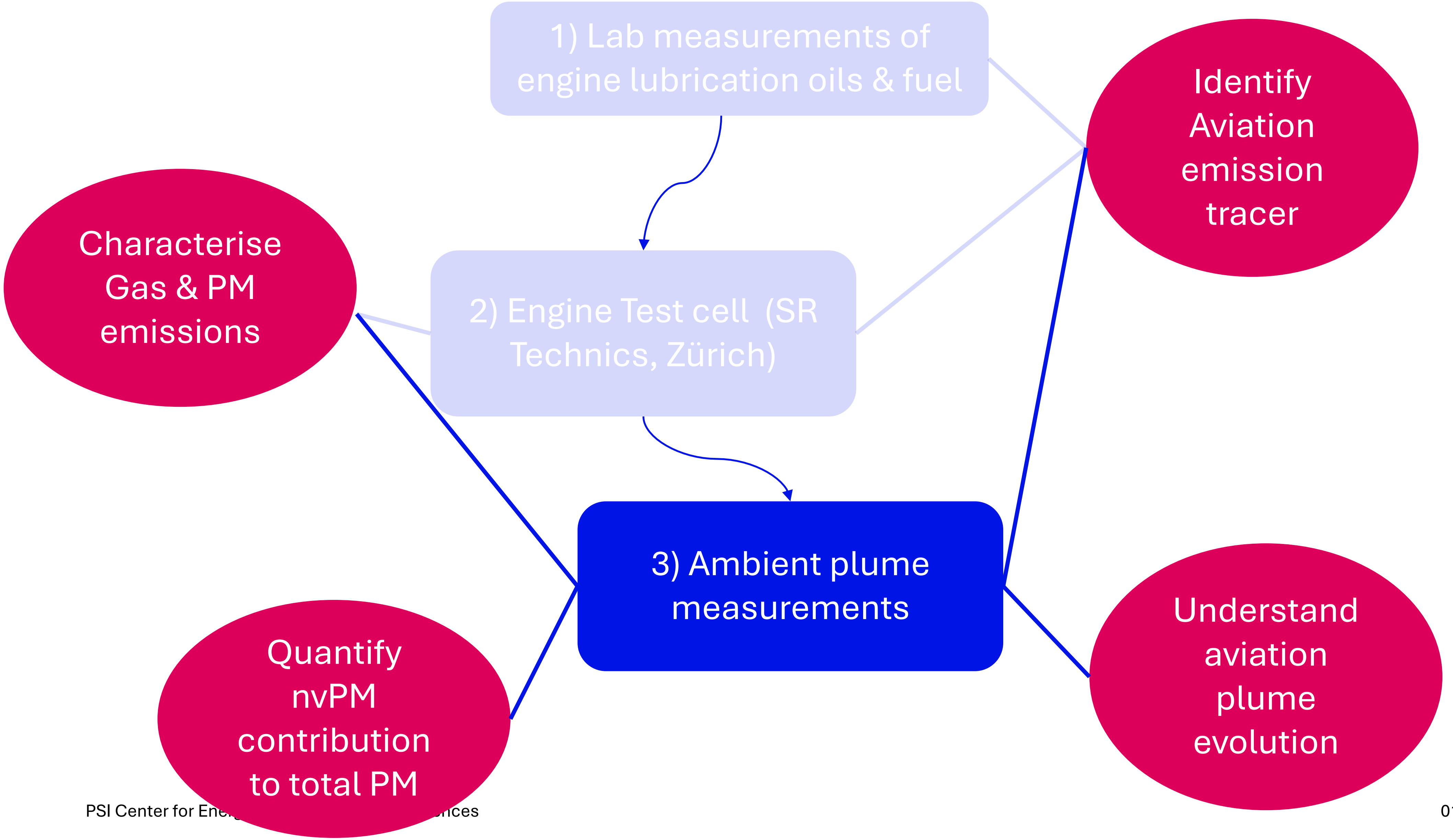


Aerosol and gases measurements downwind Zürich Airport

→ At Kloten field site in Nov 2022

+ Meteorological parameters, and gases and aerosols properties from AWEL (Office for Waste, Water, Energy and Air)

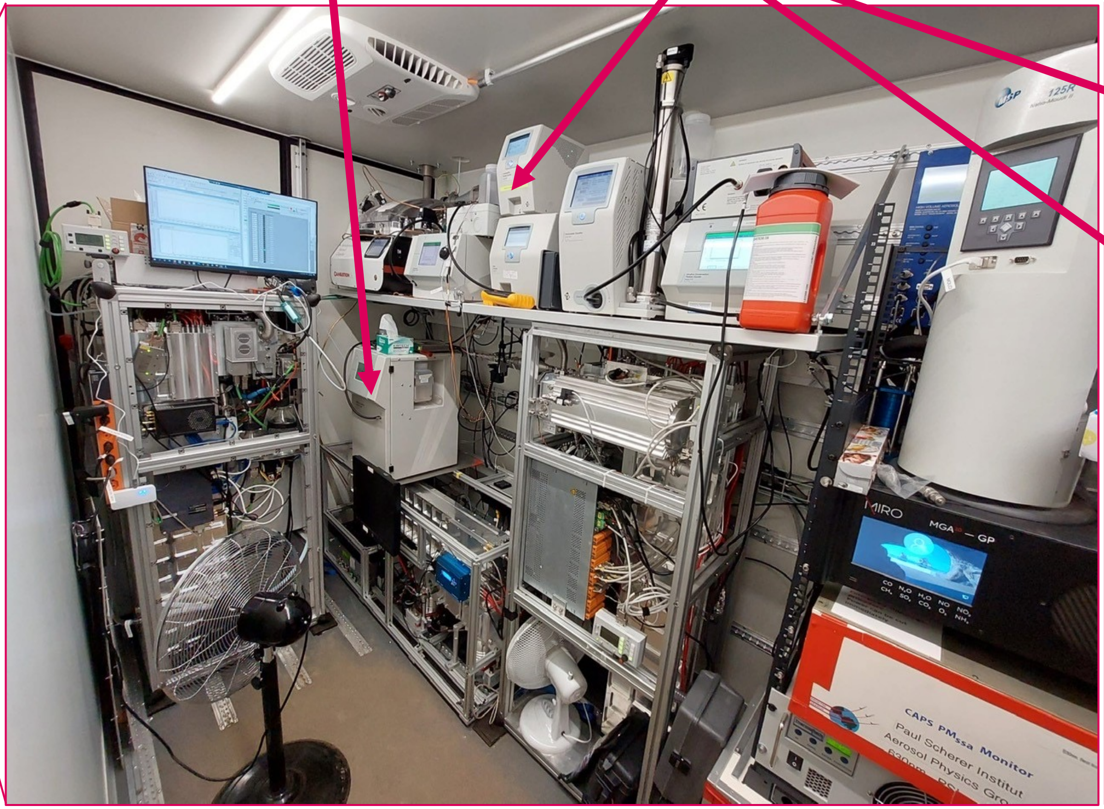
⇒ UFPs size distribution, NOx, SO_2, BC concentrations … *10min*

Aerosol and gases measurements downwind Zürich Airport

SMPS 3938 (Scanning Mobility Particle Sizer)
+ Catalytic Stripper
→ Size distribution of nvPM, *3min*

CPCs 3756, 3750, 3789 with different size cuts
(Condensation Particle Counters)
→ Number concentration of PM, *1min, 3 min*

Kloten field site – Nov 2022



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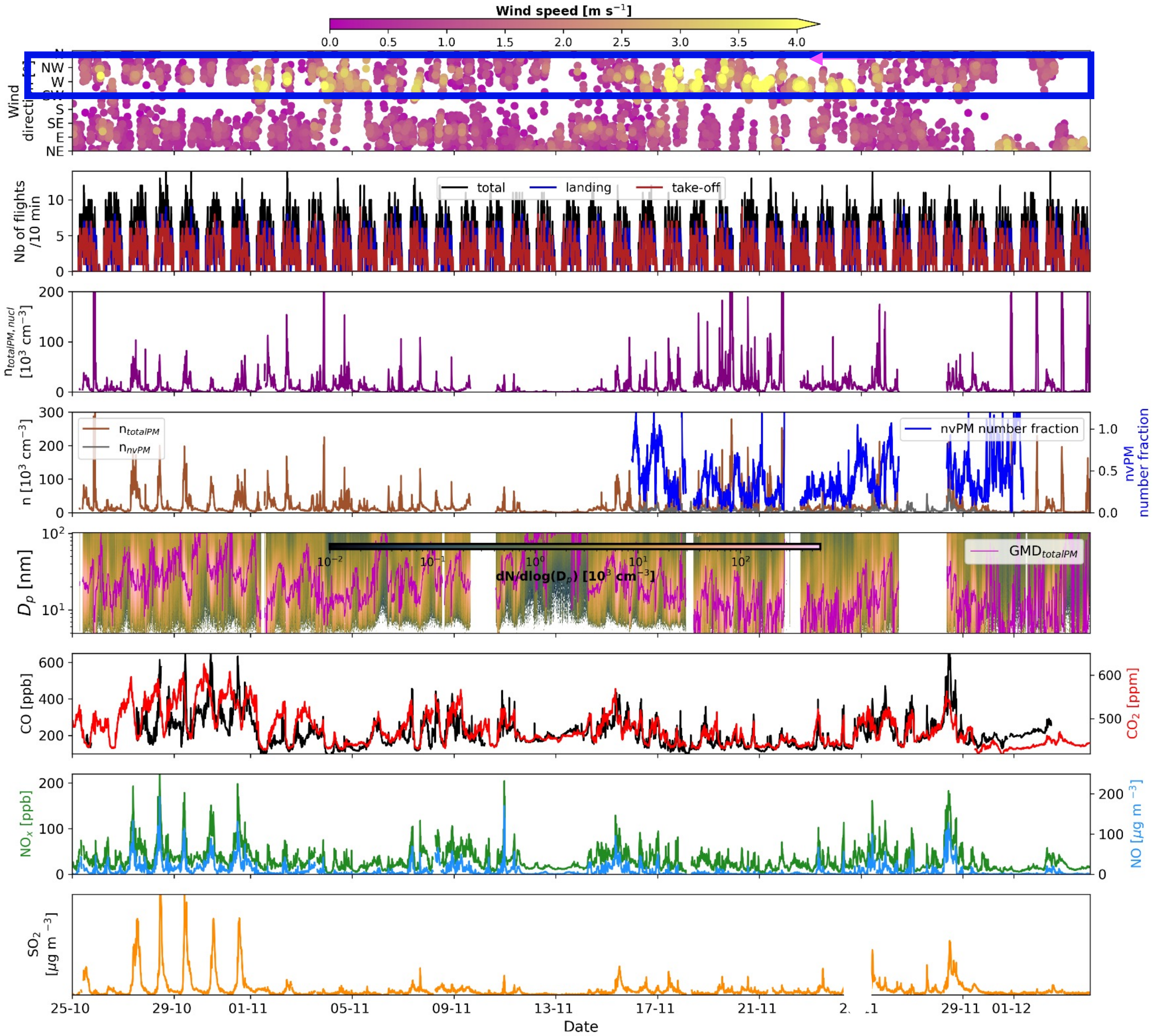
→ Number concentration of PM, *1min, 3 min*

MIRO gas analyser
→ CO, NO concentrations, *1 min*

+ Meteorological parameters, and gases and aerosols properties from AWEL (Office for Waste, Water, Energy and Air)
→ UFPs size distribution, NOx, SO_2, BC concentrations … *10min*

EESI (Extractive Electro-spray Ionization Long-Time-of-Flight Mass Spectrometer)
→ UFPs Chemical composition, *30s*

Overall UFPs and gas properties at Kloten

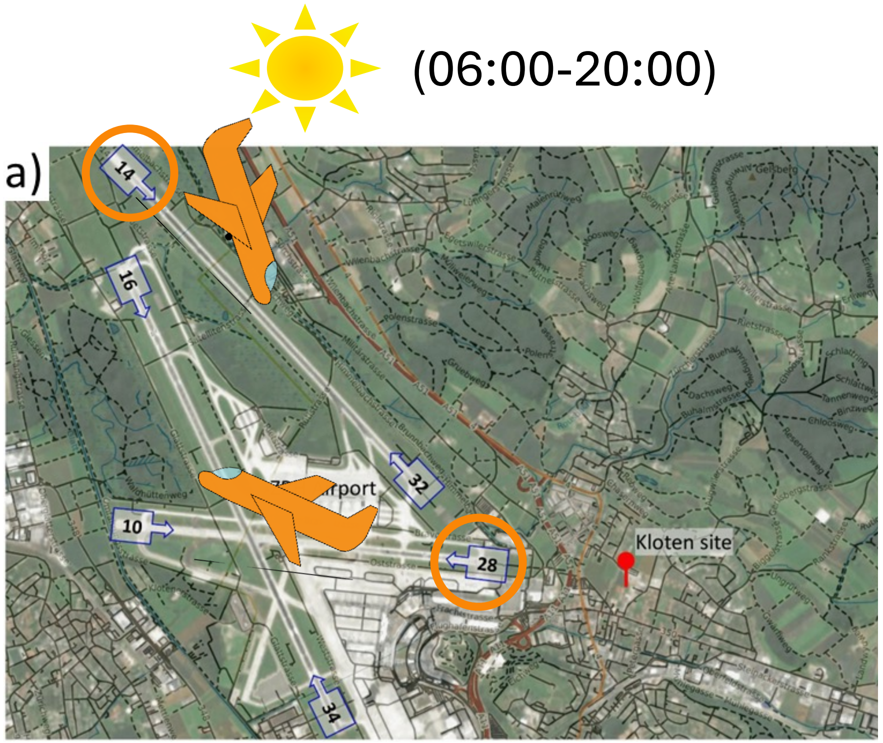


- **Wind coming from the Airport (W-NW)**

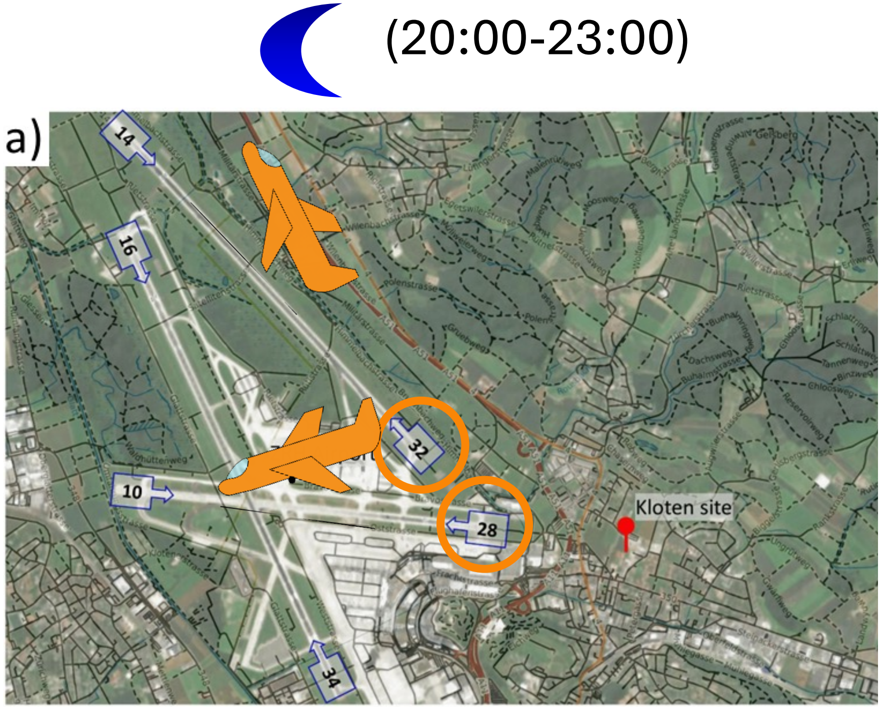
- Several **peaks of UFPs concentrations** (> 100’000 cm^{-3}) associated with :
  - **Smaller diameter** (GMD <20 nm) typical of **aircraft emissions**
  - Higher NO_x concentrations
  - Higher SO_2 concentrations

Aircraft operation rules at Zürich airport : What Emissions should we expect ?

(06:00-20:00)



(20:00-23:00)



Most frequent used runways when Kloten is downwind the airport

Aircraft operation rules at Zürich airport : What Emissions should we expect ?

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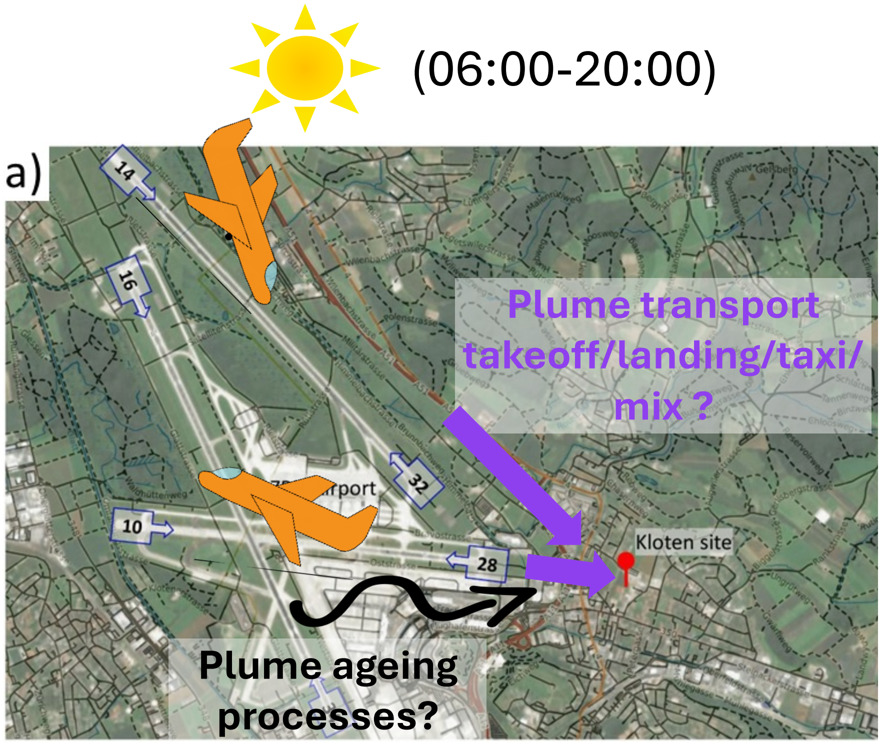

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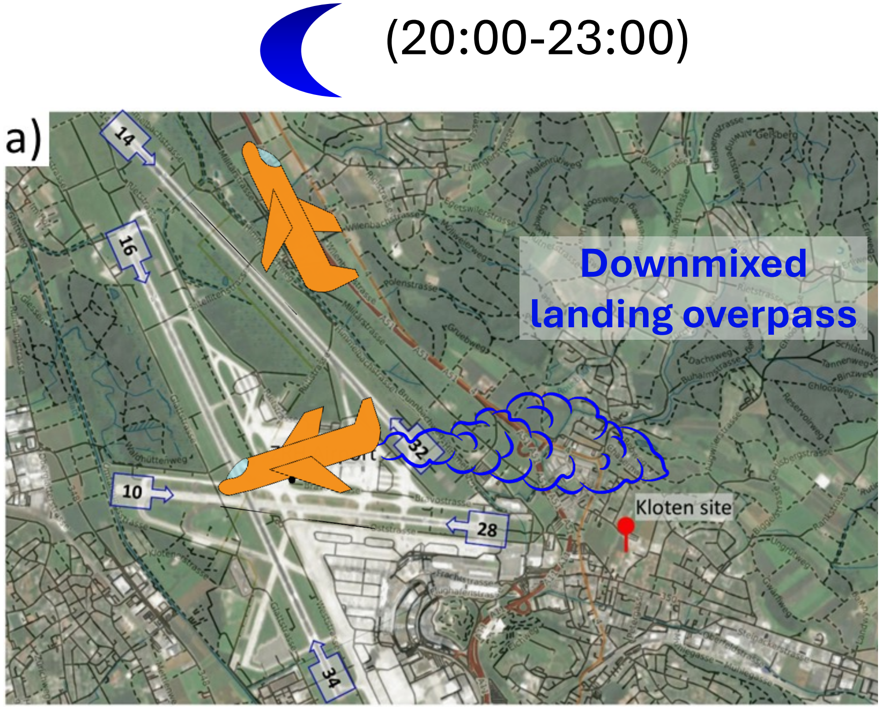
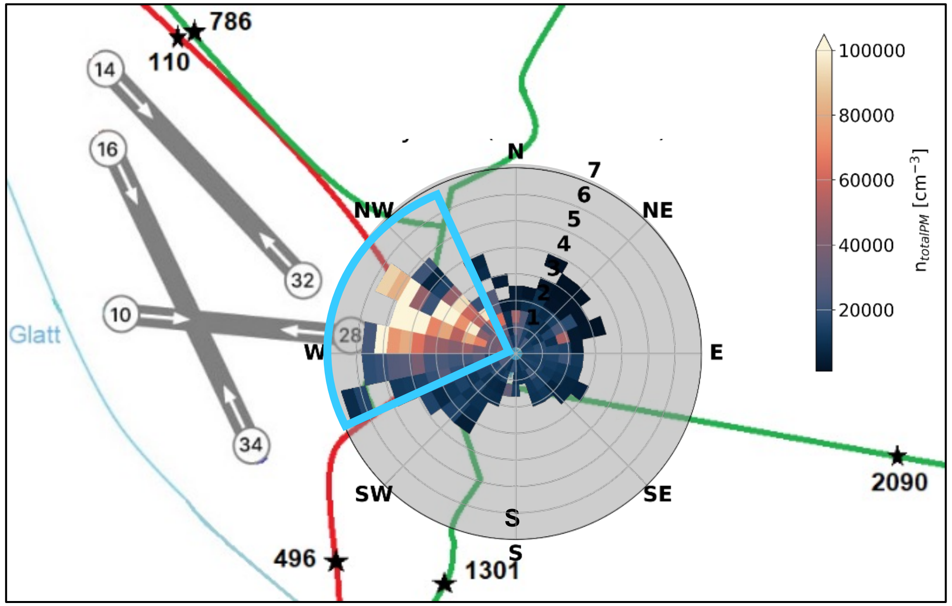
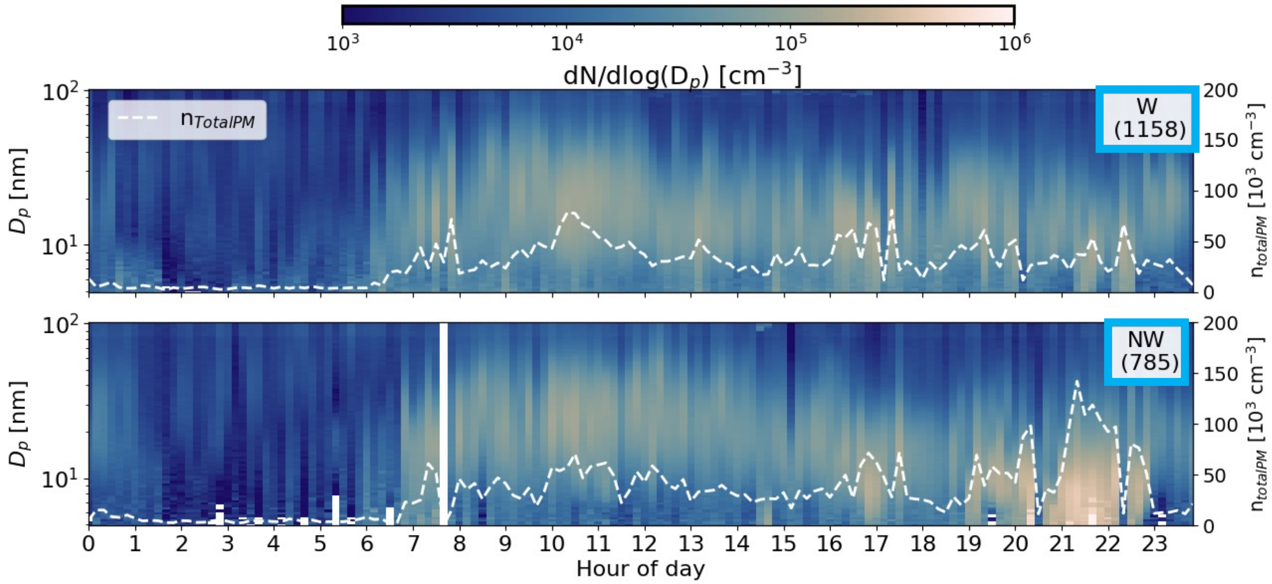


Most frequent used runways when Kloten is downwind the airport

High UFPs concentrations downwind the airport

Daytime UFPs$_{5\text{-}102nm}$ (6:00-23:00)





UFPs size distribution splitted by wind direction

High UFPs concentrations up to 300’000 cm^{-3}

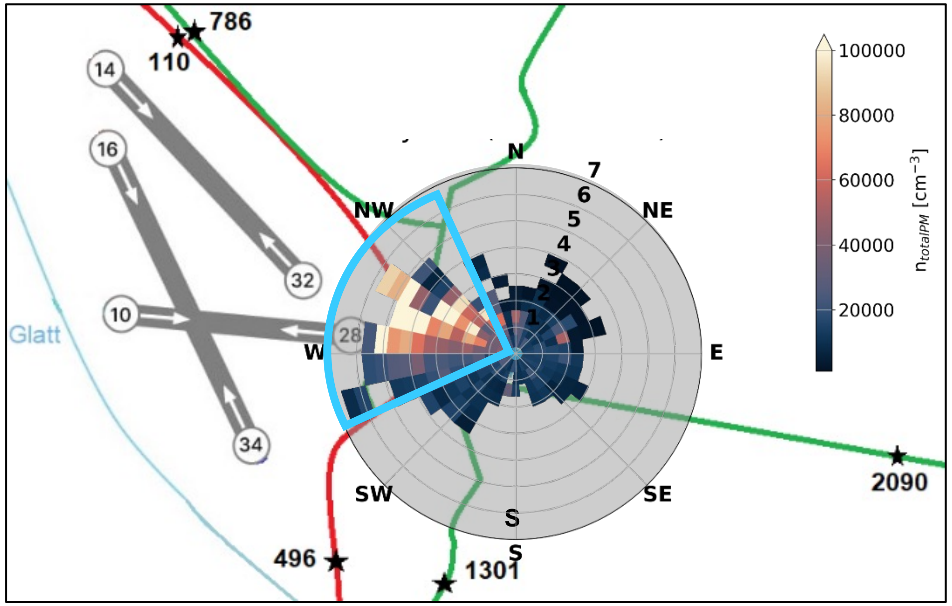
measured :

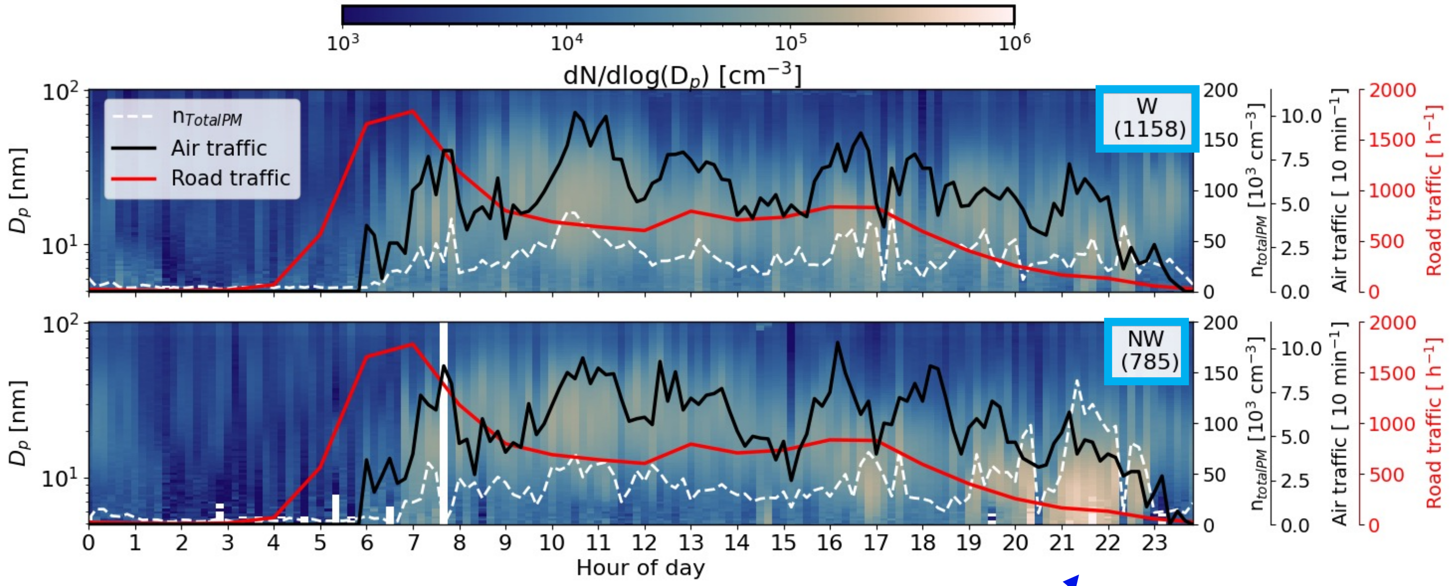
- downwind the airport

Are they coming from the airport activities or the road traffic ?

High UFPs concentrations downwind the airport

Daytime UFPs$_{5\text{-}102nm}$ (6:00-23:00)





UFPs size distribution splitted by wind direction

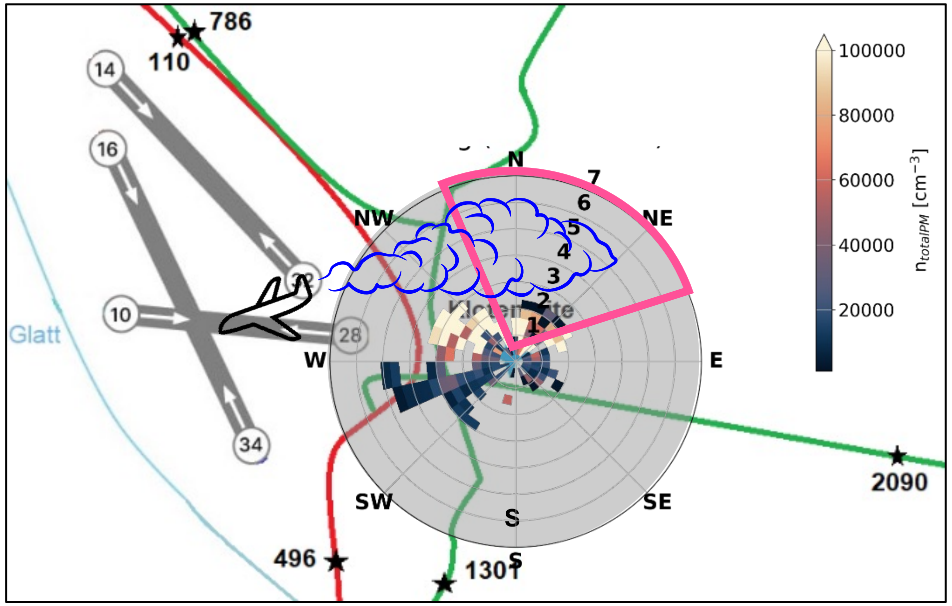
High UFPs concentrations up to 300’000 cm^{-3} measured :

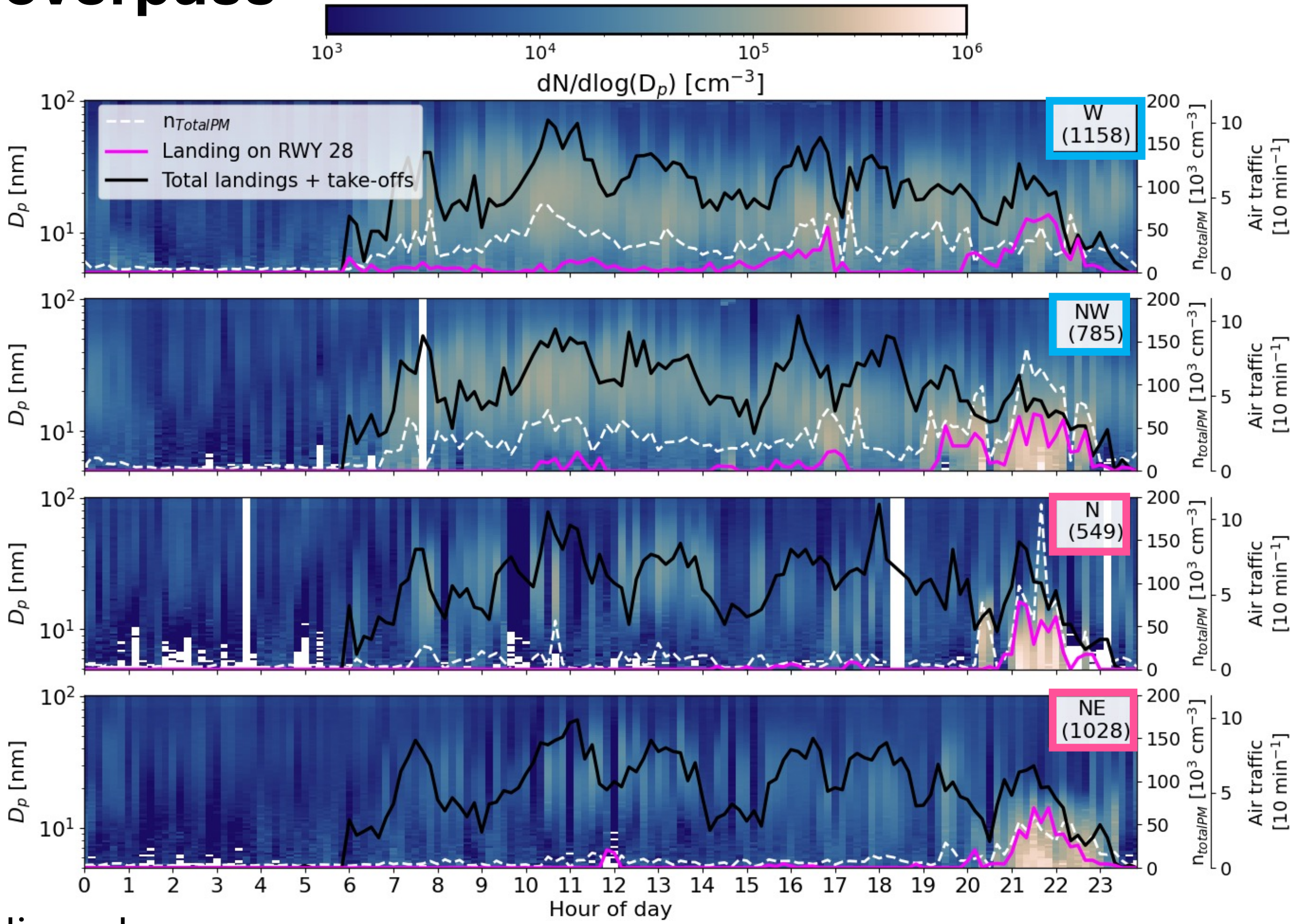
- downwind the airport and linked to total air traffic diurnal pattern

Why this evening increase ?

High UFPs concentrations downwind the airport and from landing overpass

Evening UFPs$_{5\text{-}102nm}$ (21:00-23:00)





UFPs size distribution splitted by wind direction

High UFPs concentrations up to 300'000 cm^{-3} measured :

- downwind the airport and linked to total air traffic diurnal pattern
- From NW to NE and linked to evening landing overpasses

High UFPs concentrations downwind the airport and from landing overpass

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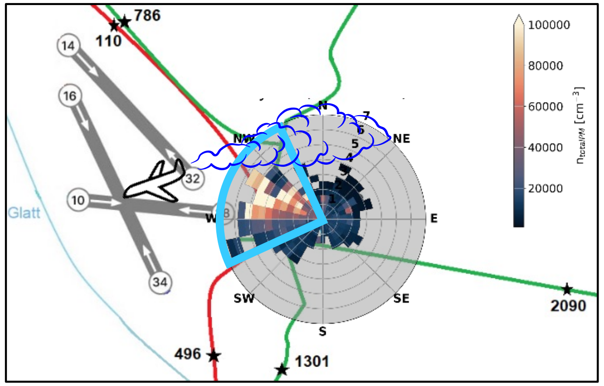
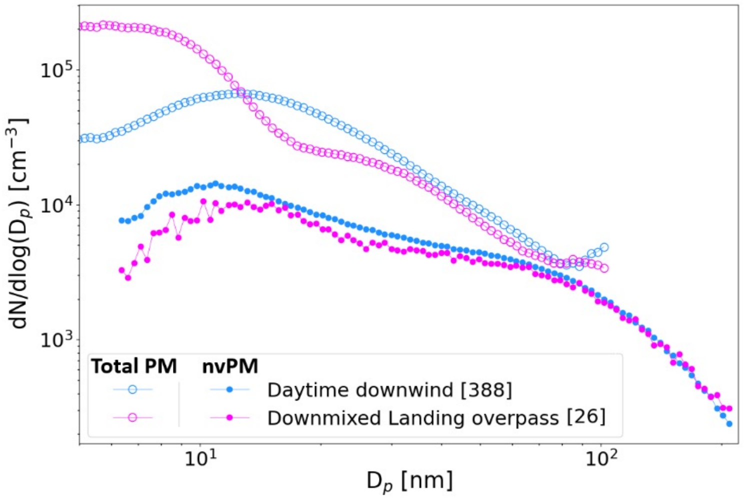
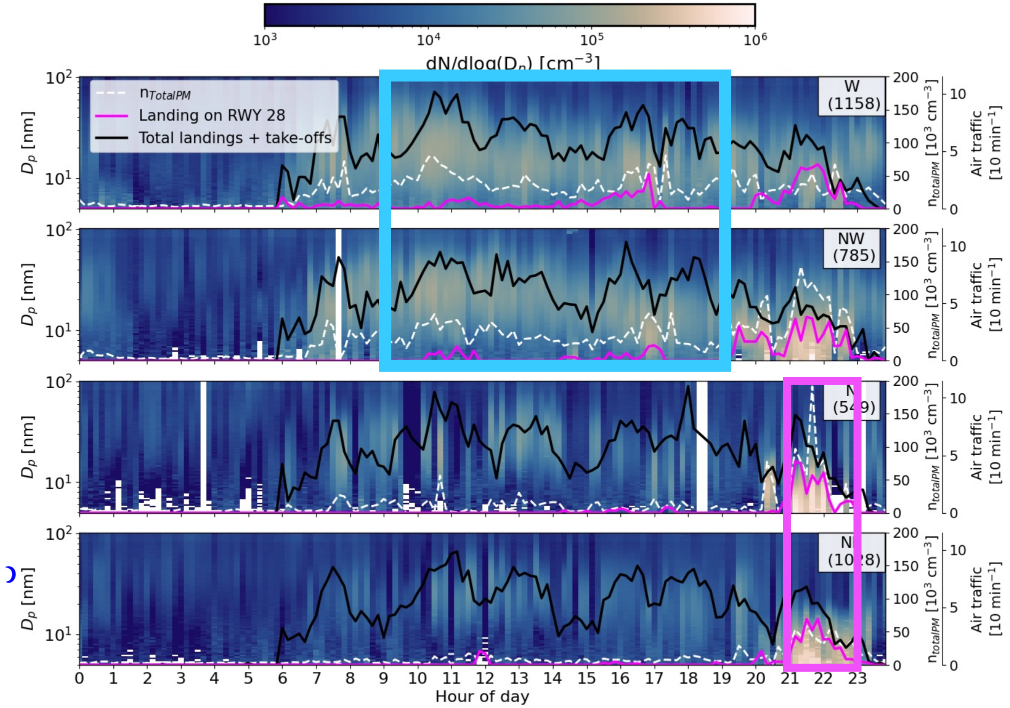






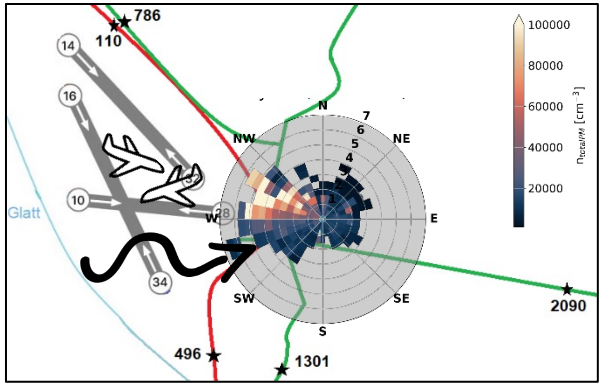
High UFPs concentrations up to 300'000 cm^{-3} measured :

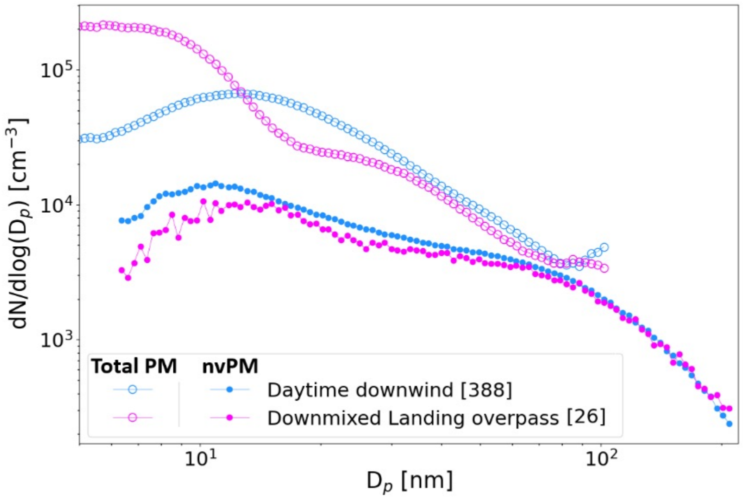
UFPs size distribution splitted by wind direction

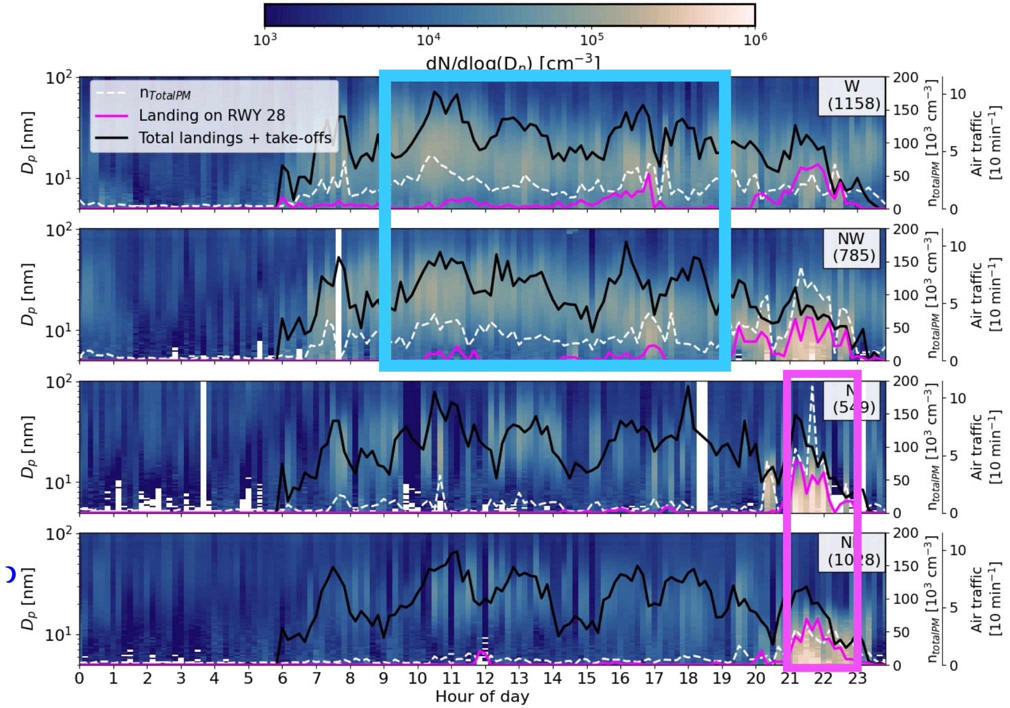
- downwind the airport and linked to total air traffic diurnal pattern → Averaged GMD ~12 nm
- From NW to NE and linked to evening landing overpasses → UFPs have a 2.5-3 times higher fraction of vPM , and smaller averaged GMD ~ 7 nm

High UFPs concentrations downwind the airport and from landing overpass

Daytime UFPs$_{5\text{-}102nm}$ (6:00-23:00)







Plume ageing processes?

High UFPs concentrations up to 300’000 cm^{-3} measured :

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Can ageing processes influence the properties of the downwind emissions ?

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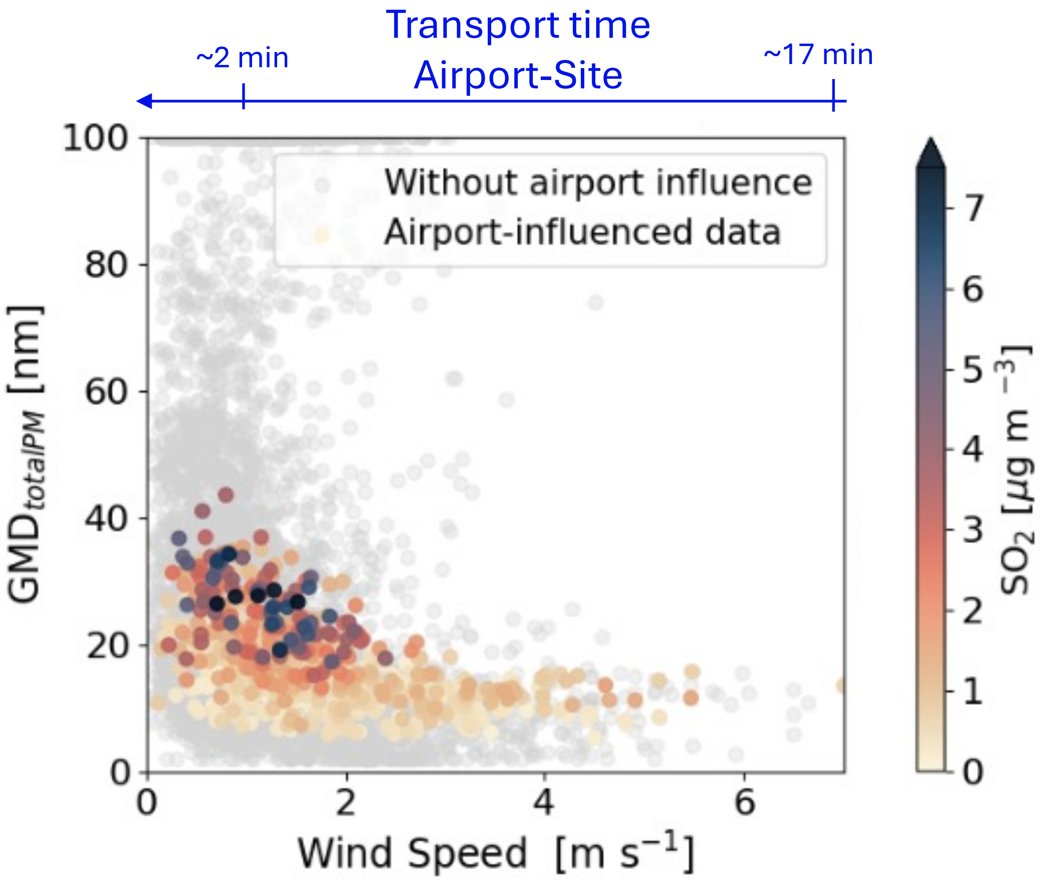

UFPs Geometric Mean Diameter vs. Sulfur dioxide and wind speed, landing overpass excluded

- SO_2 = Crude indicator of the amount of **condensable vapors emitted by aircraft** (sulfuric acid, lub oil…)
- low wind speed = less dilution of exhaust plumes (SO_2 as an indicator) and longer transport time

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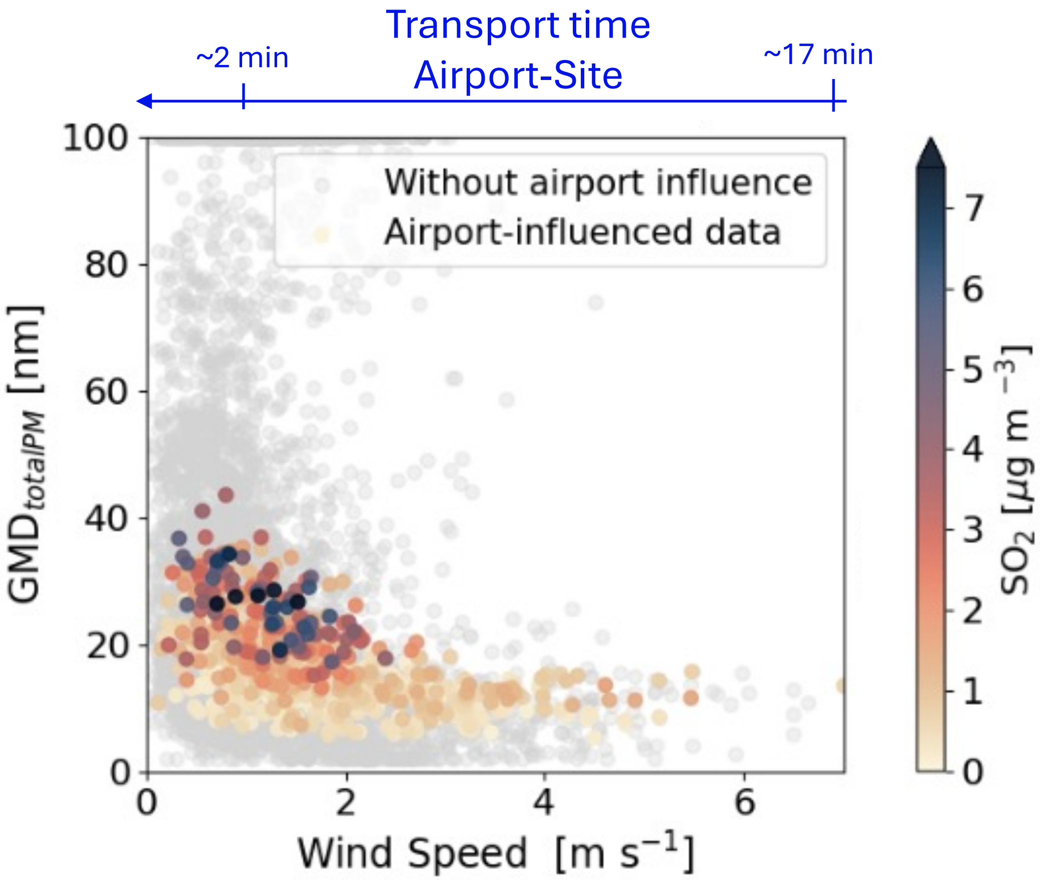

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- SO_2 = Crude indicator of the amount of **consensable vapors emitted by aircraft** (sulfuric acid, lub oil...)
- low wind speed = less dilution of exhaust plumes (SO_2 as an indicator) and longer transport time
- GMD and SO_2 are positively related, and both are inversely related to wind speed.

➔ **More coagulation and condensation growth driven by sulfuric acid and/or oil vapors**

➔ **larger GMD**

What is the overall impact of airport emissions on the air quality of Kloten site?

- UFP measurements should be included into existing air quality monitoring
- Good practice statements to outline the emission sources of UFPs that require priority for further control : **UFPs concentrations** are “high” when **> 20’000 cm^{-3} (1 h mean)**.

WHO global air quality guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Executive summary. Geneva: World Health Organization; 2021. Licence: CC BY-NC-SA 3.0 IGO (accessed 2025-06-16).

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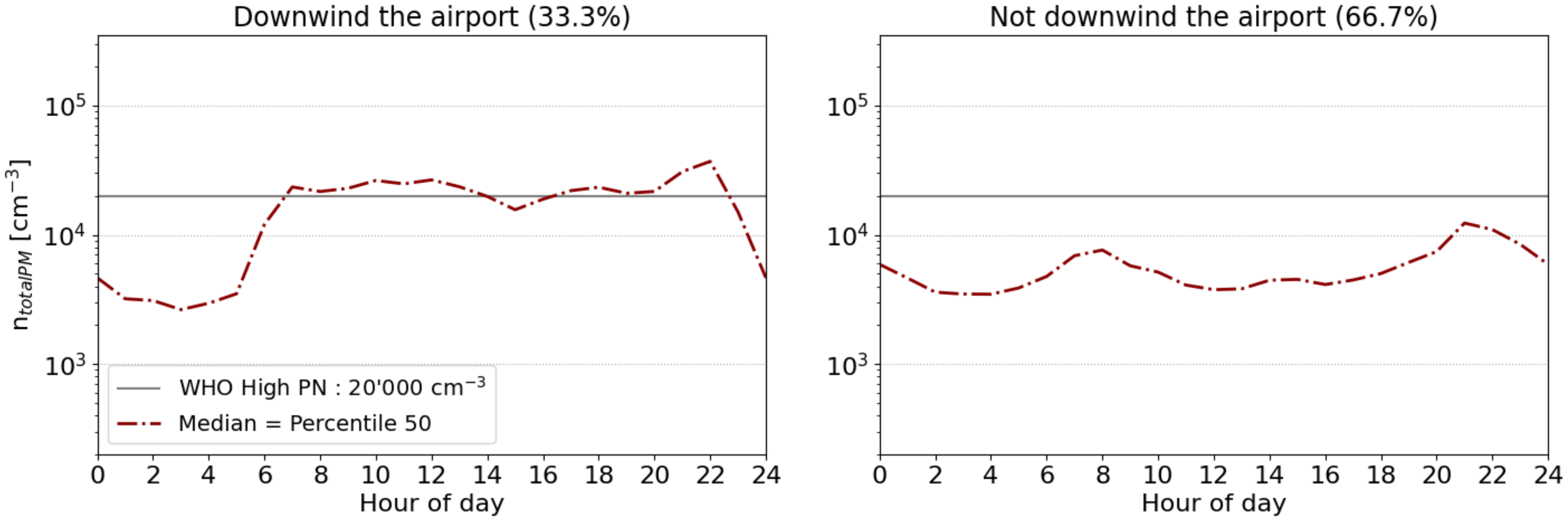

Diurnal cycle of UFPs from AWEL long-term dataset (2021 to 2023) for all WD, and downwind the airport, 1 h mean

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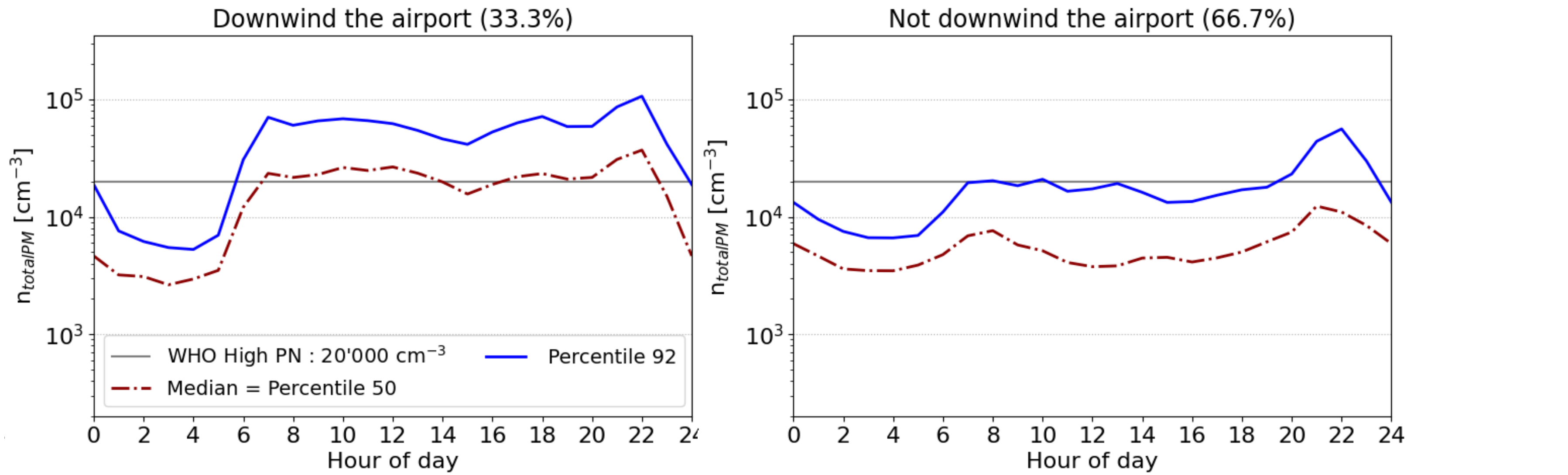

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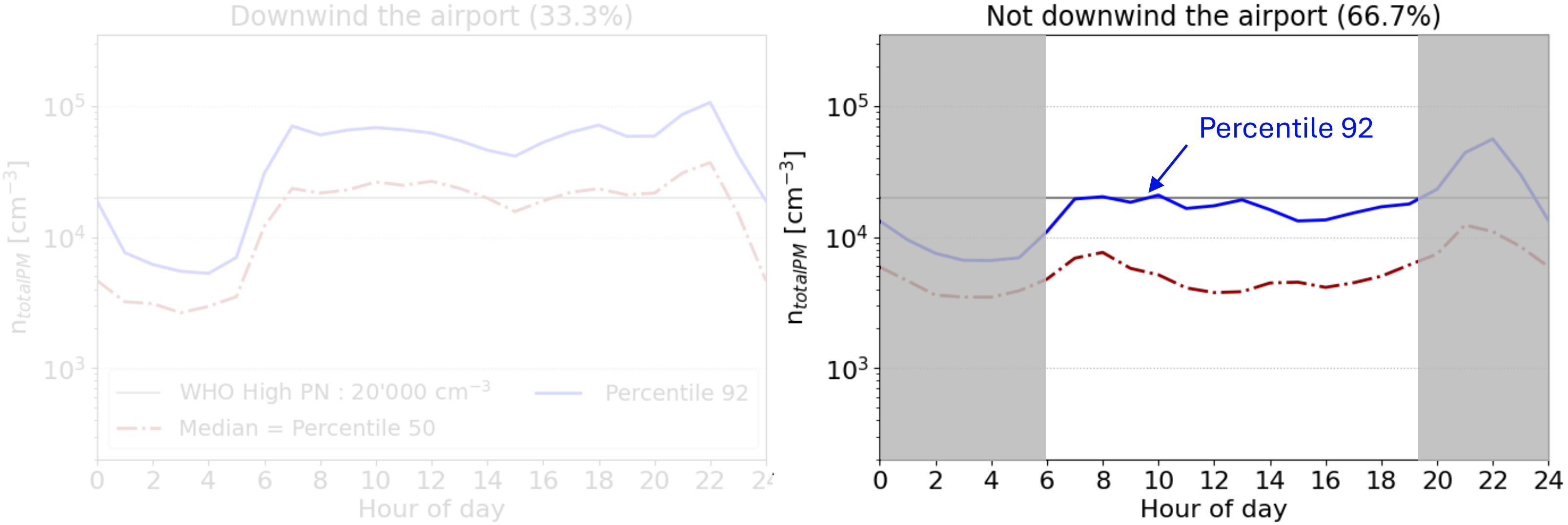

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- When the site is **not downwind** and on daytime, **only 8% of the values exceed WHO** guidelines

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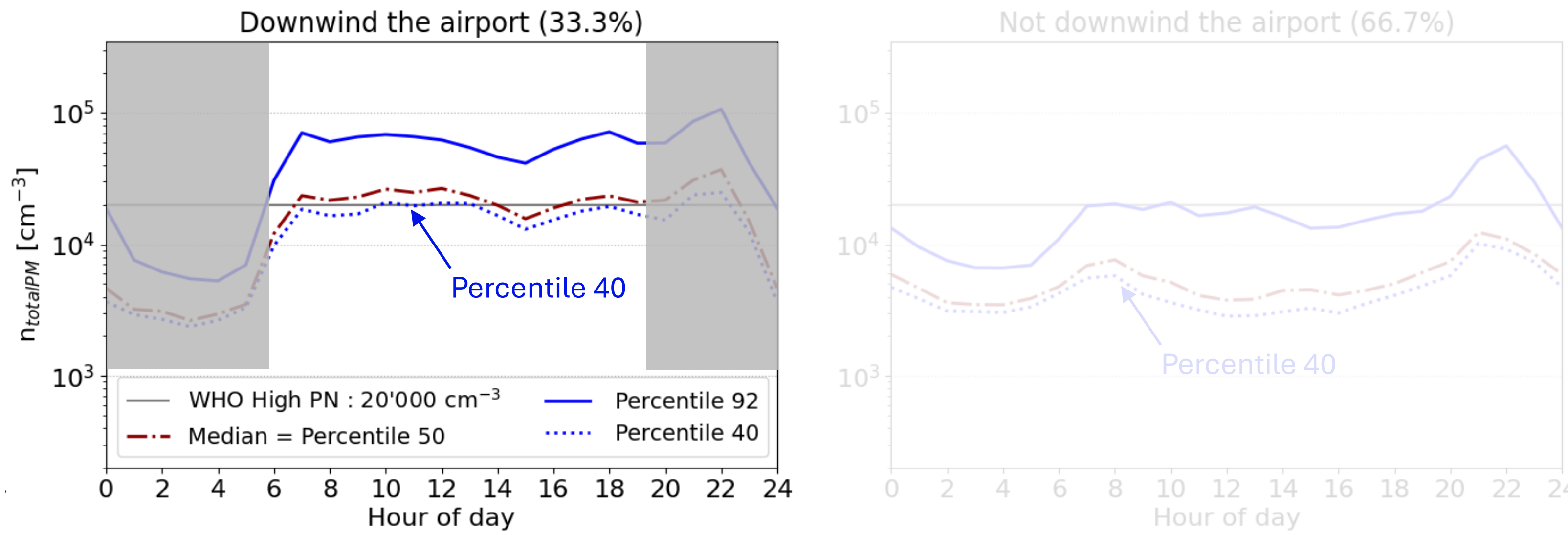

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- **Downwind** the airport and on daytime, **60%** of the values are **above WHO** guidelines

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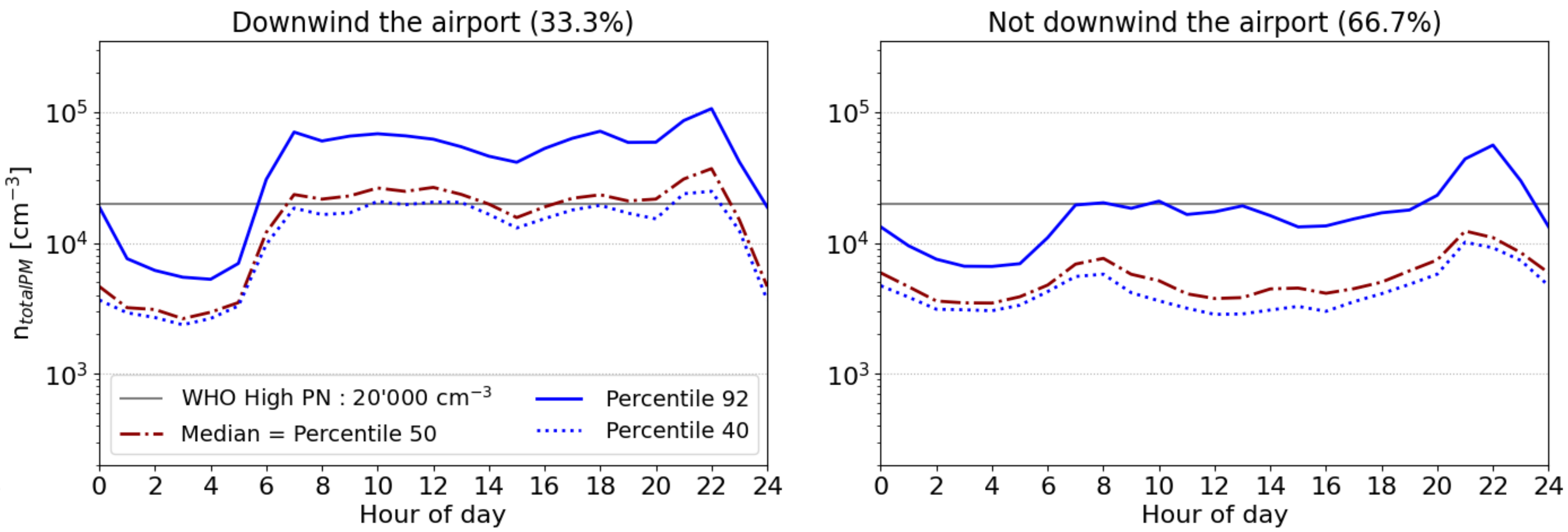

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- **Downwind** the airport and on daytime, **60%** of the values are **above WHO** guidelines
- (not shown) **Outside of the airport** wind sector/activity time, **road traffic is driving the UFPs** concentrations but never exceeding WHO guidelines

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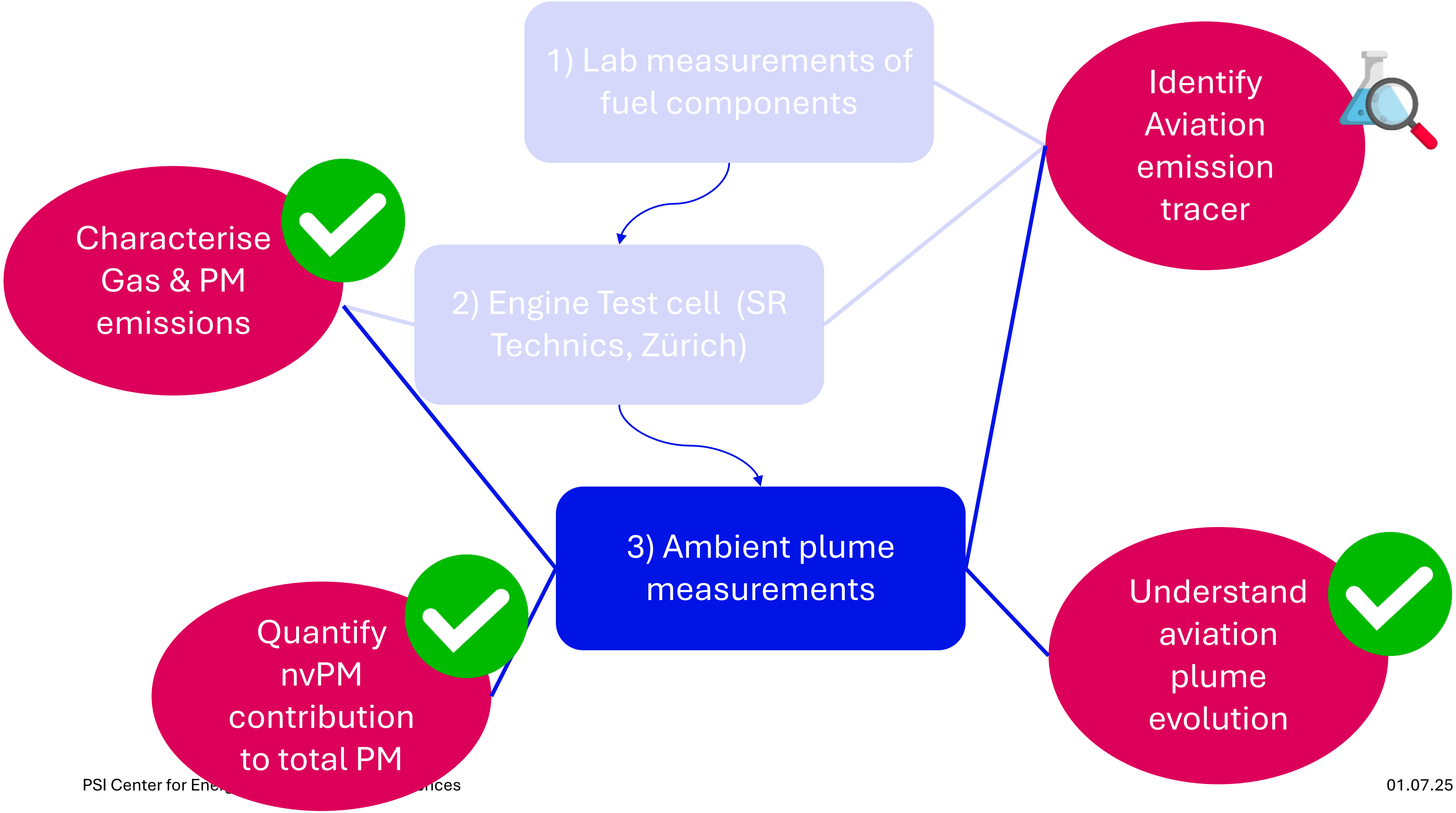

Test cell measurements revealed the presence of lubrication oil in engines exhaust

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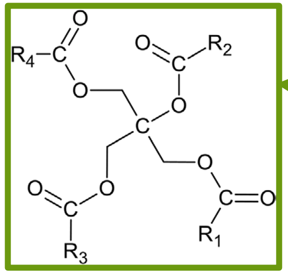
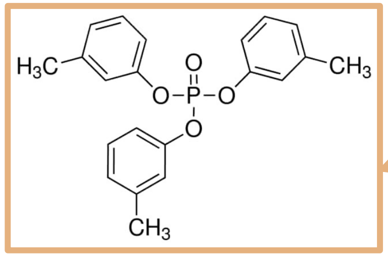


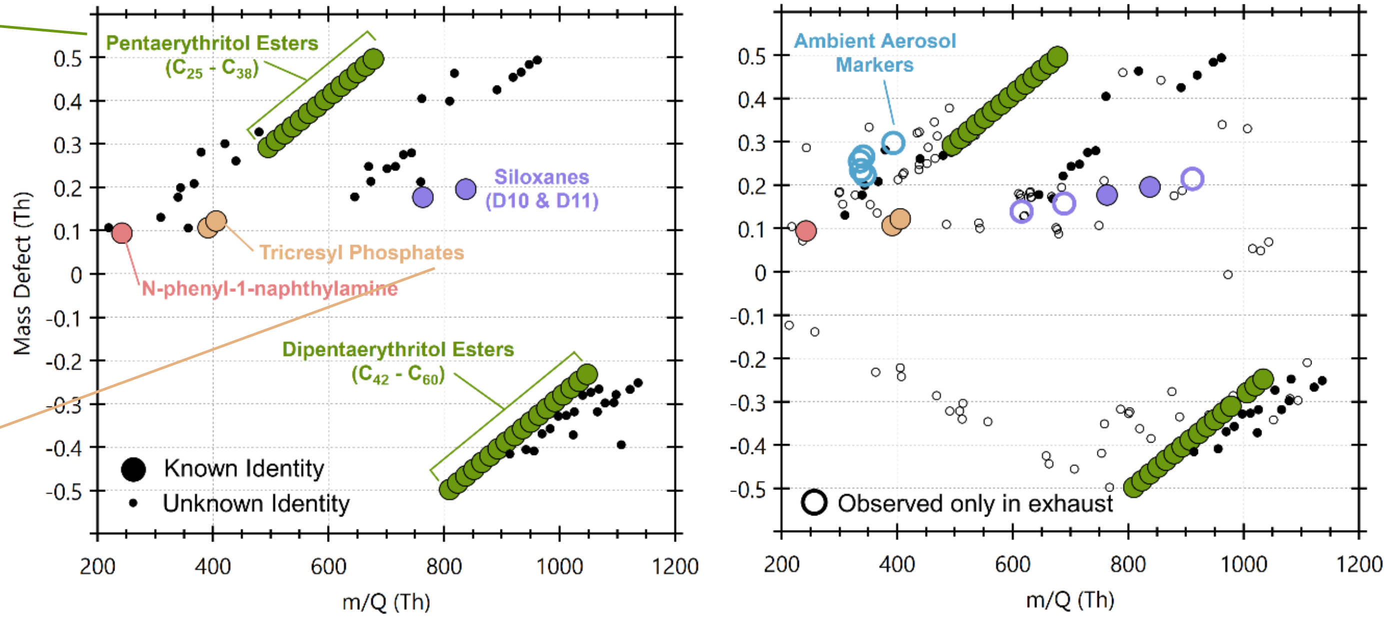
C25 Pentaeythritol ester : C25



Tricresyl Phosphates : TCP

Mobil Jet oil II chemical composition

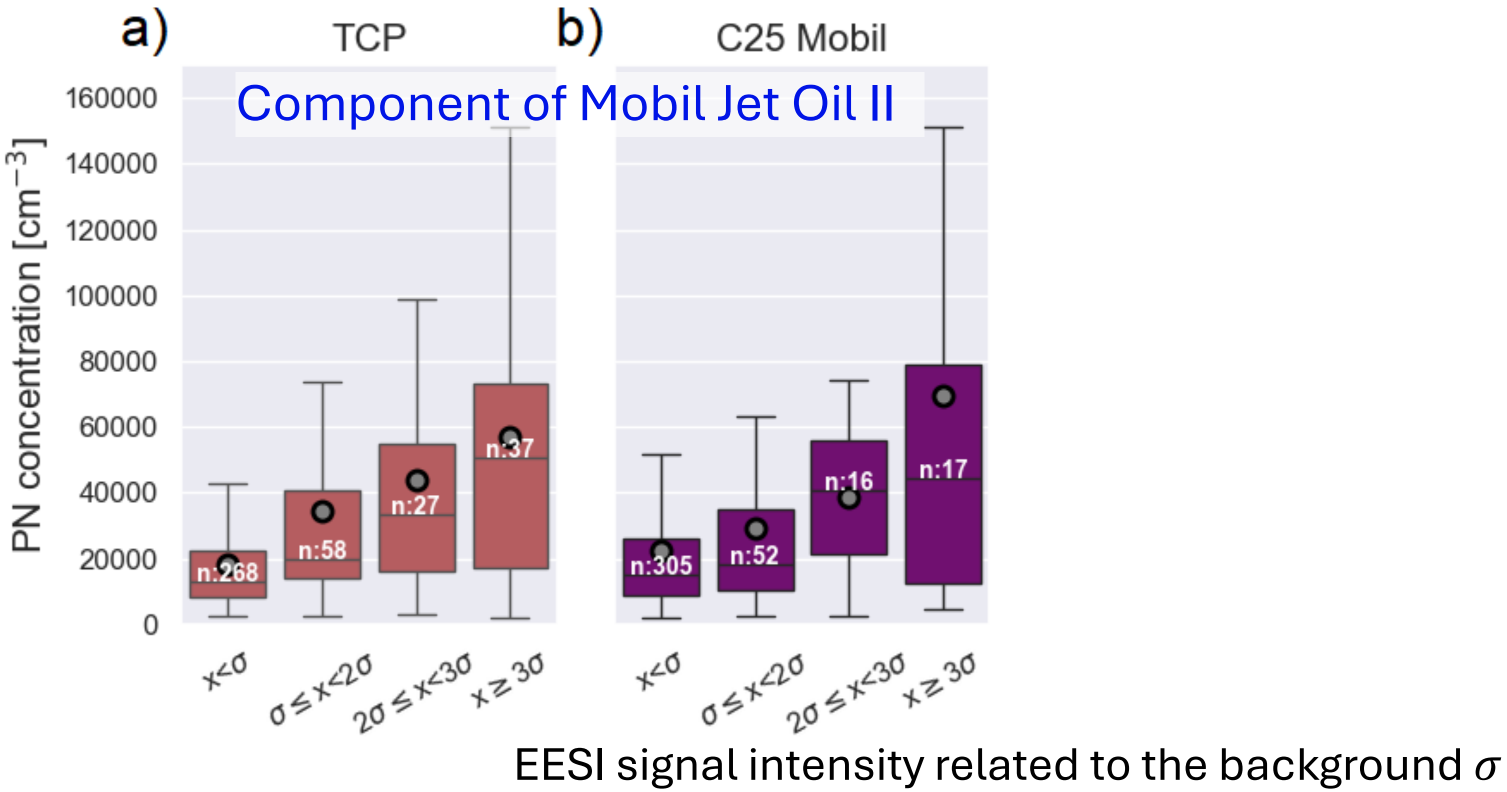
Engine exhaust chemical composition



Decker Z. C. J. et al., *Environ. Sc & Tech. Air*, 2024

Can we retrieve the lubrication oil (lube-oil) presence in the UFPs sampled on the field ?

First on-line molecular-level measurement of lube-oil compounds from Airport emissions



PN concentration vs. EESI signal intensity x related to the background signal σ during daytime, low wind speed excluded

- Increase of the PN concentration with the Lube-oil marker signals intensities

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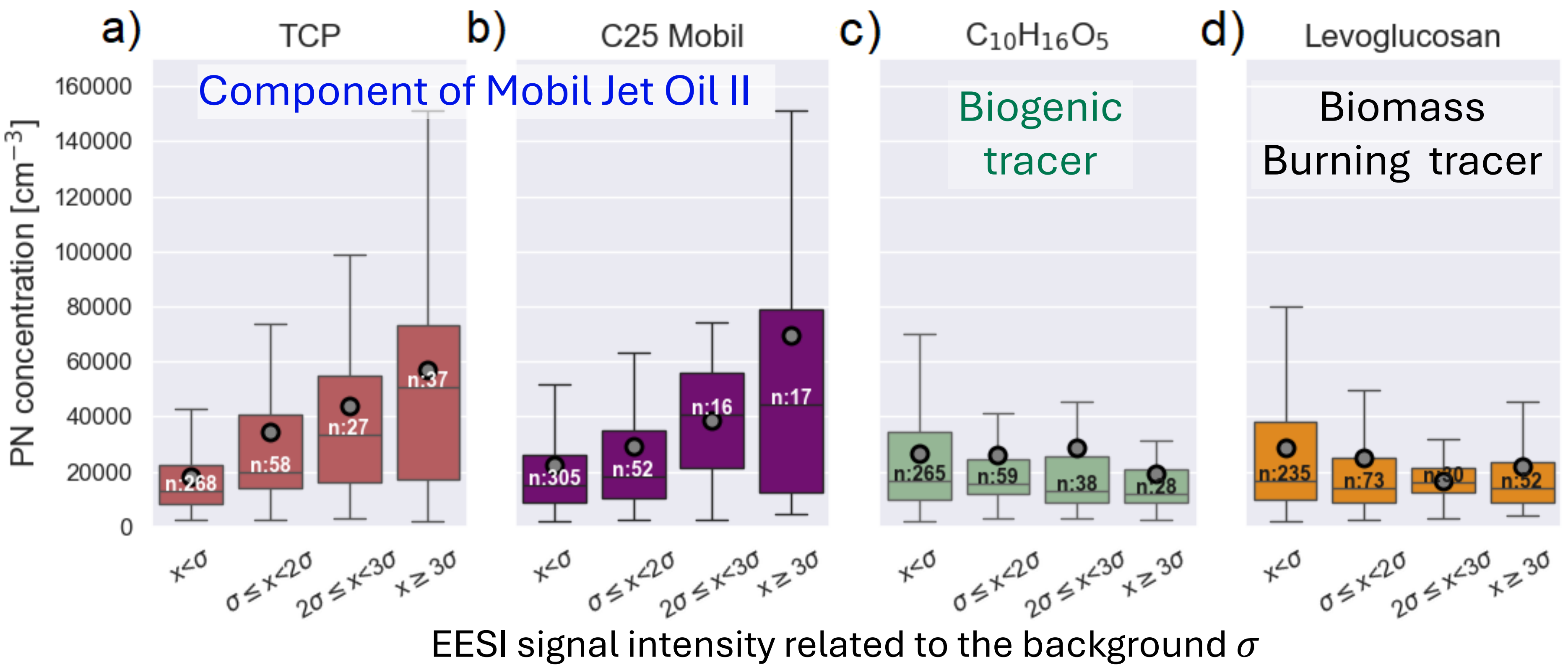
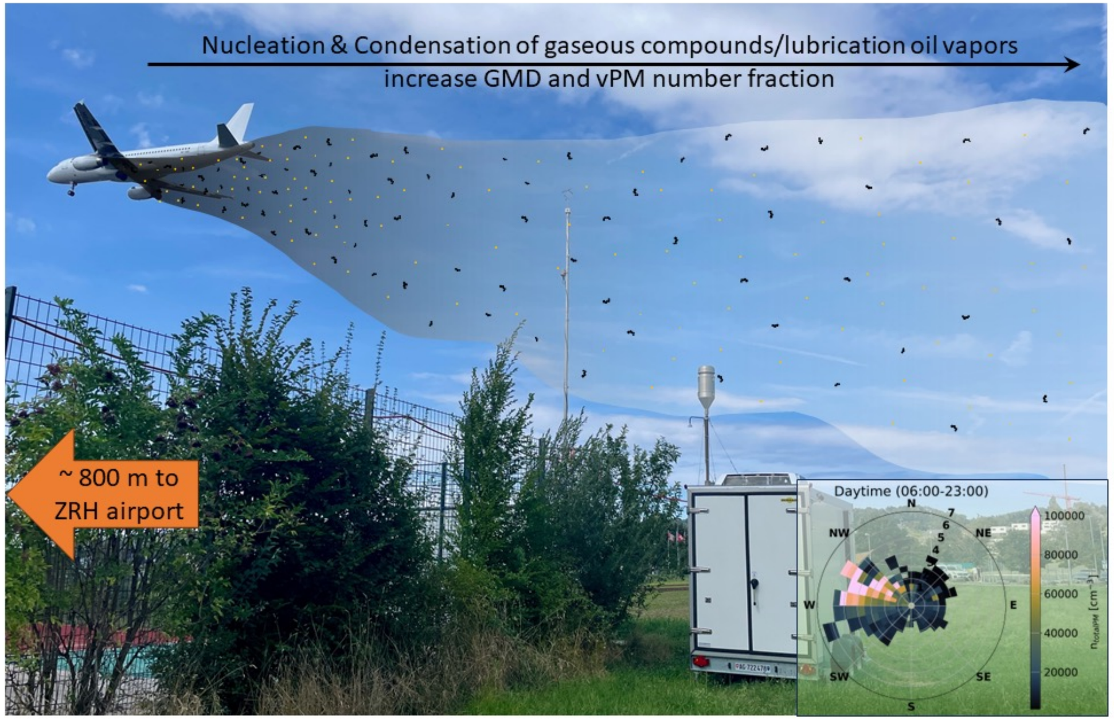


PN concentration vs. EESI signal intensity x related to the background signal σ during daytime, low wind speed excluded

- Increase of the PN concentration with the Lube-oil marker signals intensities
  → **Lube-oil markers** can be used as a **predictor for high UFPs concentrations from aviation**

Conclusions

- **High UFPs concentrations up to 300’000 cm^{-3}** were measured at ~800m **downwind** Zürich airport
- Downwind the airport, UFPs concentrations are **above the WHO threshold** for «high PNC» ~ **60% of the time**



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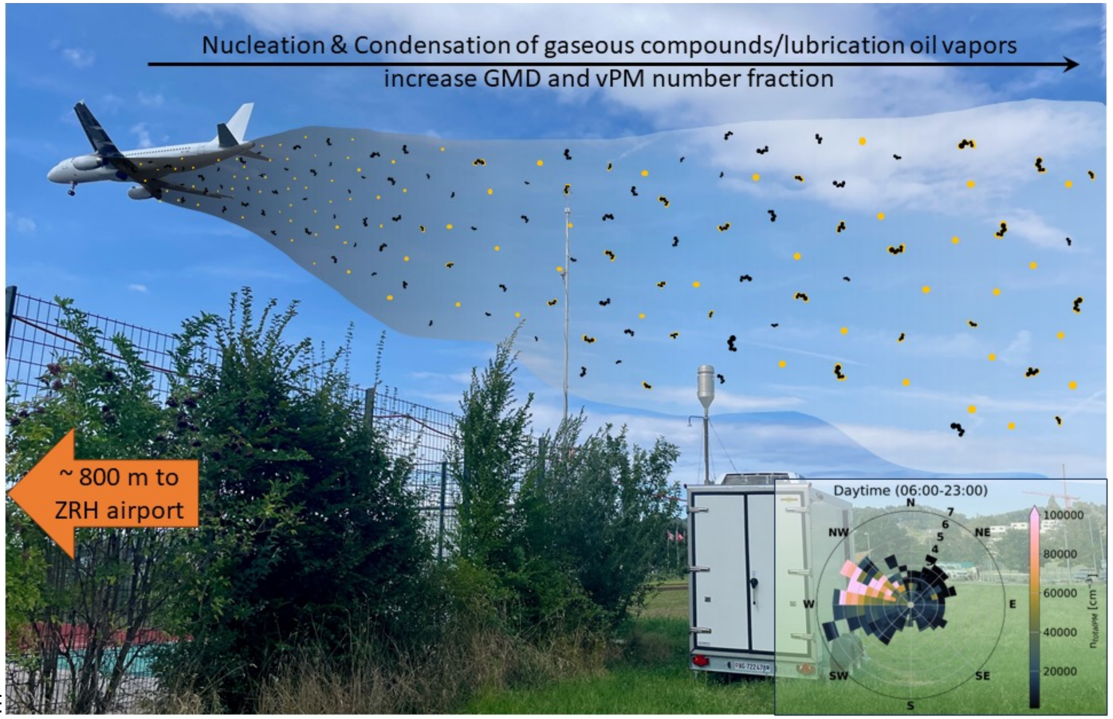

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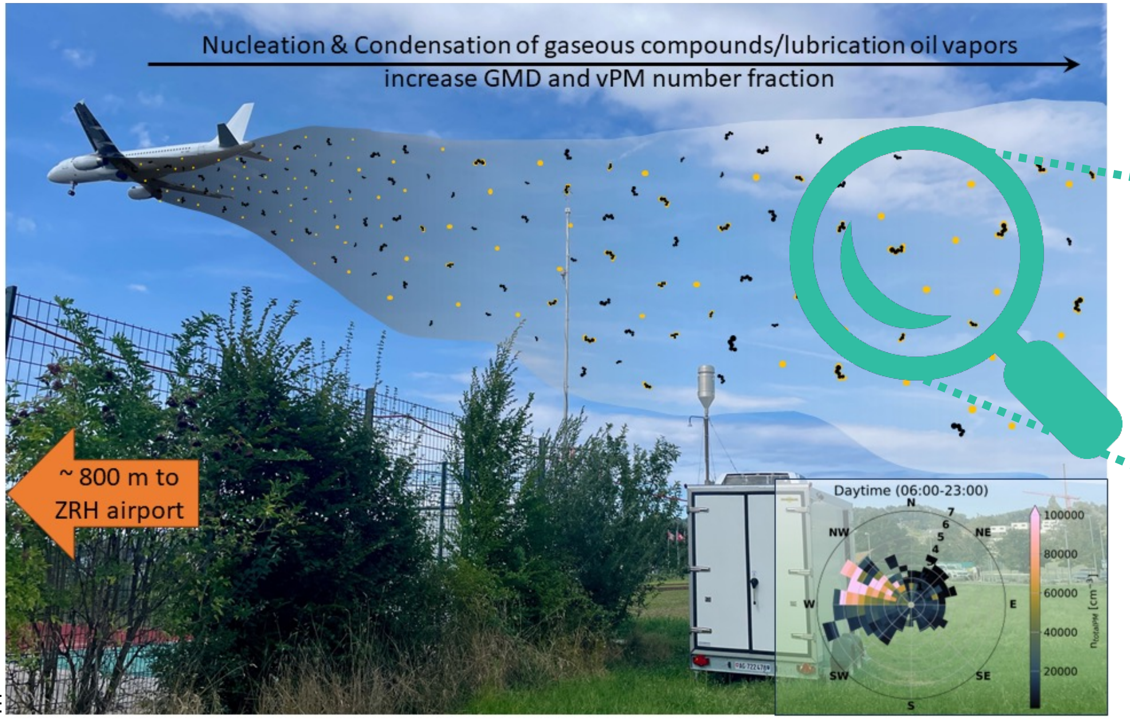
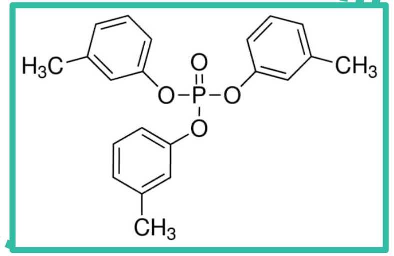
- **Online detection of lube-oil** compounds is a good **predictor for** high UFPs concentrations from **aviation emissions**





A frequent lube-oil compound : Tricresyl Phosphate

PSI Center for Energy and Environmental Sciences

A warm thank to all the collaborators

B. T. Brem, Z. C. J. Decker, J. G. Slowik, P. Alpert, M. Ammann, A. S. H. Prevot, M. Bauer , S. Mishra, M. Götsch, J. Sintermann and M. Gysel-Beer

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Stadt Kloten
WELTOFFEN UND BÜRGERNAH

Kanton Zürich
Baudirektion
Amt für Abfall, Wasser, Energie und Luft

SR Technics

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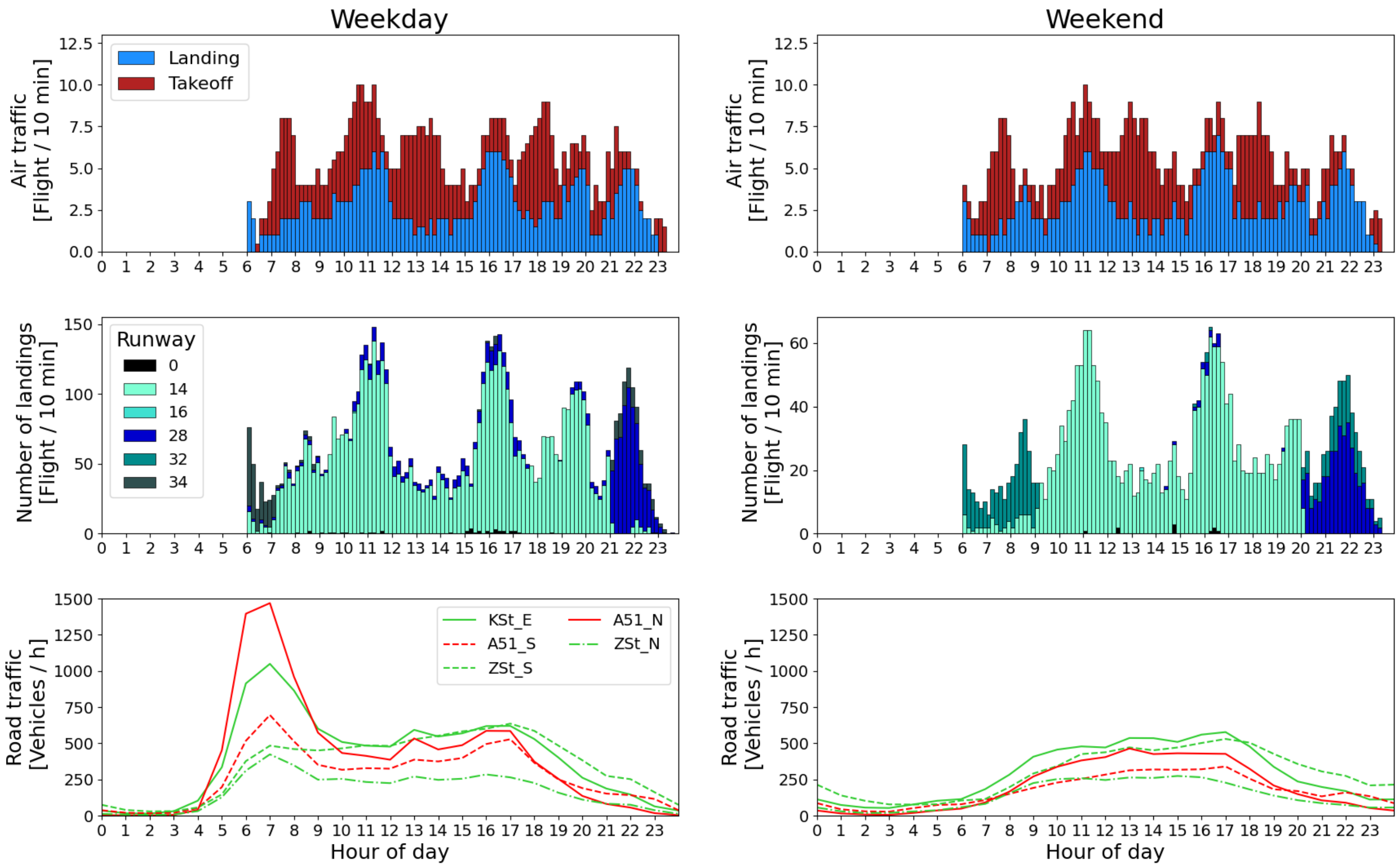
Air quality standards on gases and PM atmospheric levels

Pollutant	Concentration	Averaging period	Legal nature	Permitted exceedences each year
Fine particles ($PM_{2.5}$)	25 µg/m^3	1 year	Target value to be met as of 1.1.2010 Limit value to be met as of 1.1.2015	n/a
Fine particles ($PM_{2.5}$)	20 µg/m^3	1 year	Stage 2 limit value to be met as of 1.1.2020 ***	n/a
Sulphur dioxide (SO_2)	350 µg/m^3	1 hour	Limit value to be met as of 1.1.2005	24
Sulphur dioxide (SO_2)	125 µg/m^3	24 hours	Limit value to be met as of 1.1.2005	3
Nitrogen dioxide (NO_2)	200 µg/m^3	1 hour	Limit value to be met as of 1.1.2010	18
Nitrogen dioxide (NO_2)	40 µg/m^3	1 year	Limit value to be met as of 1.1.2010 *	n/a

Source : European Commission air quality standards : https://environment.ec.europa.eu/topics/air/air-quality/eu-air-quality-standards_en

Diurnal patterns of air and road traffic and statistics of the runways used when the site is downwind the airport



UFPs polarplots on summer 2024

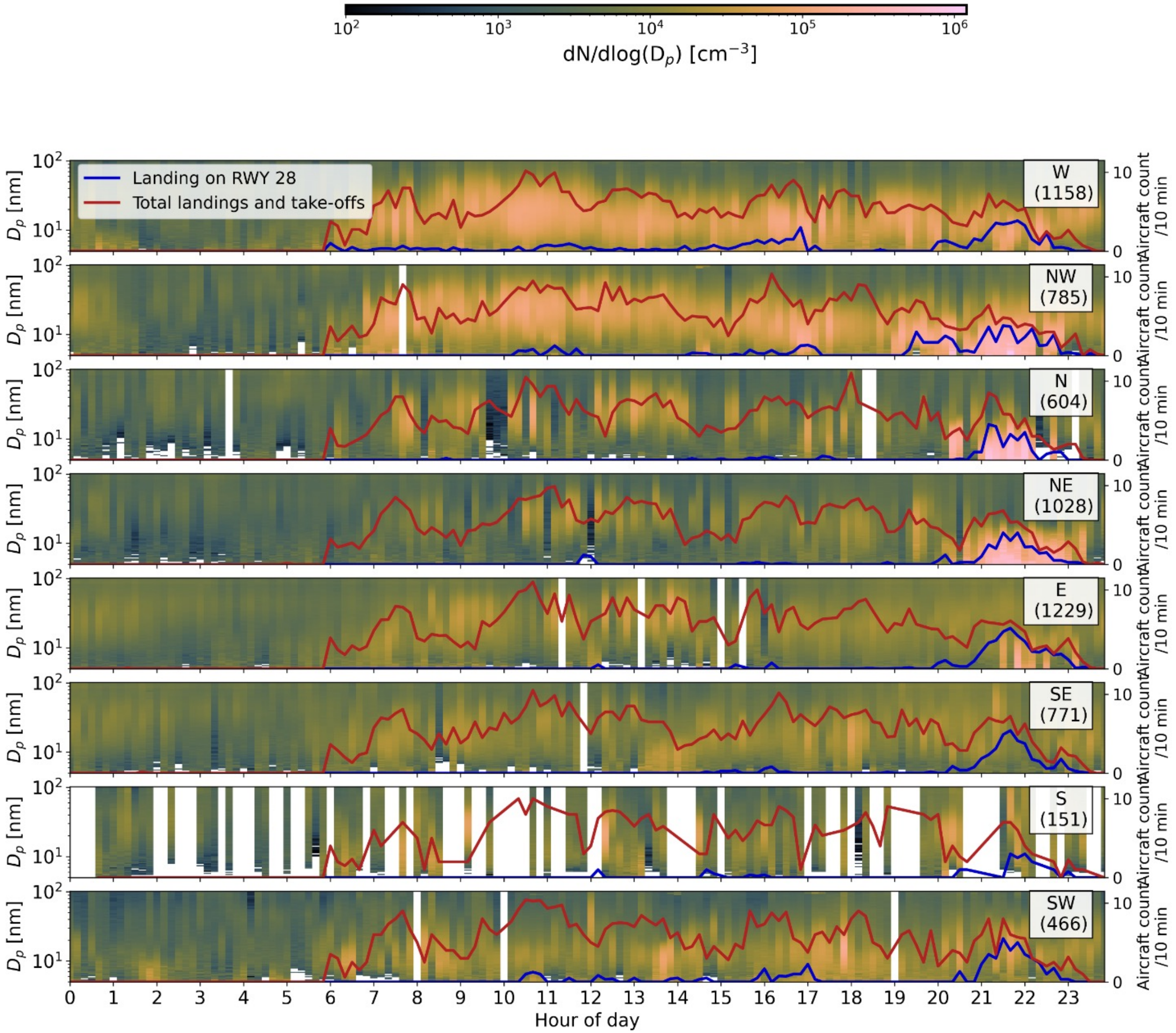
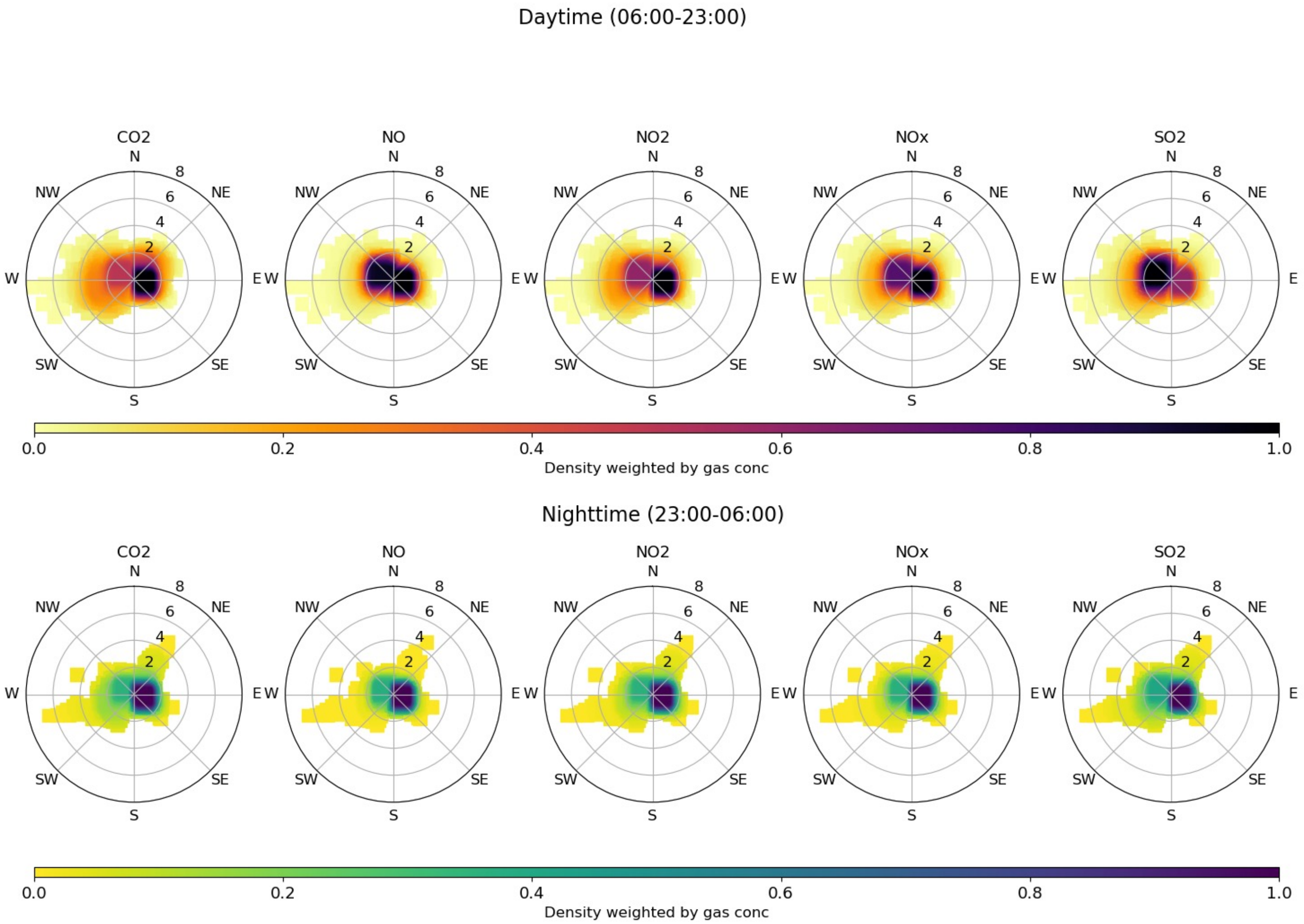
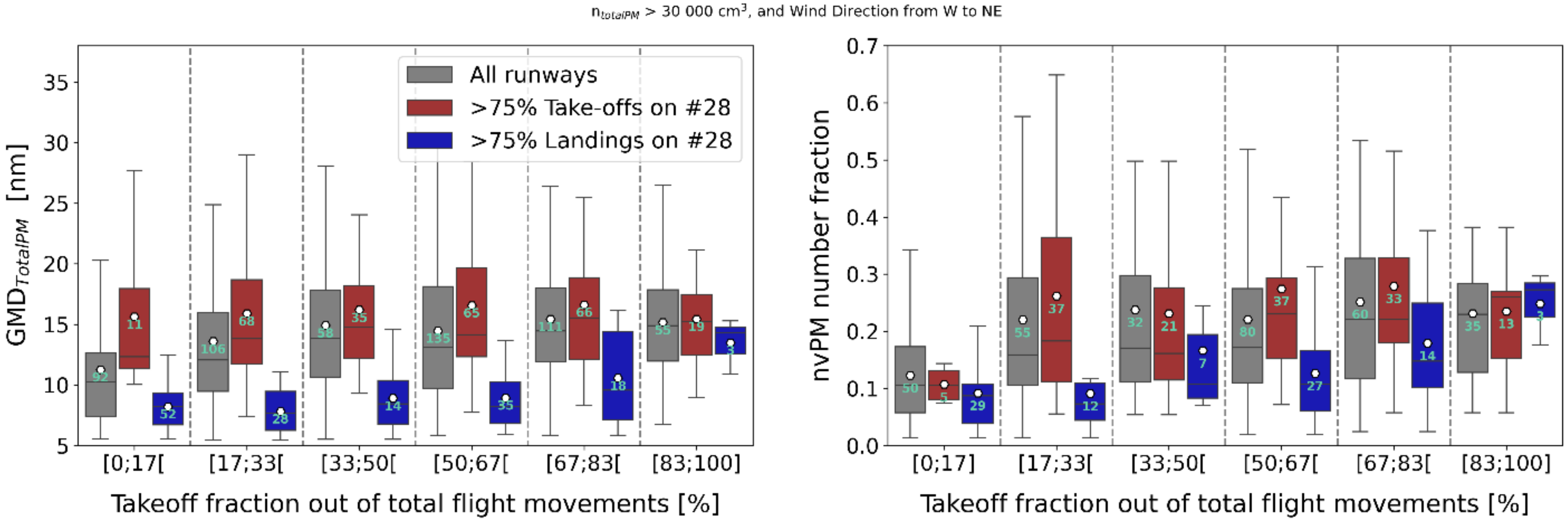


Figure S5: : UFPs size distributions averaged by wind directions from West to South-West. Number in parenthesis show the number of data-points used to plot the panel. Red and blue lines show the sum of take-offs and landings on all runways, and the landings on runway 28 per 10 minutes, respectively. The highest UFPs concentrations during the day were measured downwind the airport (W and NW wind directions)), while during the evening between 19:00 and 23:00 they were coming from the NW to NE, due to the aircrafts landing over the site from NE.

Polarplots of gas measurements



Takeoff-related emissions are likely driving the UFPs properties during daytime

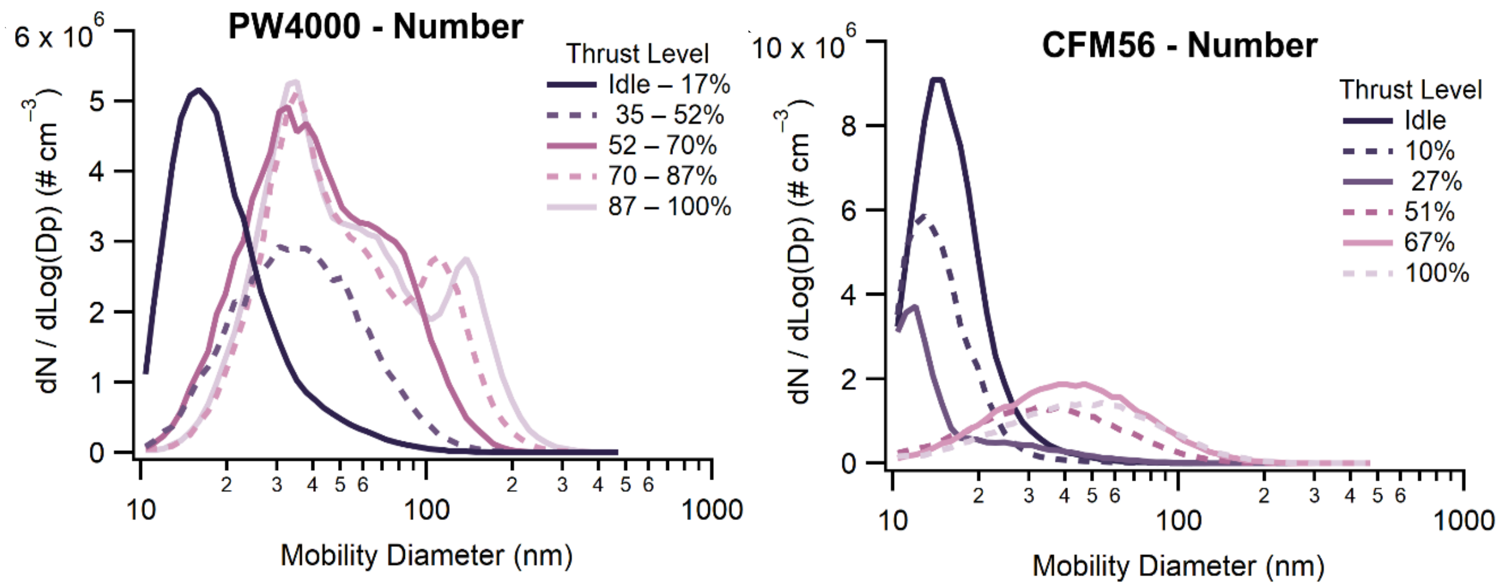


Boxplot of total fitted PM on the left column and nvPN number fraction on the right column as a function of a) and c) the takeoff fraction and b) and d) the landing fraction of aircrafts. The grey boxes represent the data for all the runways, while the colored boxes show only the data for which more than 75 % of the movements occurred on runway 28, for which aircraft flew over the measurement site

Both the GMD and the nvPM number fraction were constant with the takeoff fraction, indicating that takeoff-related emissions are likely driving the UFPs properties during daytime. -the decrease of both GMDs and nvPM number fraction during landing overpass confirms the presence of smaller UFPs and a higher fraction of vPM.

Can we distinguish takeoff vs. Landing emissions with UFPs properties ?

Size distributions for different aircraft engines at different thrusts measured at the SR technics test cell

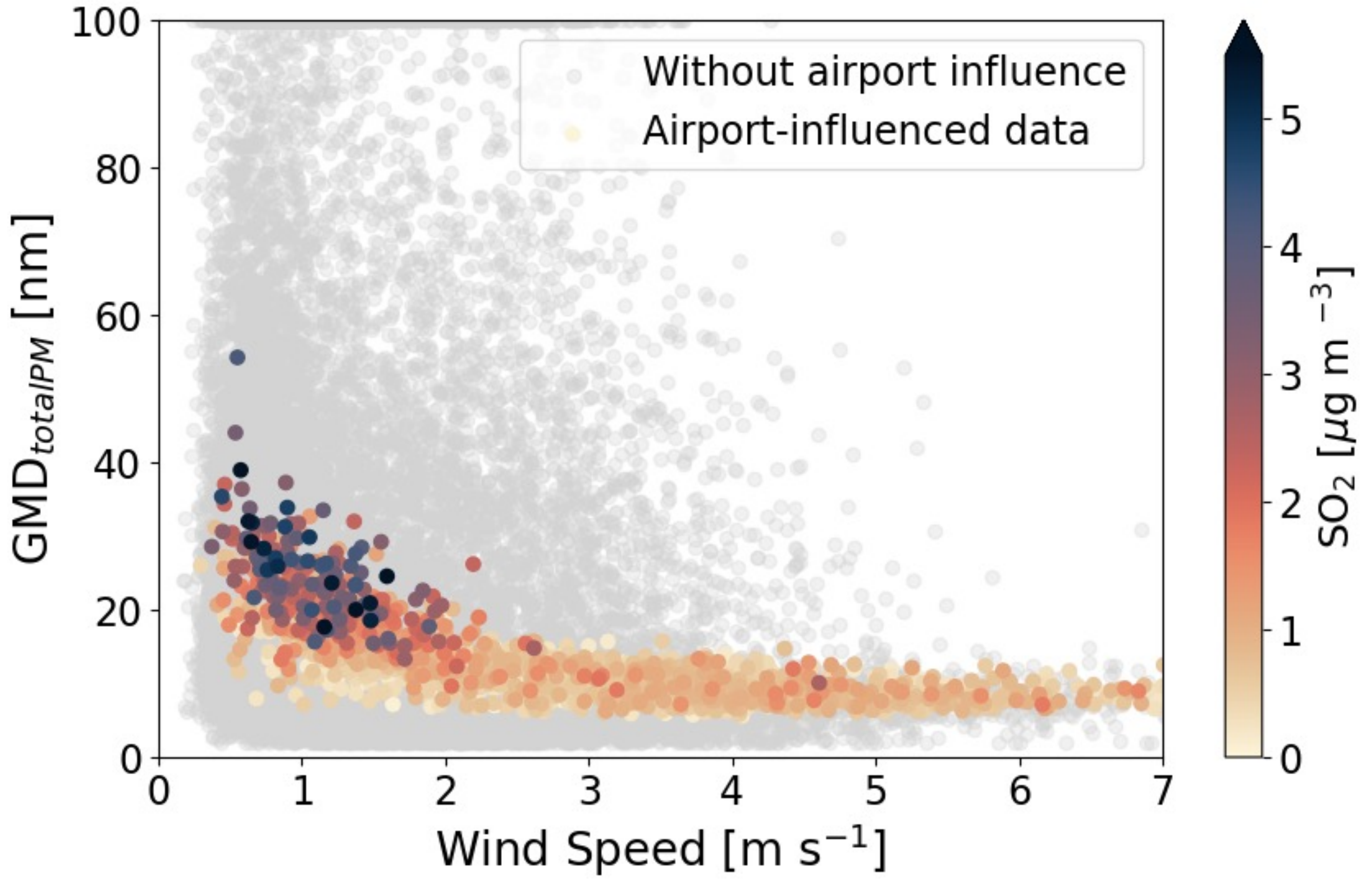


Adapted from Z. C. J. Decker et al., 2024

The Test cell measurements suggest different UFPs sizes as a function of the thrust engine

Growth of UFPs GMD due to condensation processes on long-term data

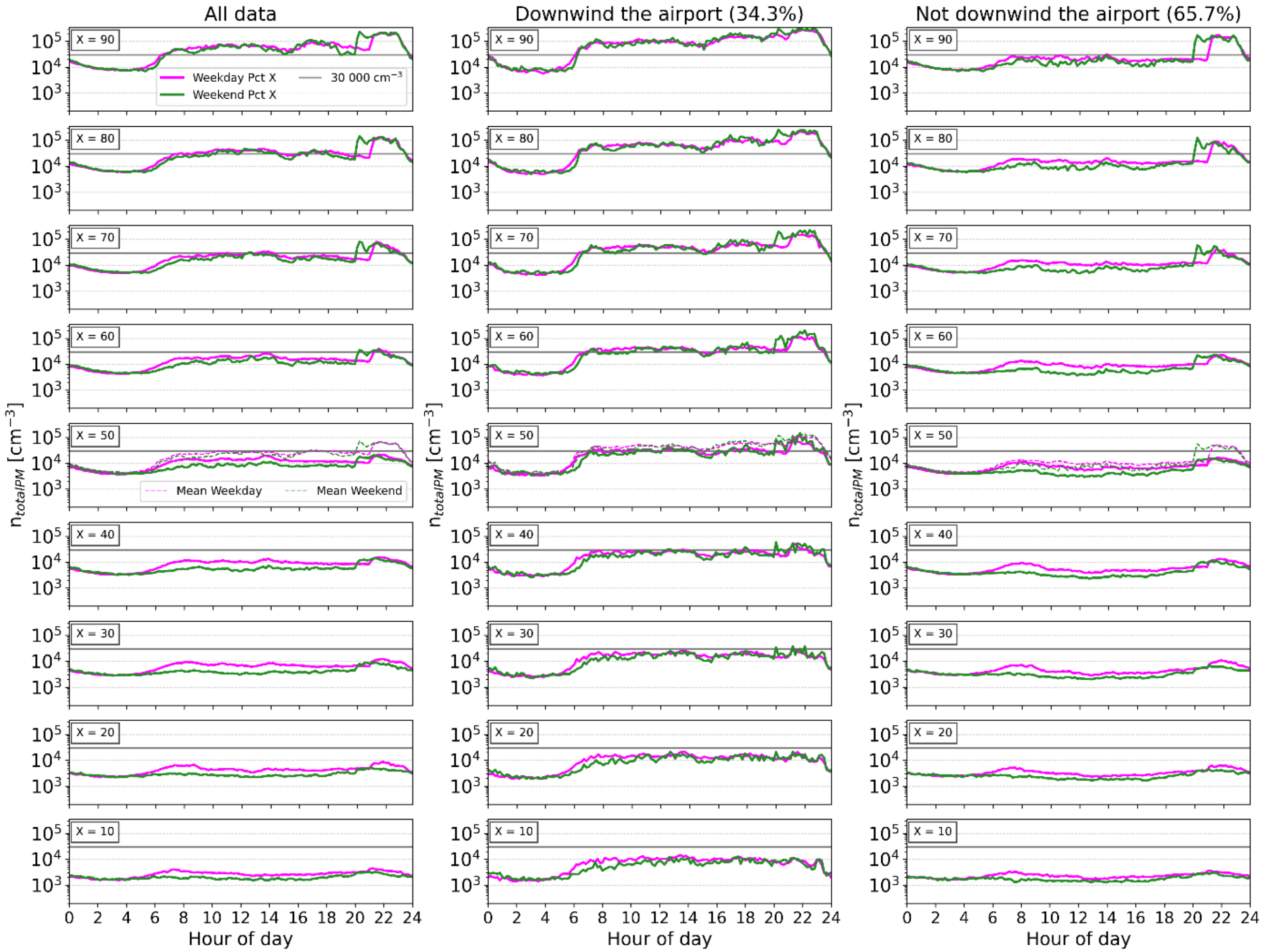
1h-averaged data - Airport-influenced data : when PN > 30K cm-3, downwind the airport and before 19:00



UFPs Geometric Mean Diameter vs. wind speed colored by sulfur dioxide concentration, landing overpass excluded for 2020-2023 dataset

Long-term (2021-2023) data analysis : diurnal cycles of $n_{TotalPM}$ percentiles

Increasing percentile of the $n_{TotalPM}$ distribution

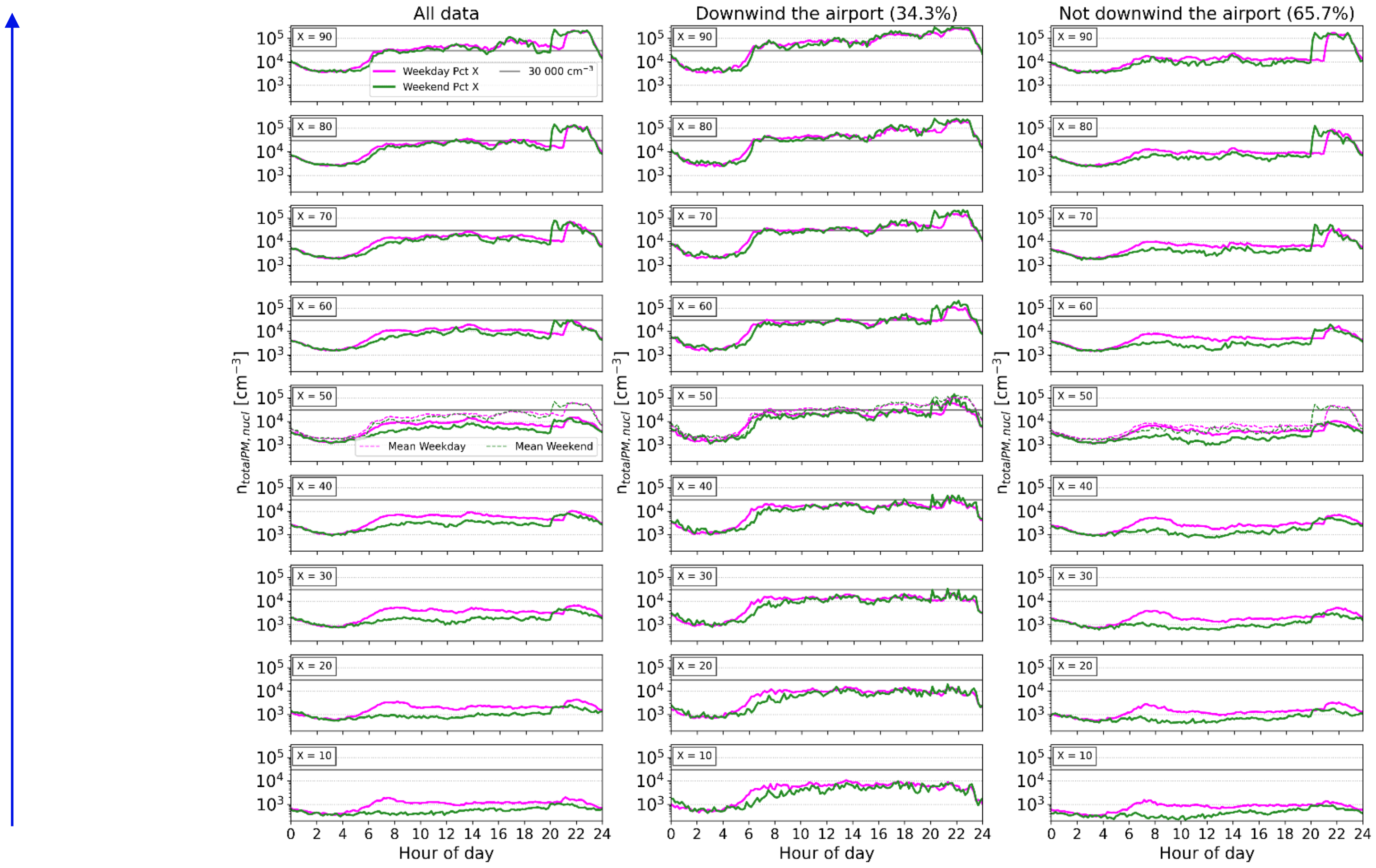


Daily cycle of UFP's number concentration from the long term (2021 to 2023 included) dataset for different decreasing percentiles, from 90th to 10th, for all data, downwind and not downwind data. For each panel, weekdays and weekends diurnal cycles are represented. In addition, on the 50th percentile panel are plotted the mean values in dashed lines, with the same color-code as the plain lines. A horizontal grey line represent on every panels a UFPs number concentration of 30 000 cm^{-3}, which is our criteria for high concentrations influenced by aviation

Long-term (2021-2023) data analysis of the diurnal cycles of $n_{TotalPM,nucl}$ percentiles : clear influence of road traffic

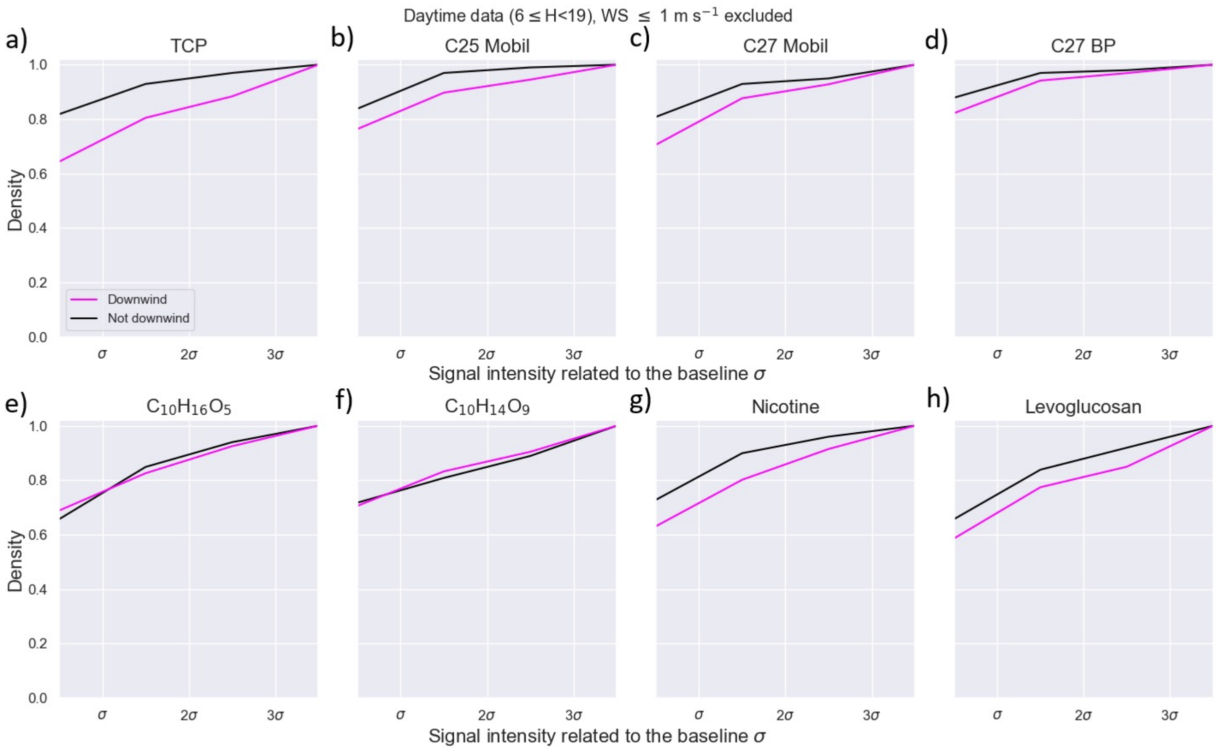
PSI

Increasing percentile of the $n_{TotalPM}$ distribution



Same previous Fig. but for nucleation mode UFPs, ie < 20 nm. A nucleation mode from road traffic is visible for at least 70 % of the data. The overall lower $n_{totalPM,nucl}$ concentrations compared to $n_{totalPM}$ during the day downwind the airport indicates a contribution of airport emissions to the Aitken mode.

Lubrication-oil compounds have a stronger measurement signal downwind the airport



Compound	Formula	m/z	Notation	Comment
Tricresyl Phosphate	C21H21O4PNa+	391.106967	TCP	Present in jet engine oils and exhausts (Decker et al)
C25 PA Ester	C25H44O8Na+	495.292839	C25 Mobil	Present in jet engine oils and exhausts (Decker et al)
C27 TMP Ester	C27H48O8Na+	523.324139	C27 BP	Present in jet engine oils and exhausts (Decker et al)
α-Pinene hydroxy dihydroperoxide	$C_{10}H_{16}O_5Na+$	239.089	$C_{10}H_{16}O_5$	Present in α-pinene derived SOA; Tracer for biogenic PM
Alpha-pinene SOA	$C_{10}H_{14}O_9Na+$	301.053	$C_{10}H_{14}O_9$	Present in α-pinene derived SOA; Tracer for biogenic PM
Nicotine	$C_{10}H_{14}N_2Na+$	163.123	Nicotine	Tracer for anthropogenic emissions
Levoglucosan	$C_6H_{10}O_5Na+$	185.042	Levoglucosan	Tracer for biomass burning

Downwind and not-downwind normalized cumulative distribution function of EESI signal intensity for different compounds. Signal intensities have been grouped to ranges representing around one, two or three times the standard deviation (σ) of the blank measurement of each compound. Only daytime data (from 06:00 to 19:00) with wind speeds above 1 m s^{-1} were considered to exclude stagnant conditions with poorly defined airport plume.