PSI Center for Energy and Environmental Sciences

Toward a unique aviation emission tracers using aerosol- and gas measurements

S. Tinorua[1], B. T. Brem[1], Z. C. J. Decker[1,a], P. Alpert[1], J. G. Slowik[1], M. Ammann1, A. S. H. Prevot[1], M. Bauer[1], M. Götsch[2], J. Sintermann[2] and M. Gysel-Beer[1]

[1] Laboratory of Atmospheric Chemistry, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland
[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

UFP Conference, Brussels, July 3rd 2024

Aircraft engines emissions : Major impacts on climate and health !!

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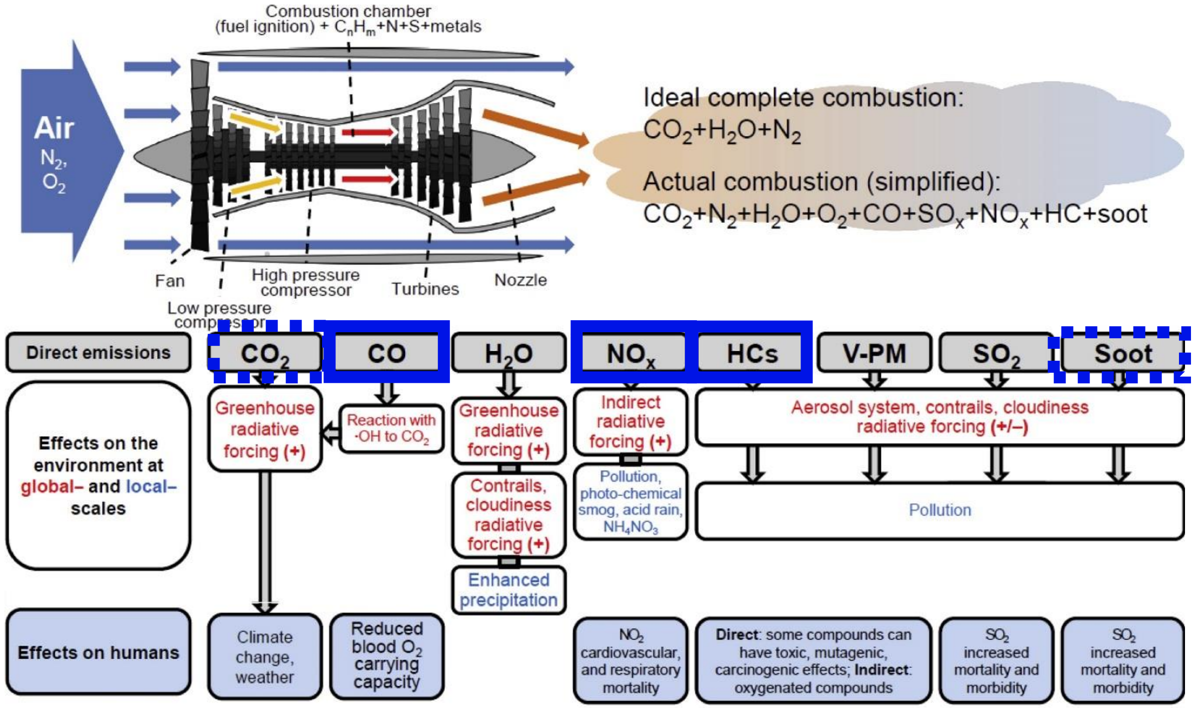
What is emitted :



Adapted from Masiol et al. 2014[1]

Internationally regulated[3]

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

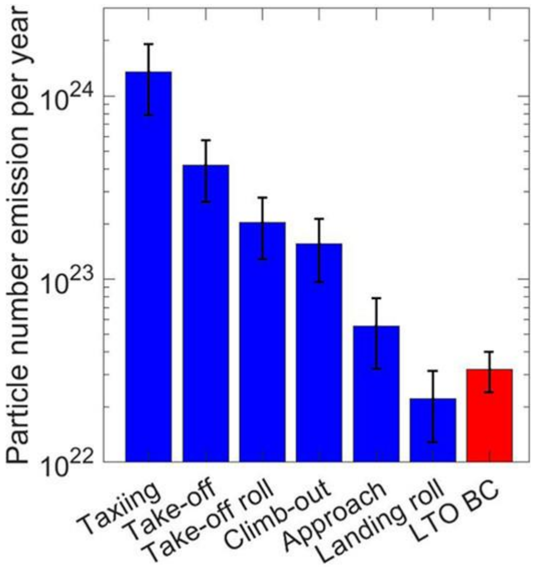
Problem : + 1.9 % of flights per year predicted in Europe
=> Number of passengers doubled by 2040 (Eurocontrol, 2018)

[1]Masiol, M. et al. *Atmos. Environ.* **2014**, *95*, 409–455.

[2]*Aviation Outlook 2050 | EUROCONTROL*. Online (accessed 2024-06-21).

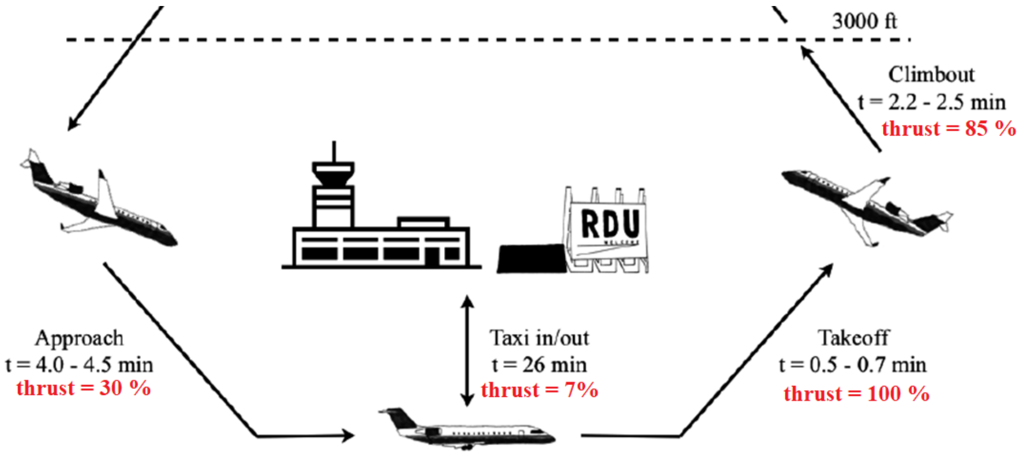
[3]*Emissions Certification Policy and Guidance | Federal Aviation Administration*. (accessed 2024-06-29).

Aviation emissions are a major contributor to UFPs loading



Total particle number emissions at Zurich Airport (1)

Landing & Take-off cycle (LTO)



- At the engine exit plane, Particle Matter (PM) is dominated by non-volatile (nvPM) from fuel combustion + volatile PM from homogeneous nucleation
- nvPM can undergo condensation growth (volatility ↗) and be mixed with carcinogenic compounds[1]
- Median diameter between 15-95 nm[2]
- UFPs concentration and size are depending on the engine thrust but not only ! (ageing processes, environmental conditions, ...)

[1]Zhang, C. et al. Sci. Total Environ. 2022, 820, 153233.
[2]Stacey, B. Atmos. Environ. 2019, 198, 463–477

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

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Characterise Gas & PM emissions with thrust

Identify Aviation emission tracer

Quantify nvPM contribution to total PM

Understand aviation plume evolution

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

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3) Ambient plume measurements

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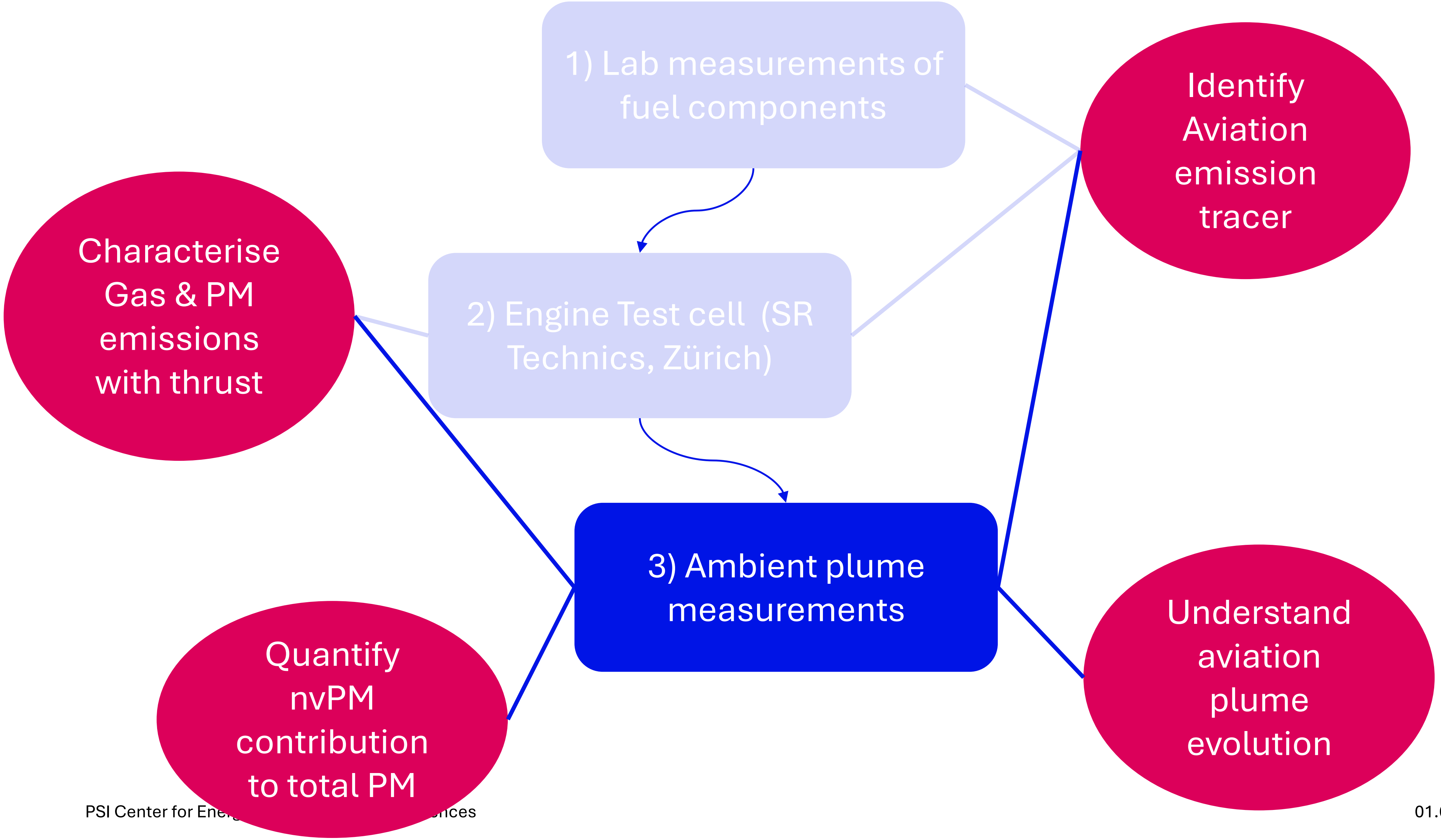

Aerosol and gases measurements in Nov 2022 near the Zurich Airport

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Kloten field site

+ 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 in Nov 2022 near the Zurich Airport

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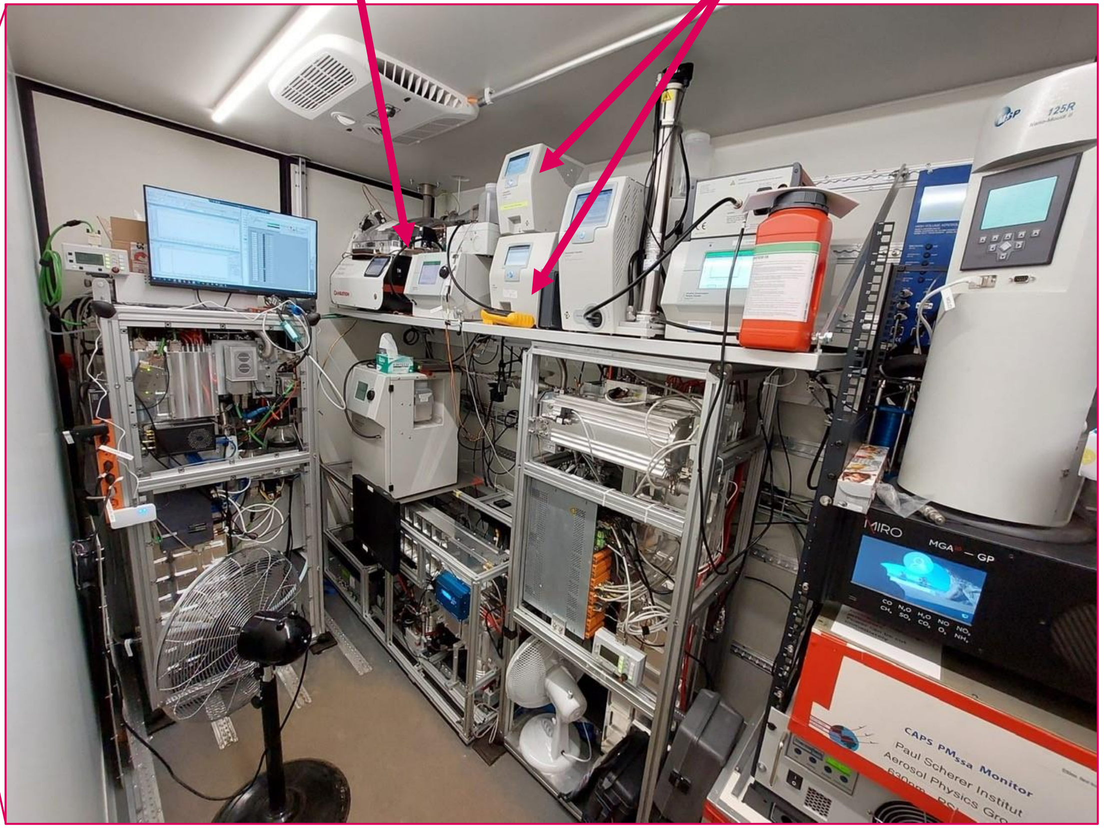
SMPS 3938 (Scanning Mobility Particle Sizer) + Catalytic Stripper
=> nvPM size distribution, *3min*

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



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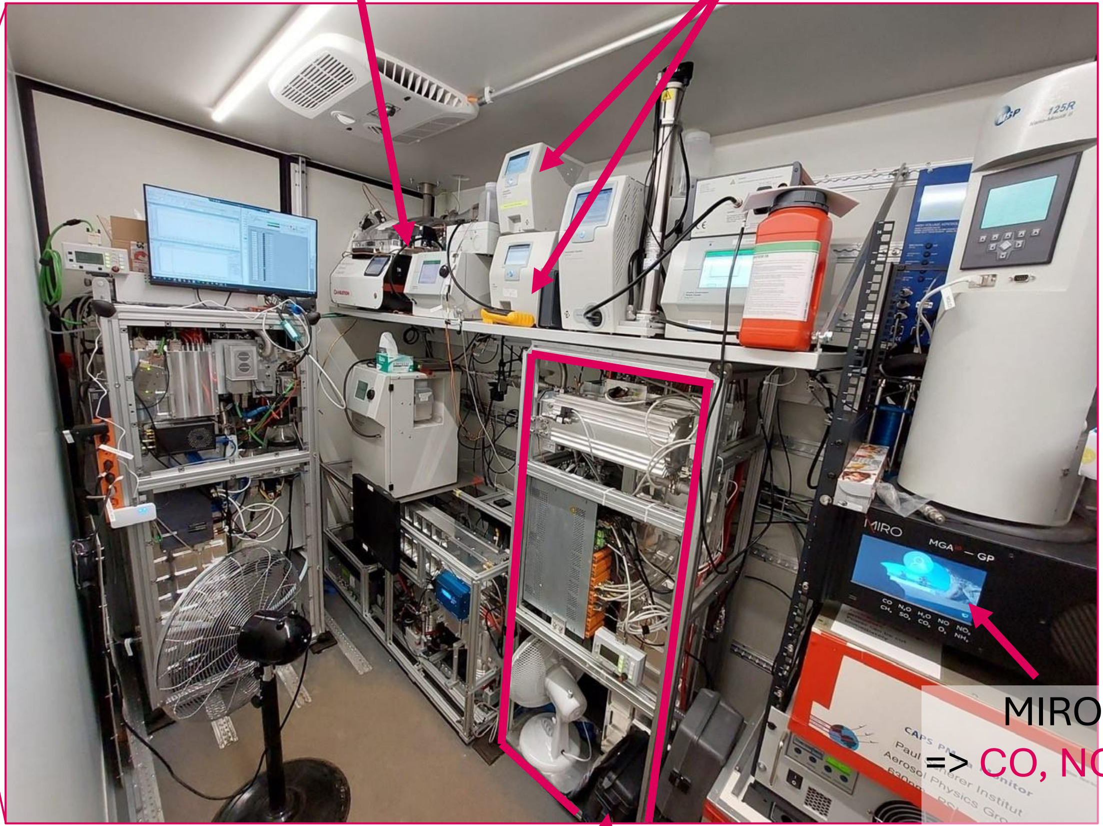


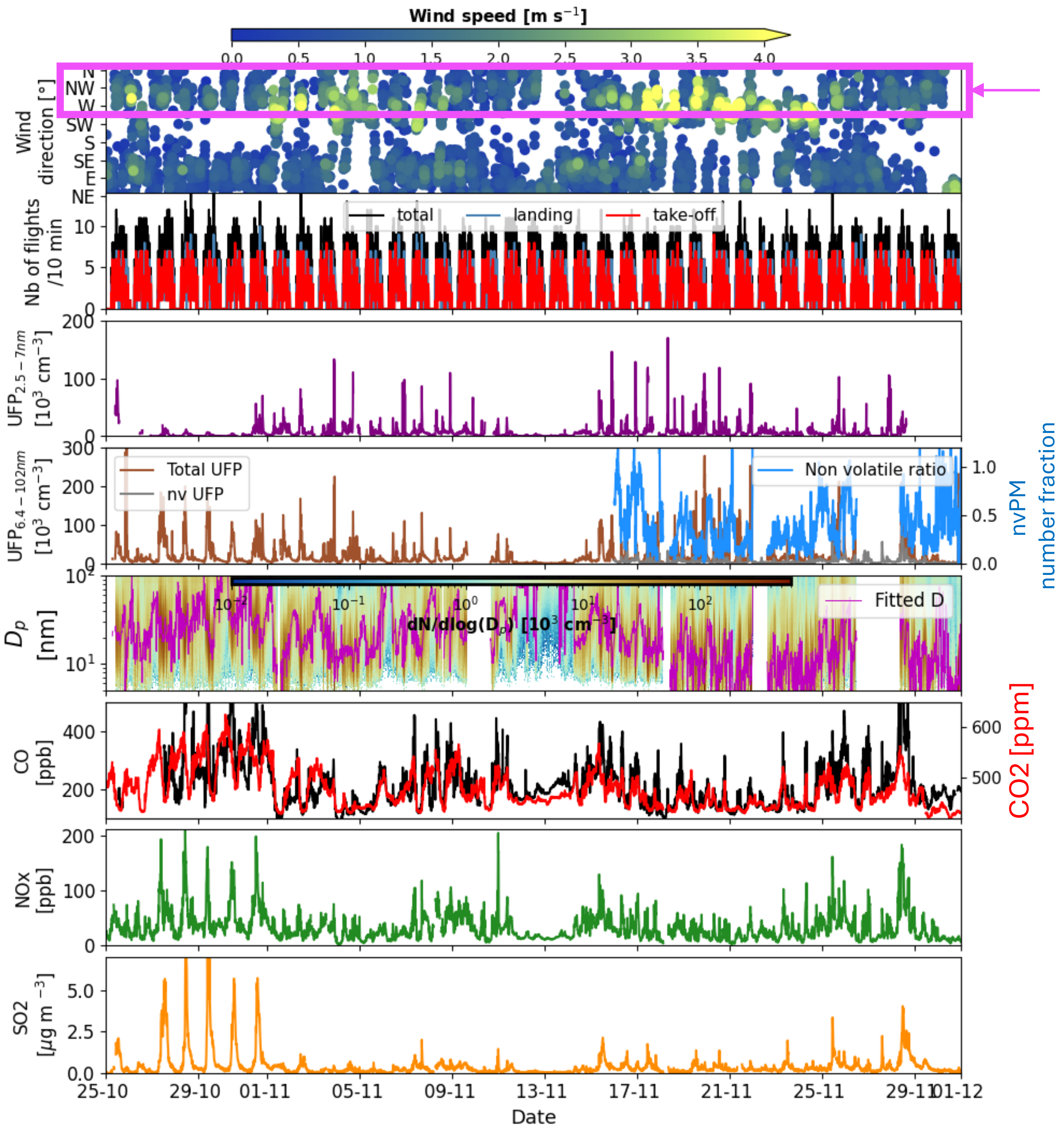
MIRO gas analyser
=> CO, NO concentrations, *1 min*

+ 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**

Overall UFPs and gas properties at Kloten

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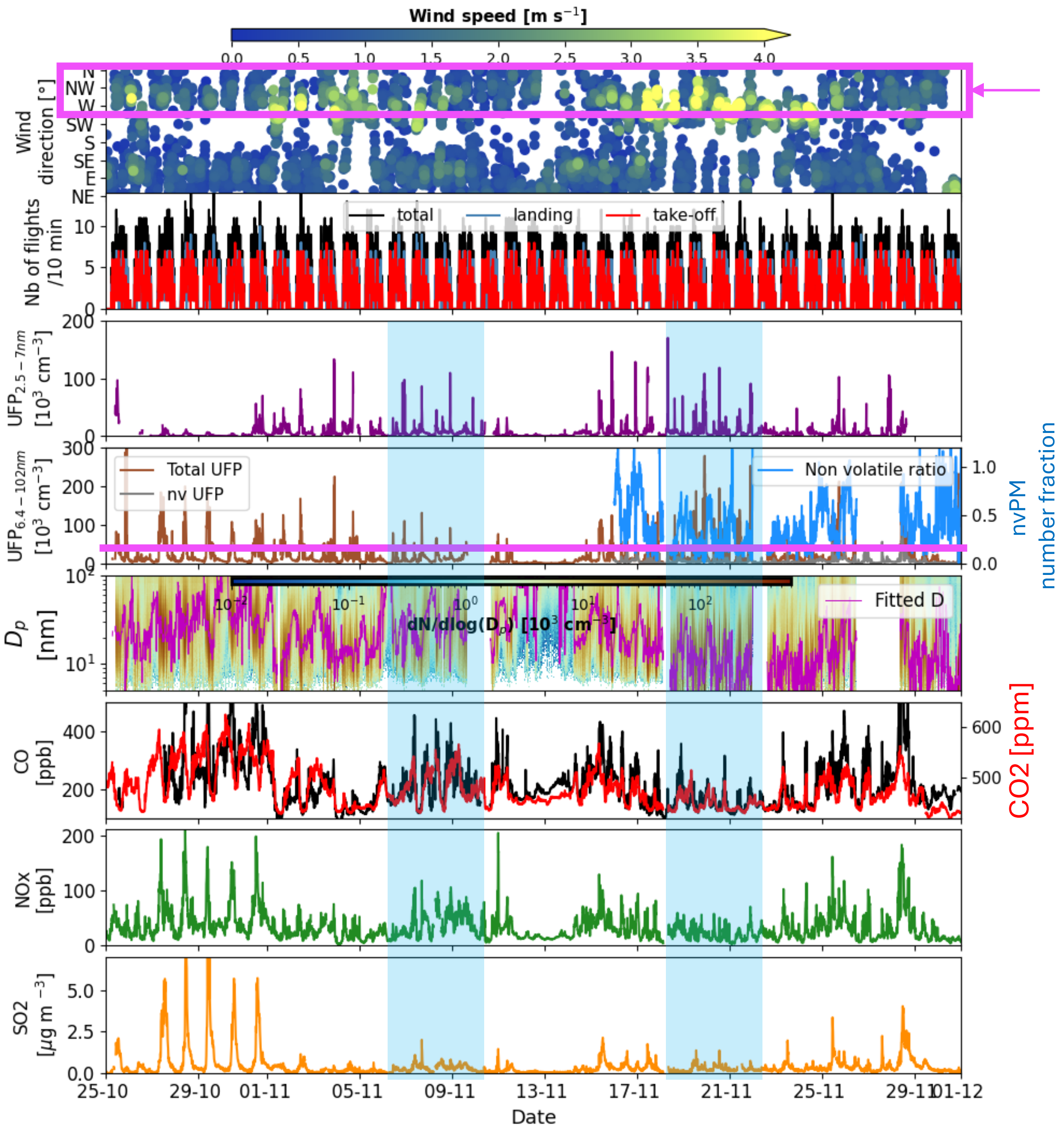

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- Several **peaks of UFPs concentrations** (> 30.10^3 cm^{-3}) associated with :

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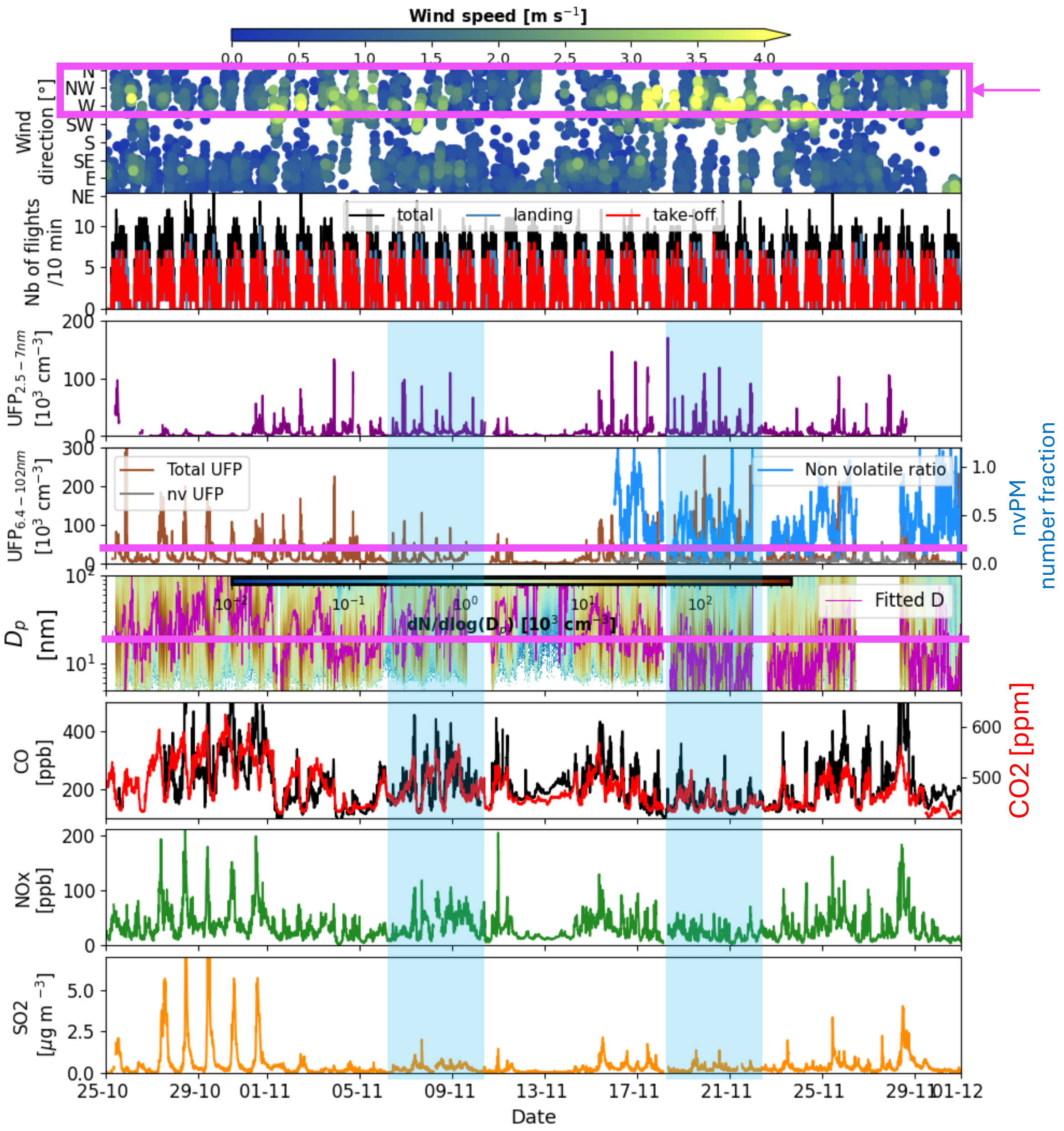

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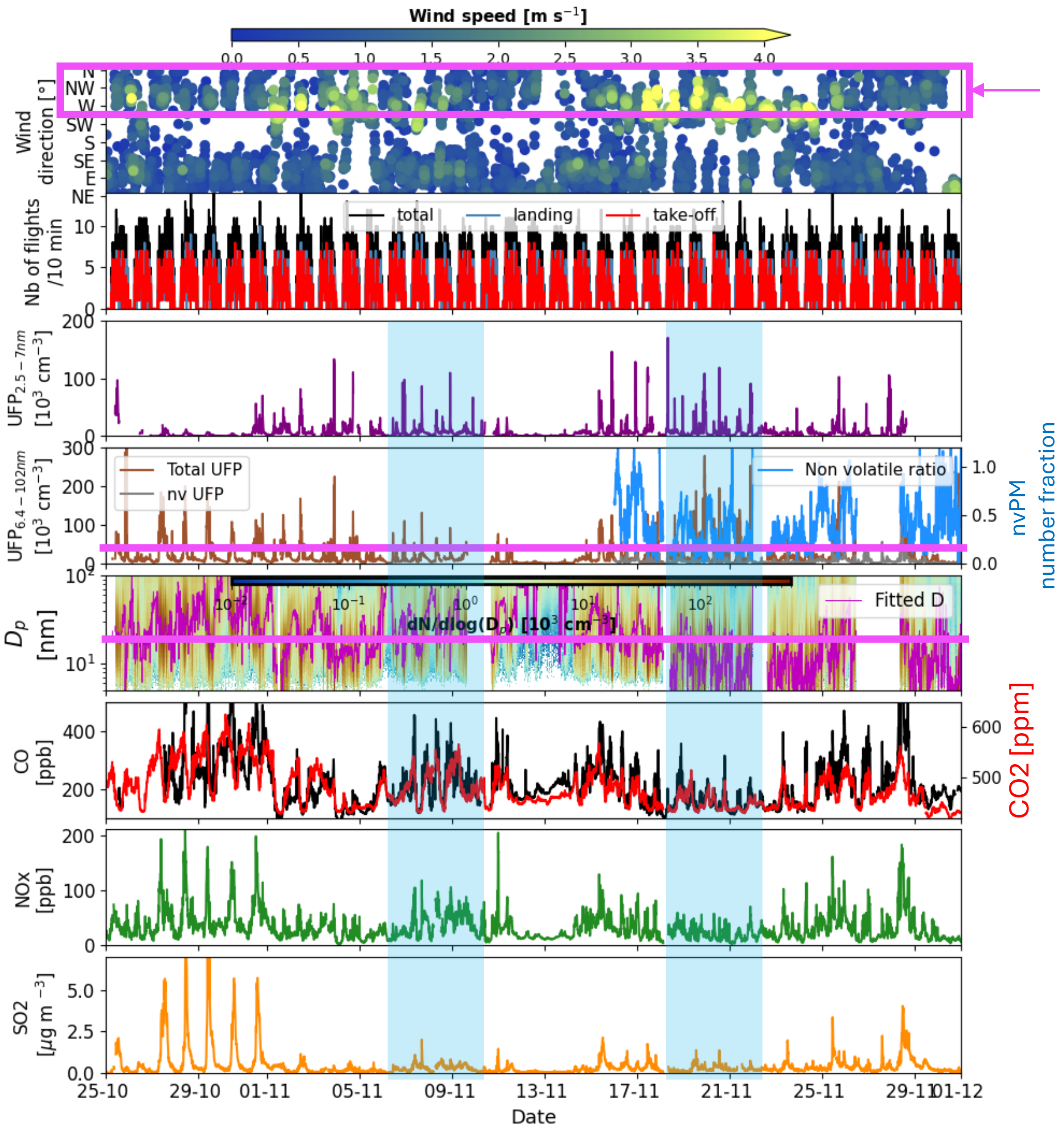

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  – Higher NO_x concentrations

  – Higher SO_2 concentrations

Diurnal patterns of UFP concentrations and aircraft and road traffic

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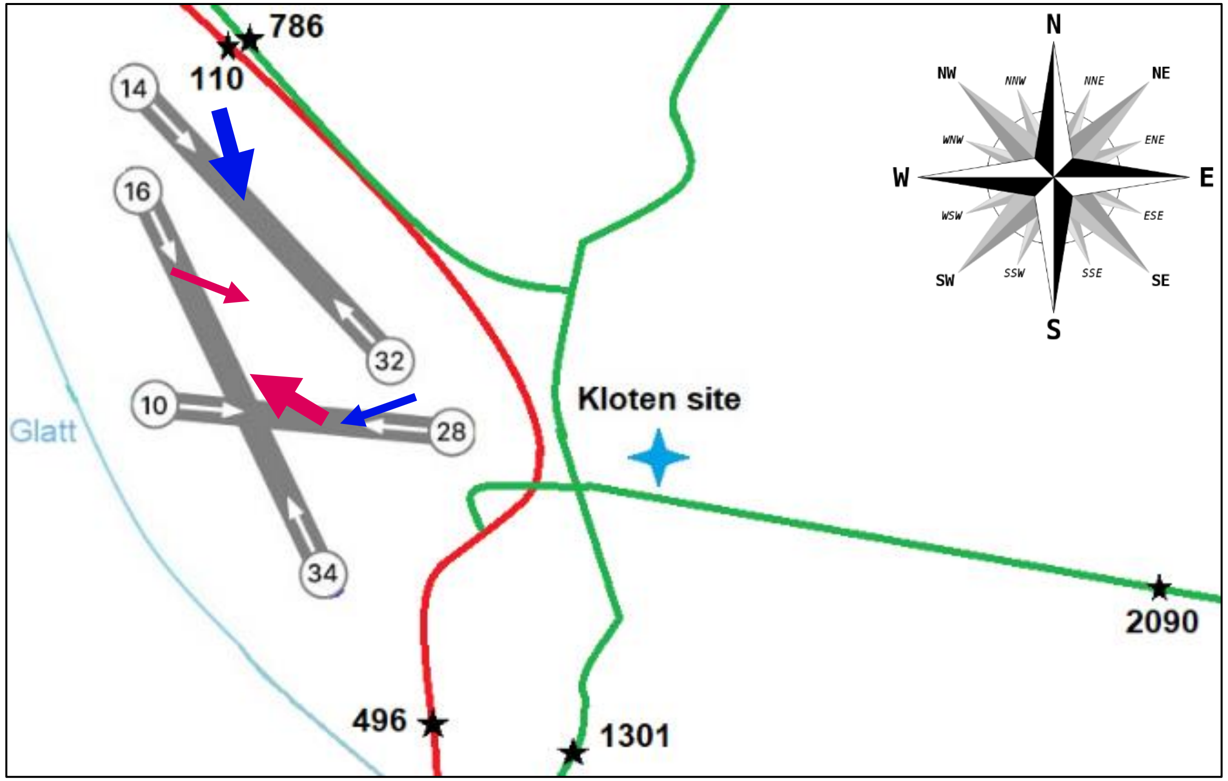
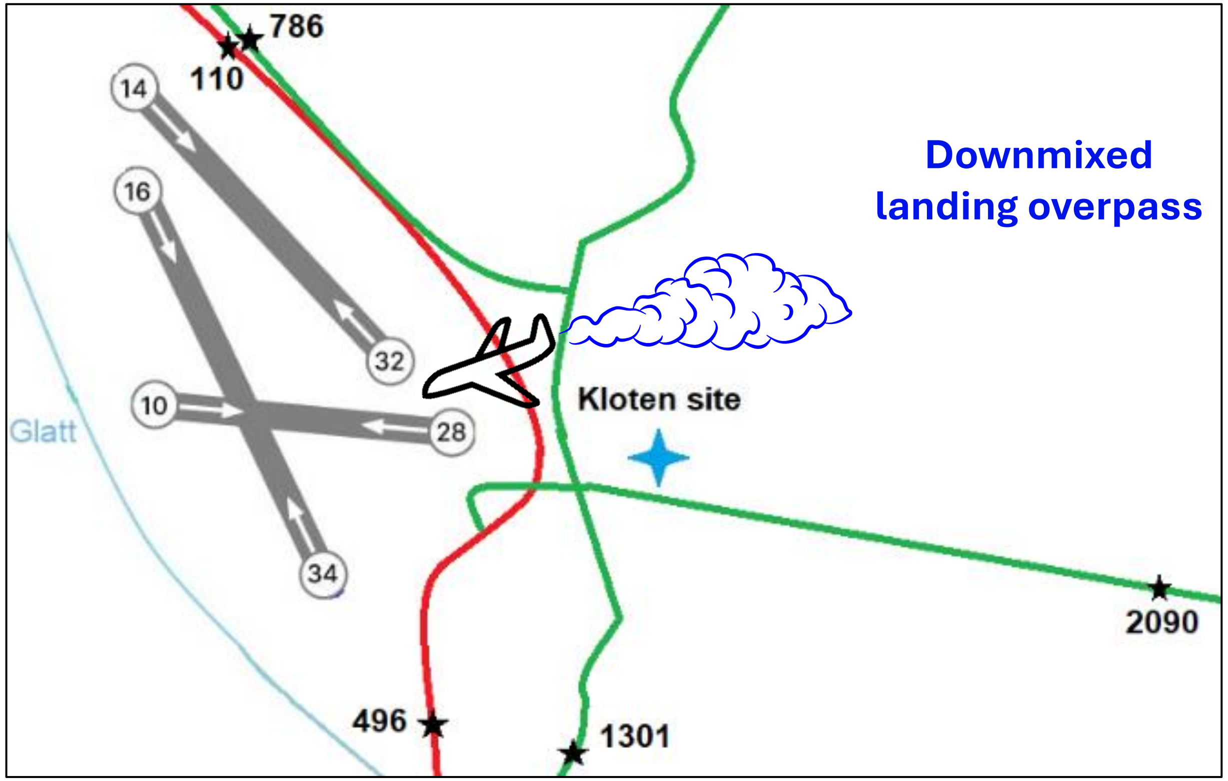


Most frequent used runways when Kloten is downwind the airport :

For takeoffs: 28, 16

For Landings : 14, 28

Diurnal patterns of UFP concentrations and aircraft and road traffic



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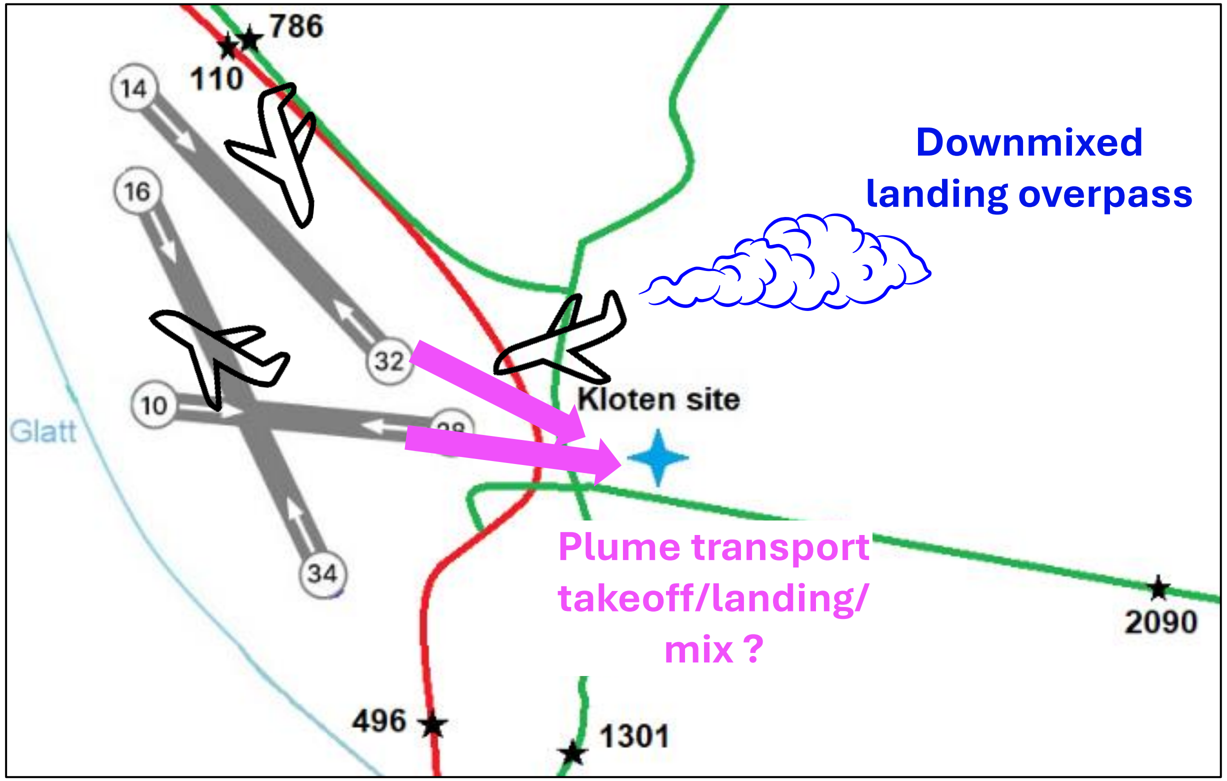

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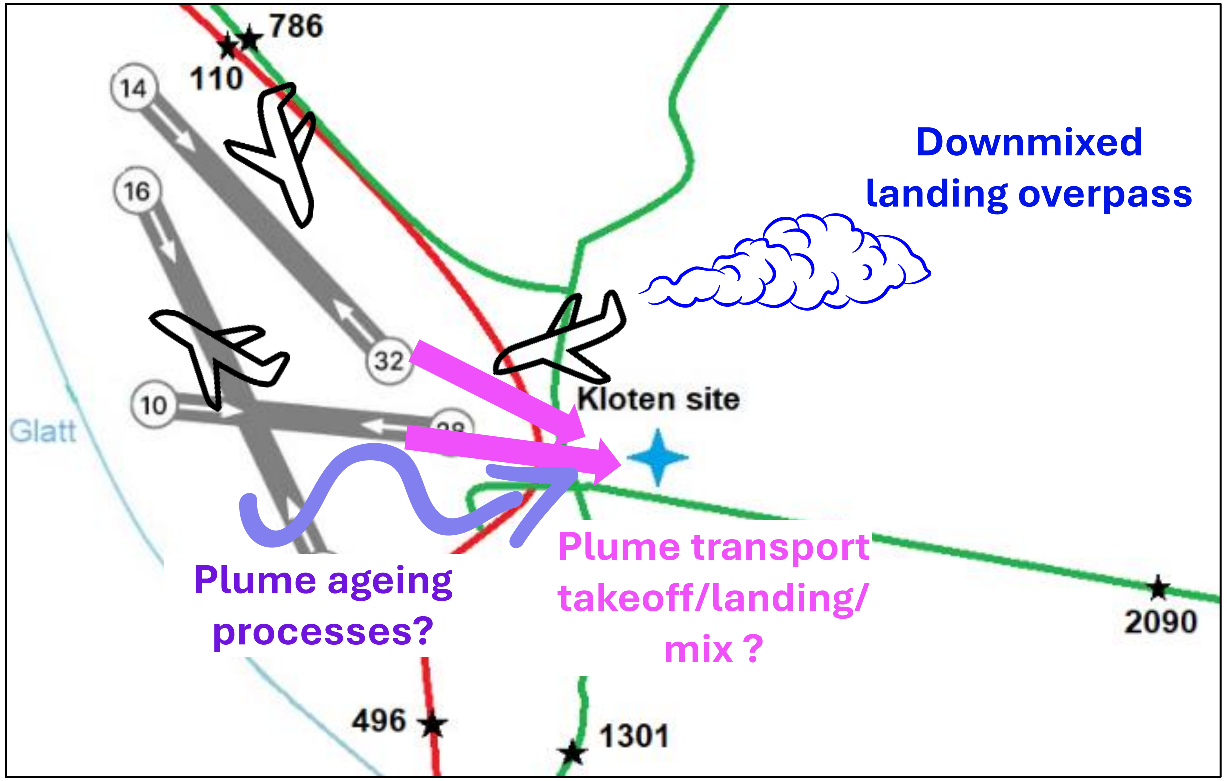

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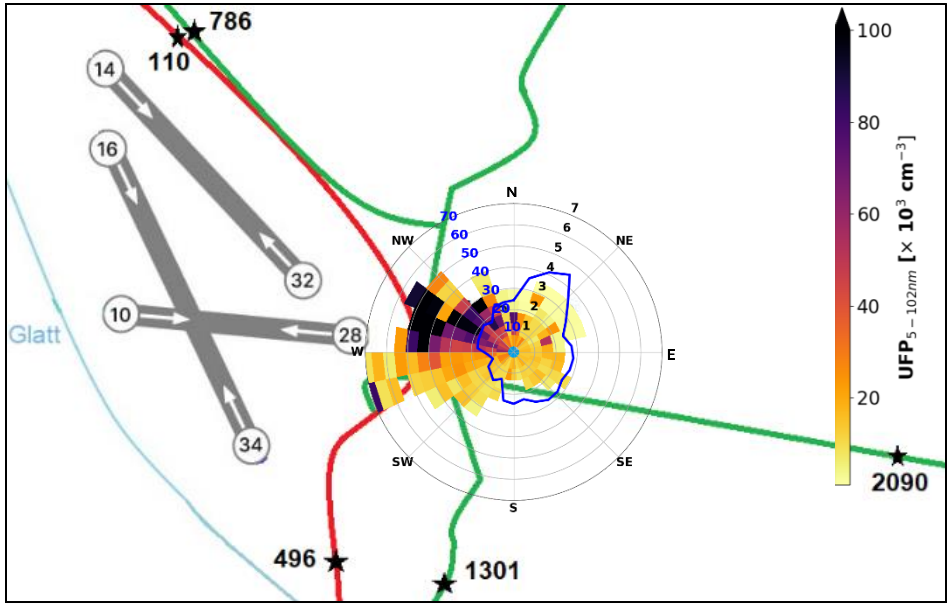
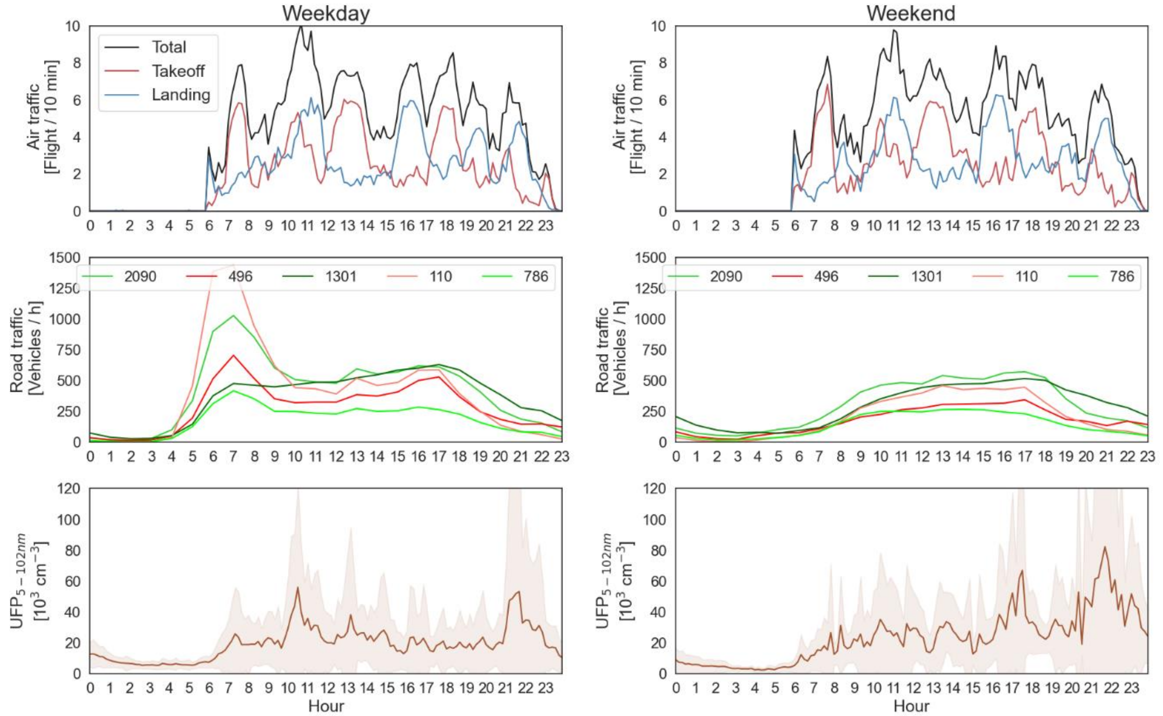
Diurnal patterns of UFP concentrations and aircraft and road traffic

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





Daily cycles of aircraft movements, road traffic and UFPs concentration

Diurnal patterns of UFP concentrations and aircraft and road traffic

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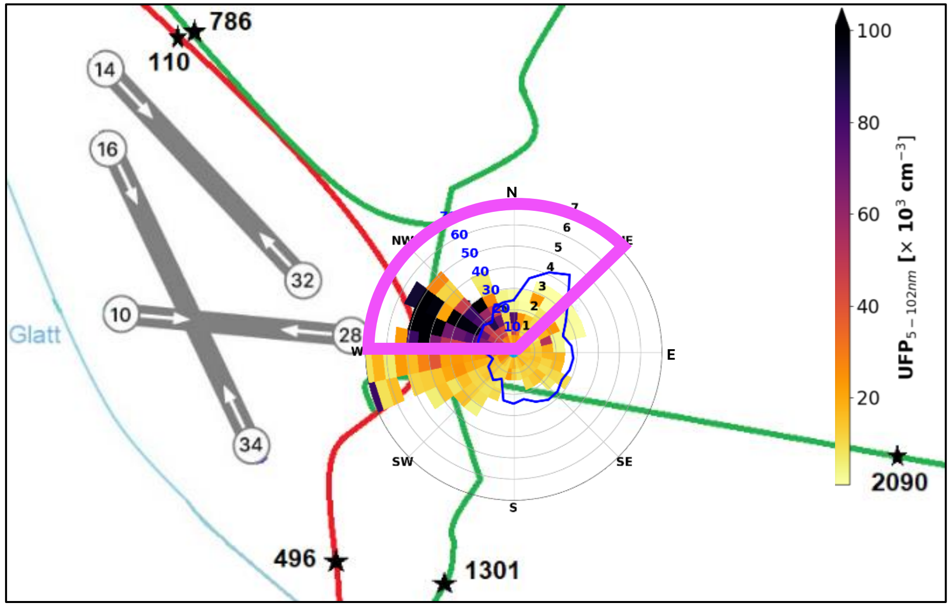

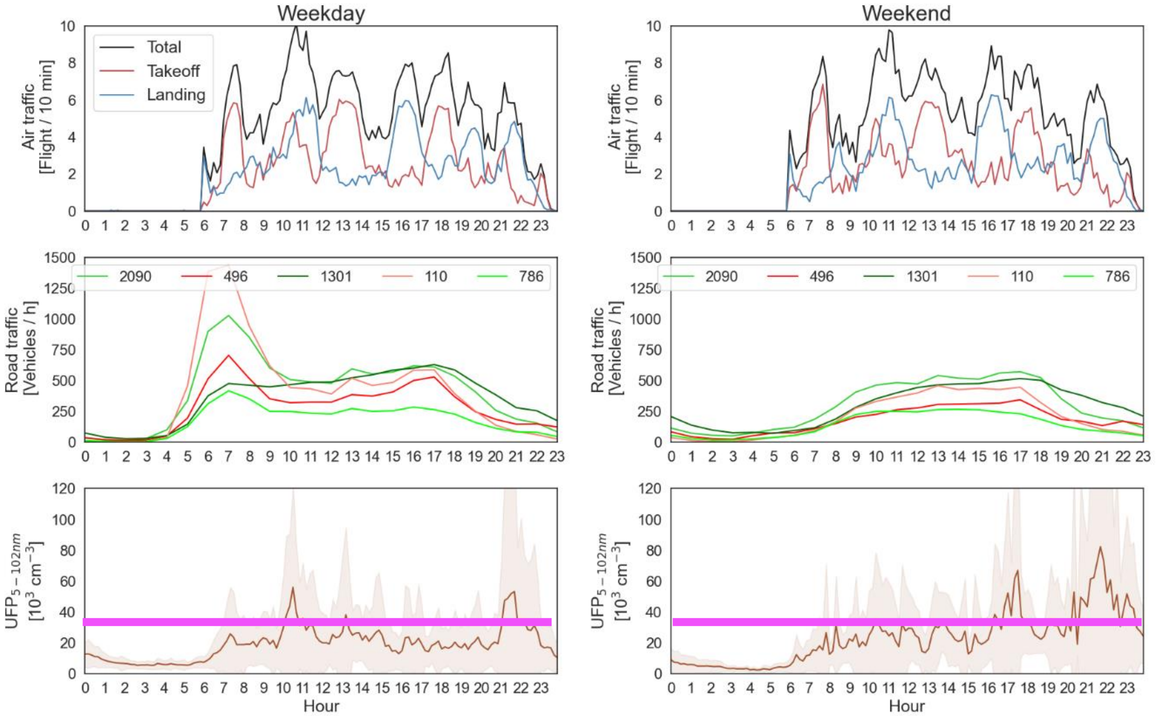

Daily cycles of aircraft movements, road traffic and UFPs concentration

- UFPs >30 000 cm^{-3}
- wind direction from W to NE
  => UFPs certainly dominated by airport emissions

Diurnal patterns of UFP concentrations by wind direction

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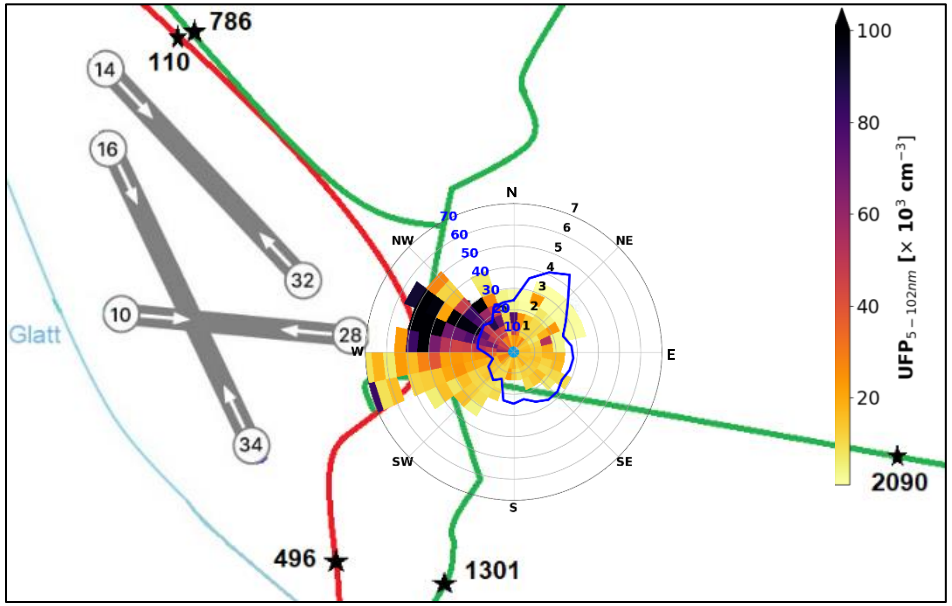

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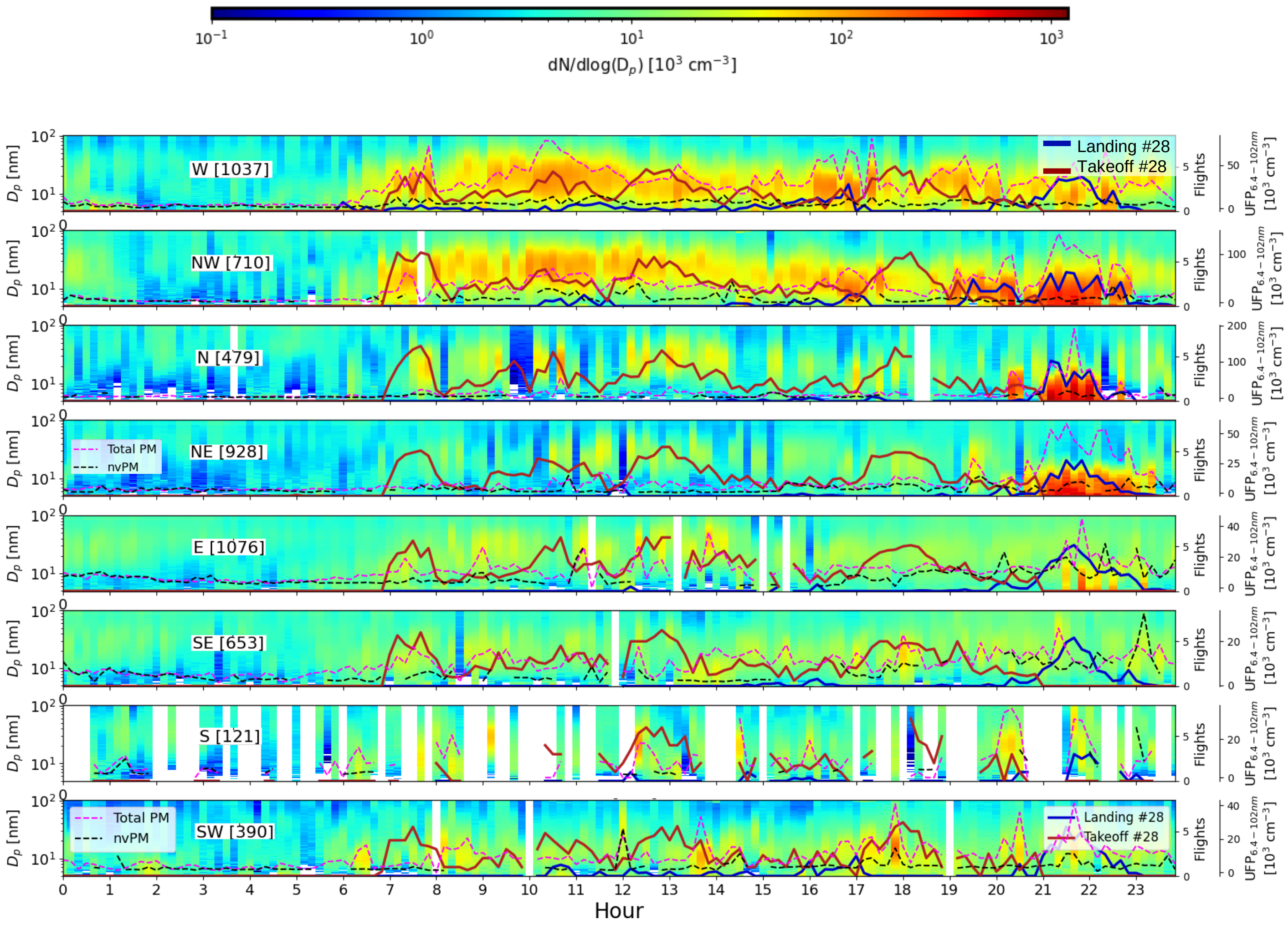

UFPs size distribution splitted by wind direction

Diurnal patterns of UFP concentrations by wind direction

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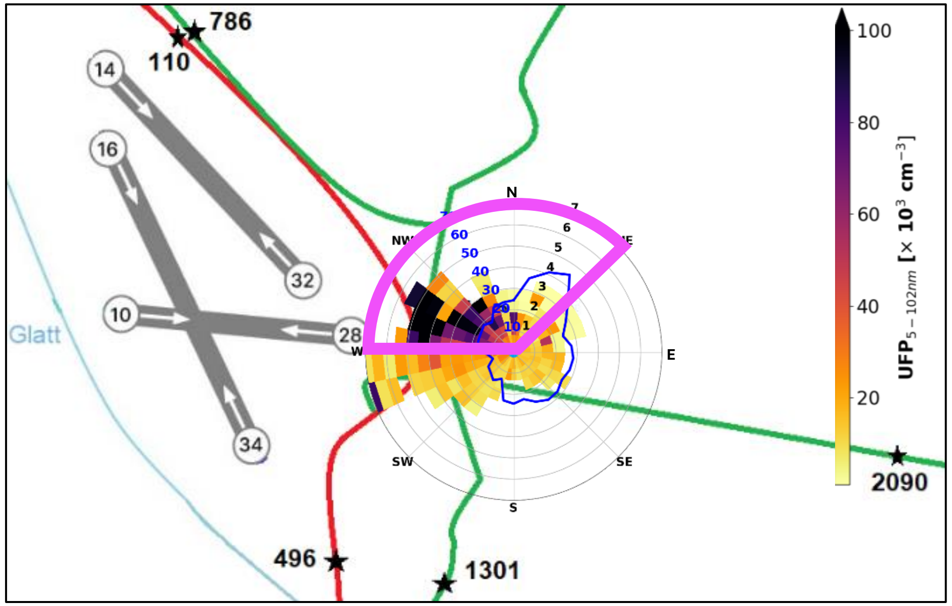

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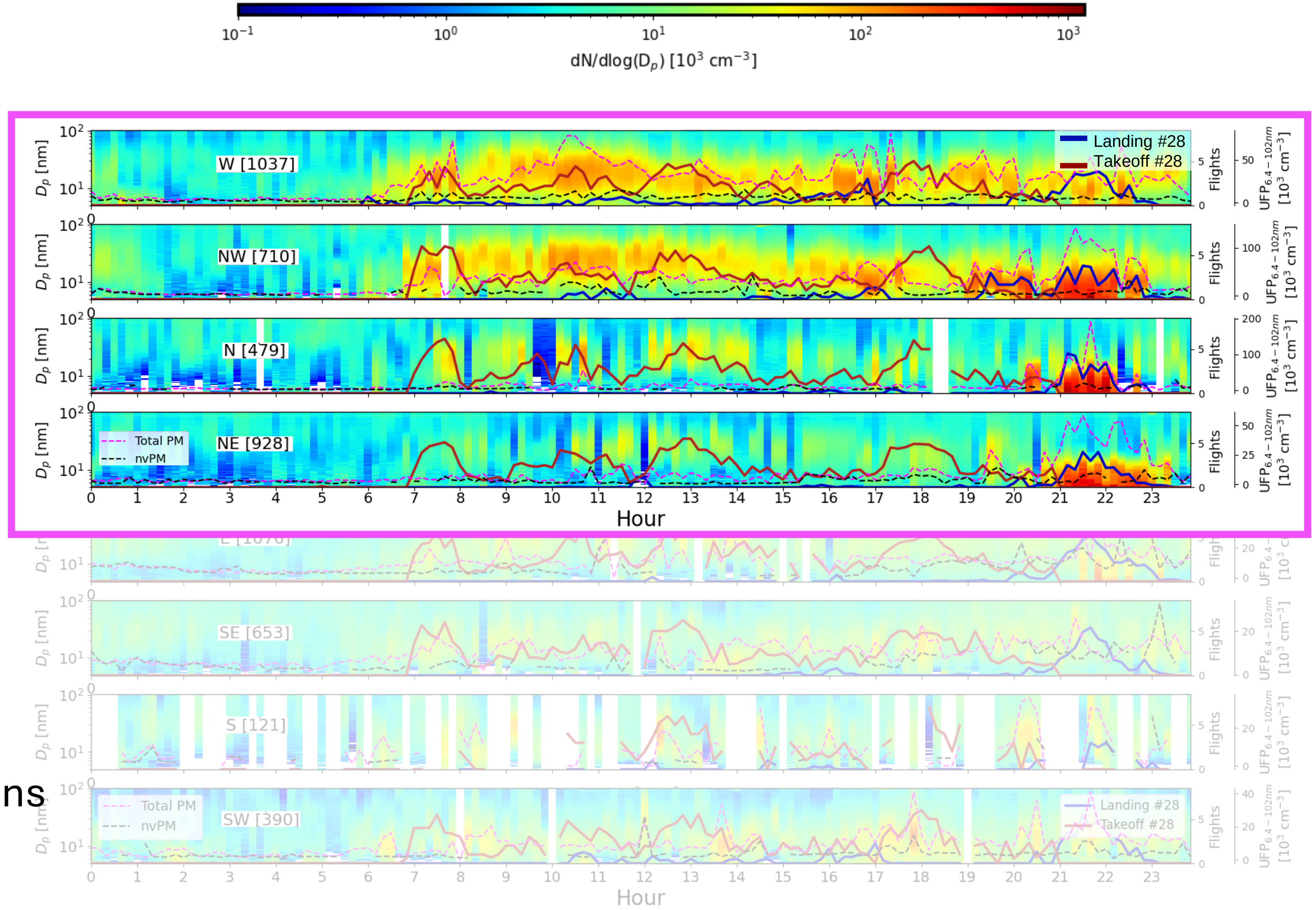

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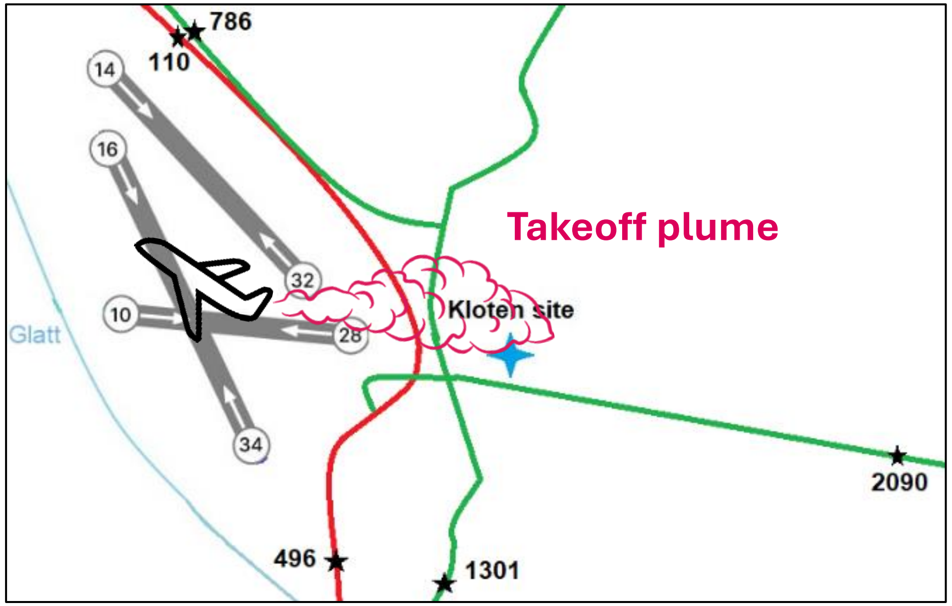

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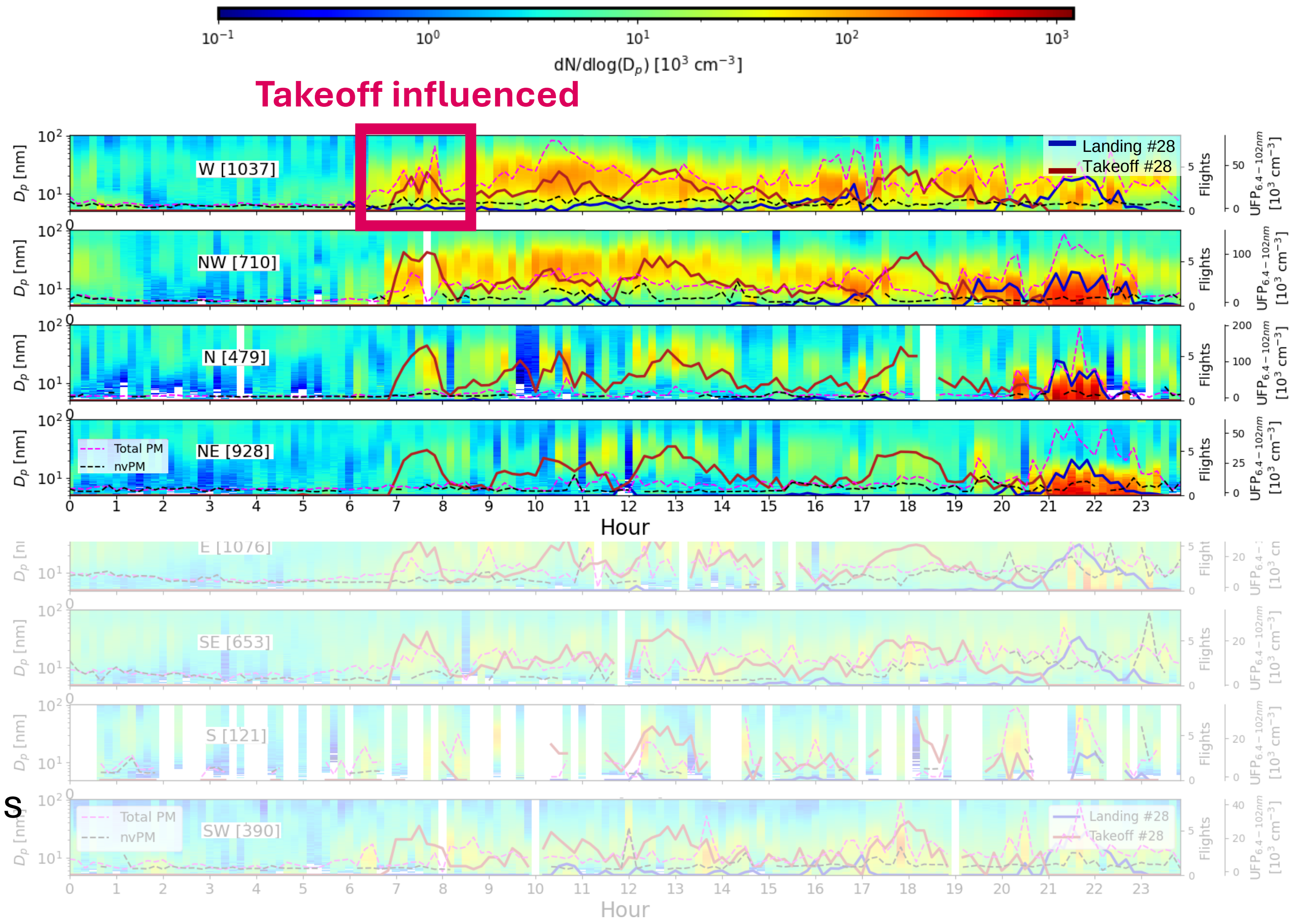

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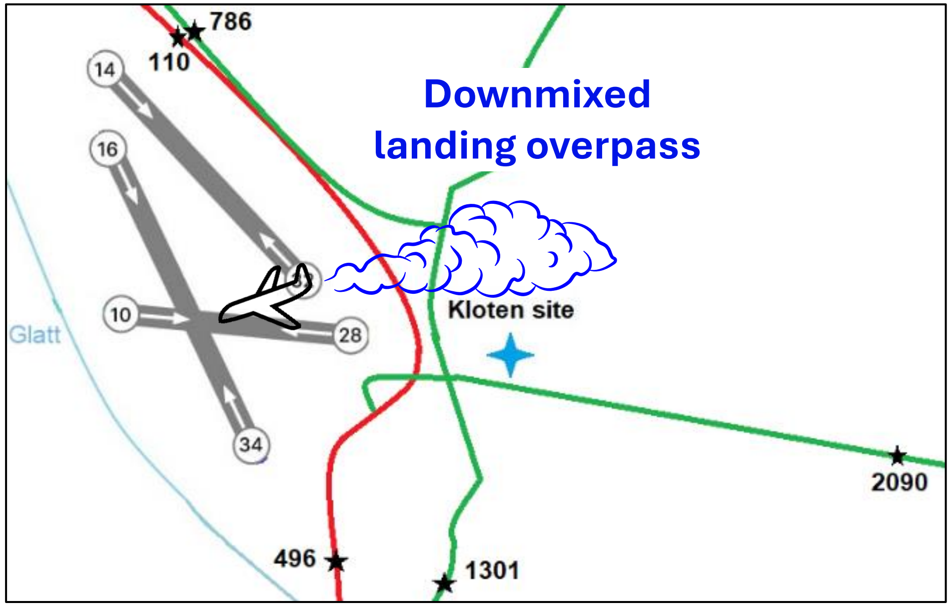

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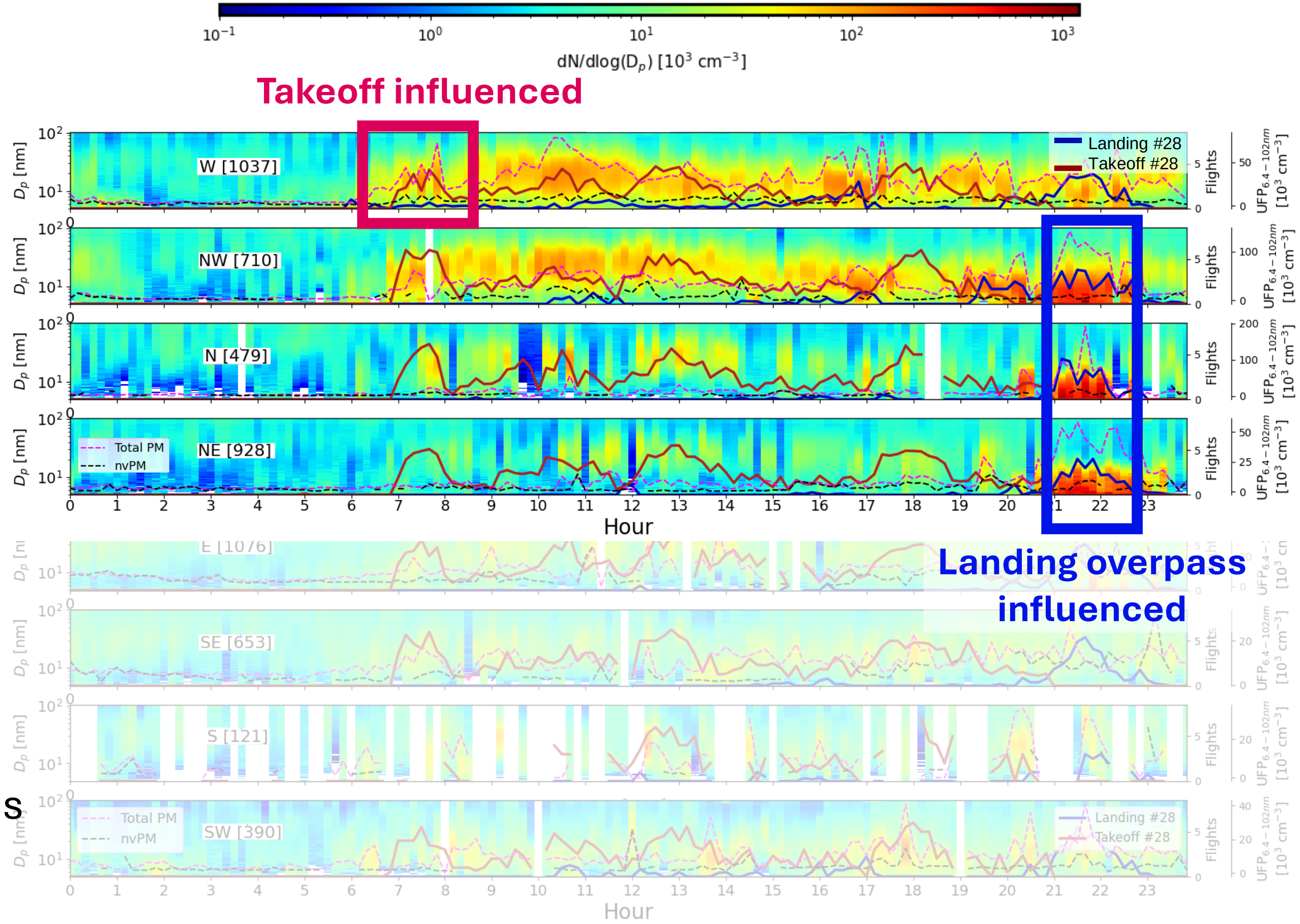

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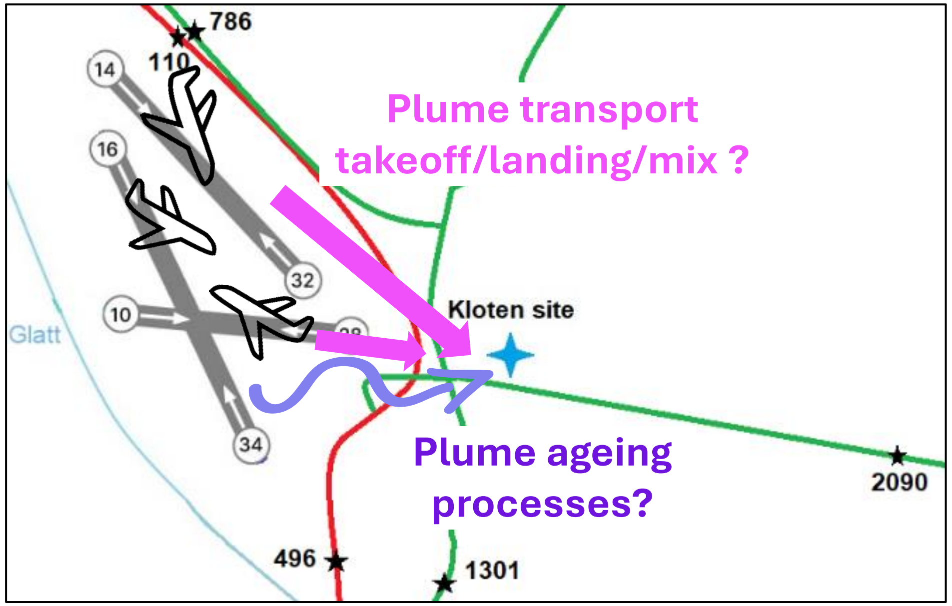

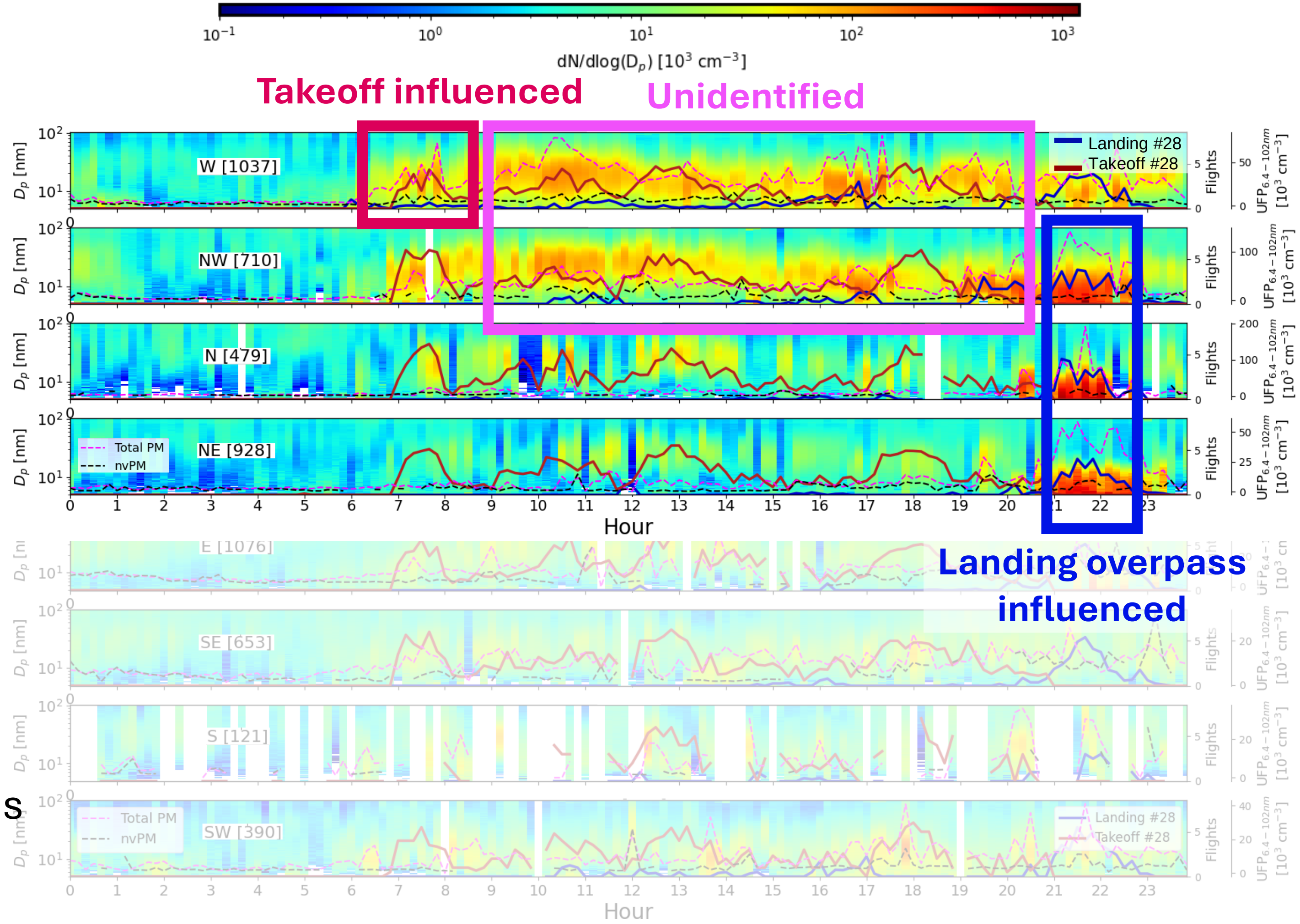

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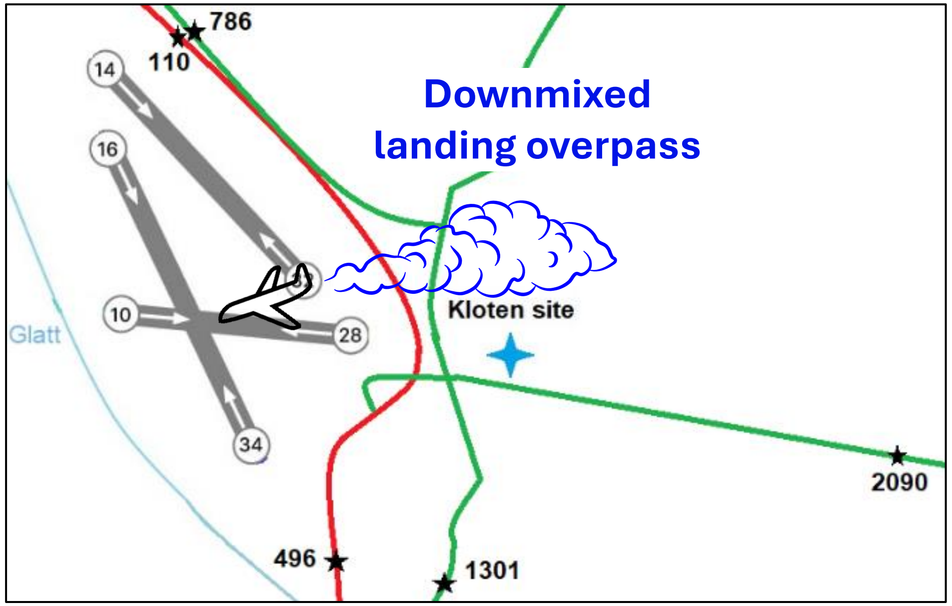

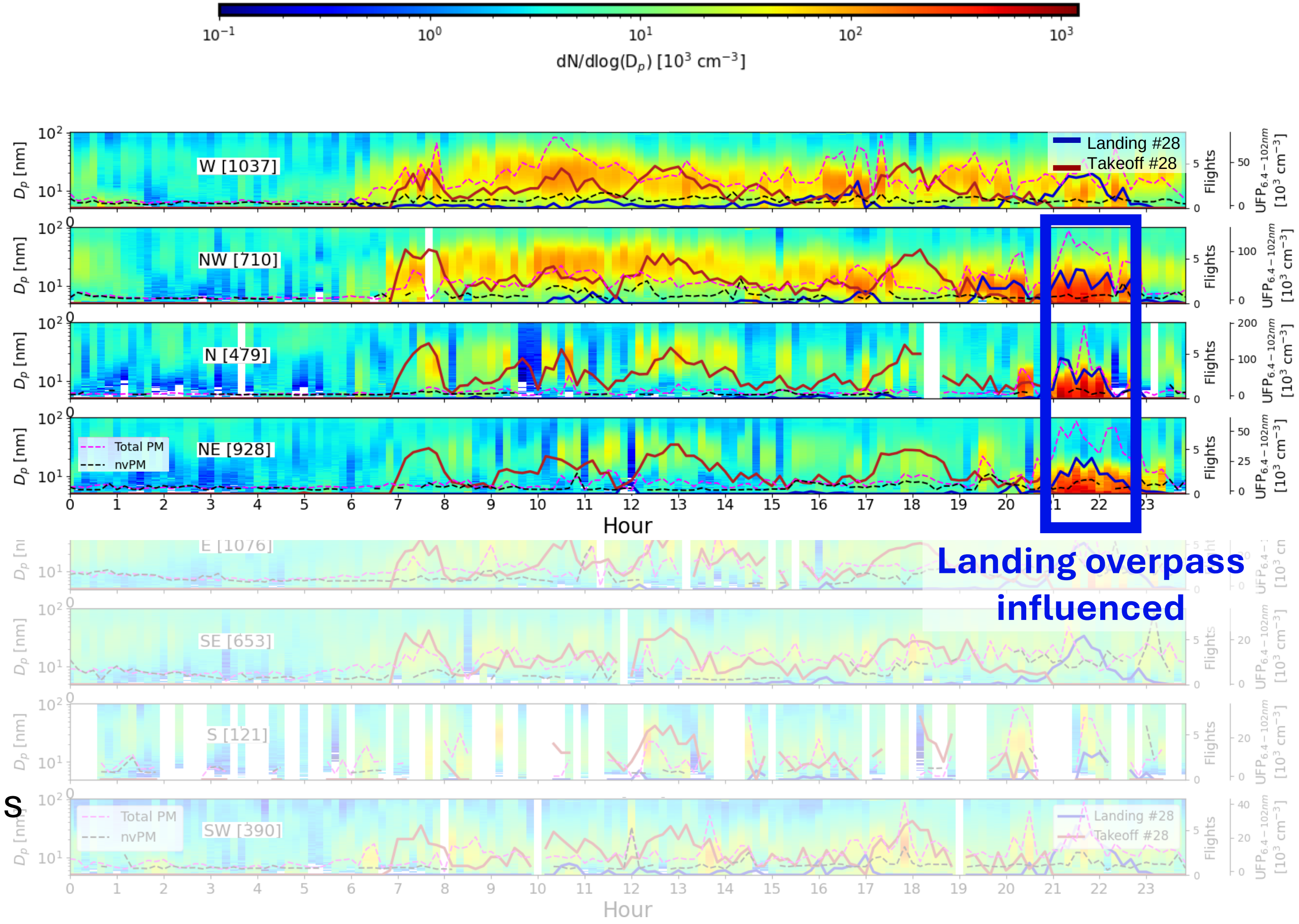

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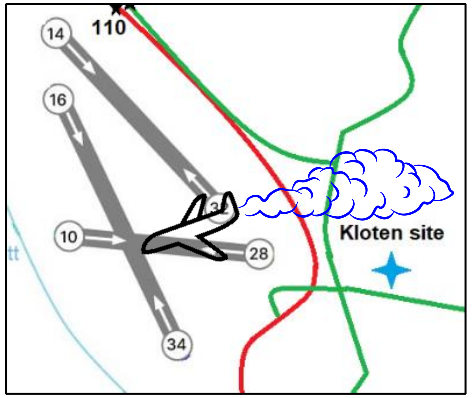
1) What can we say about the landing overpass emissions?

Landing overpass UFPs concentration,size and volatility

1) Selecting daytime data > 30 000 cm^{-3} and wind direction between West and North-East => aviation emission



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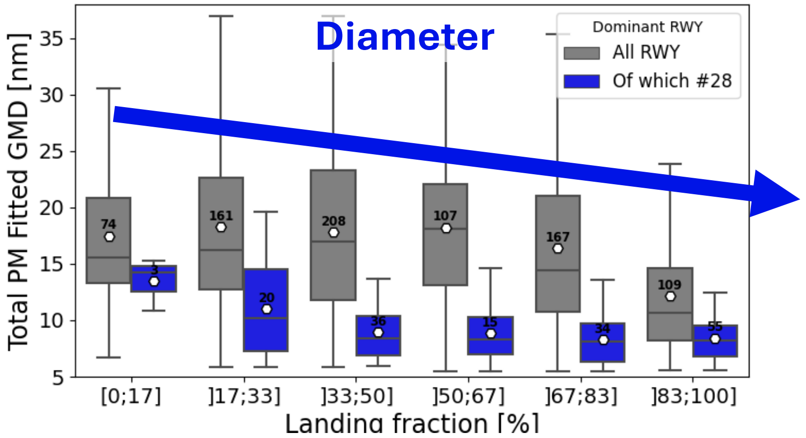
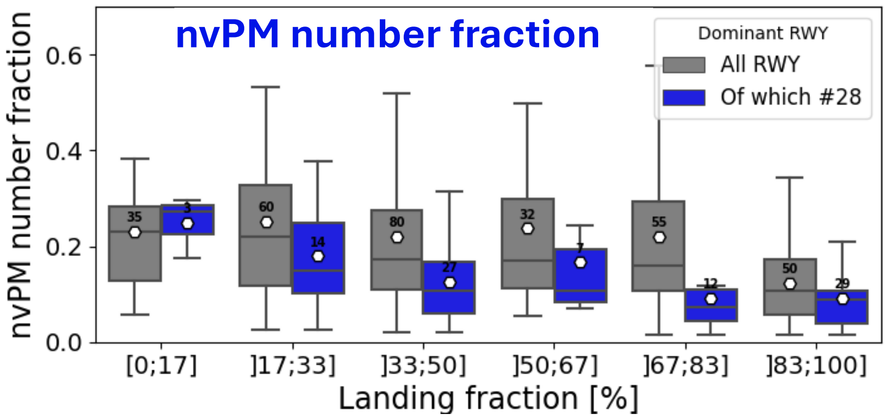
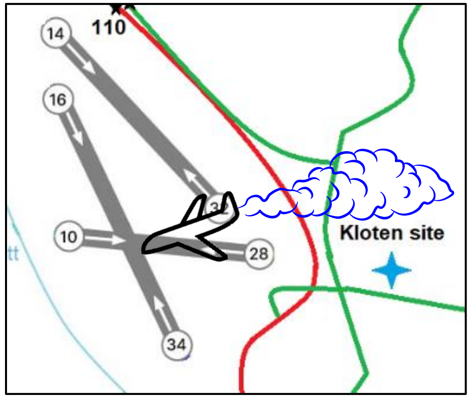


GMD as a function of landing fraction



nvPM number fraction as a function of landing fraction

Smallest GMD



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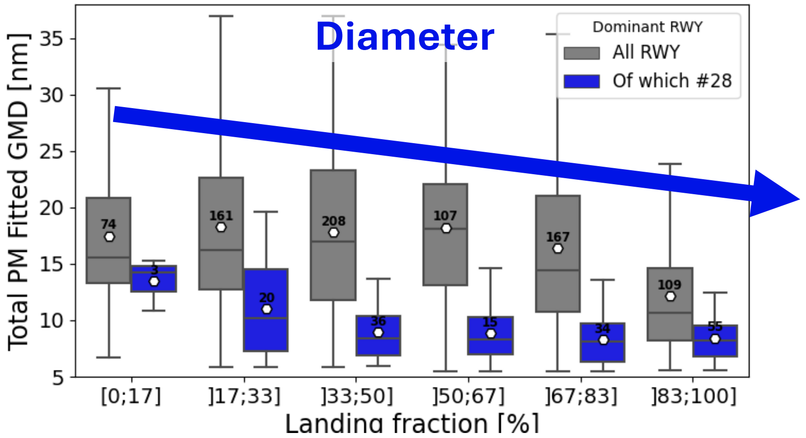

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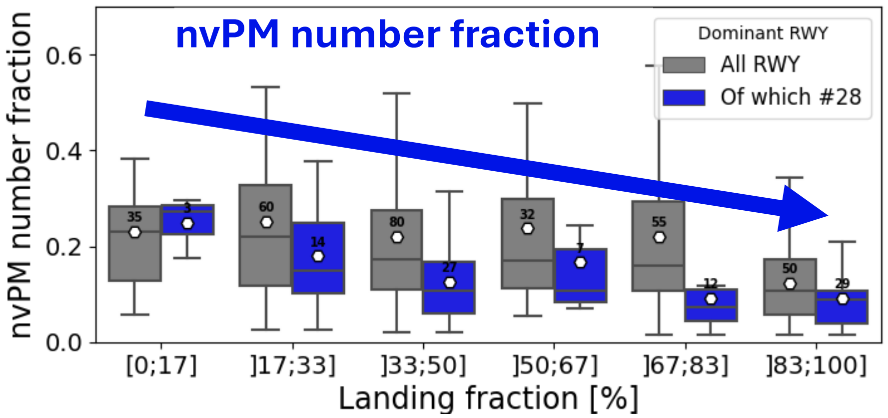
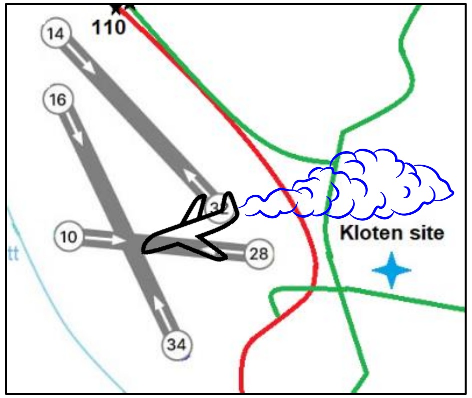


nvPM number fraction as a function of landing fraction

Smallest GMD & **lowest nvPM number fraction** for landing overpass



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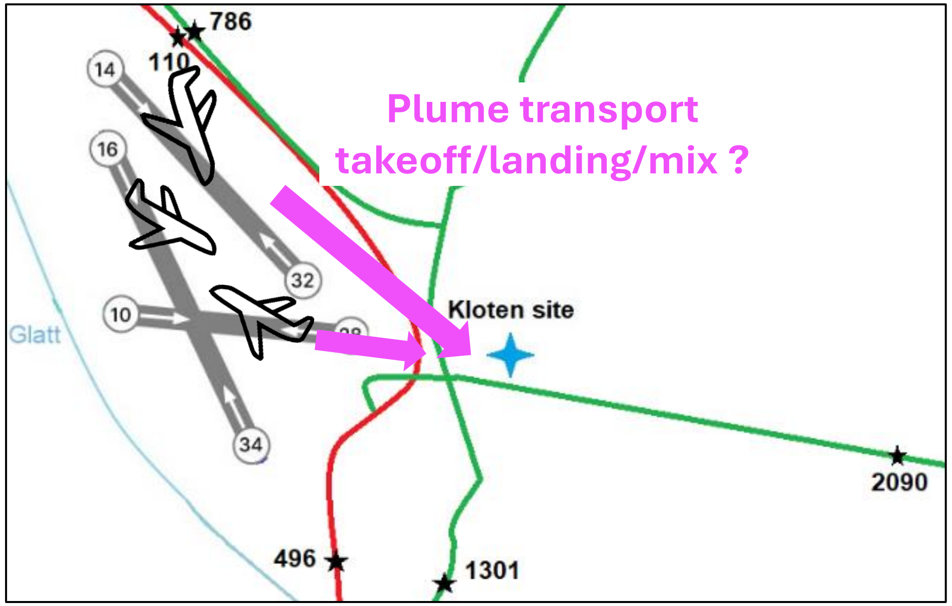
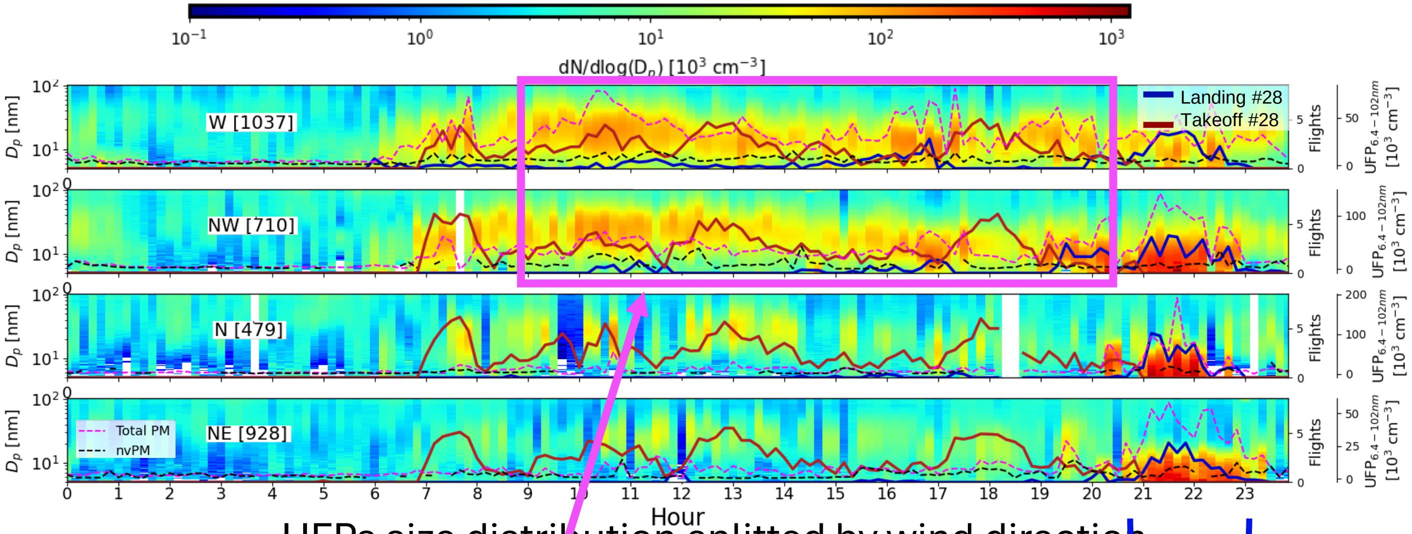




UFPs size distribution splitted by wind direction

Landing, take-off or mixed ?

Smaller and more volatile UFPs

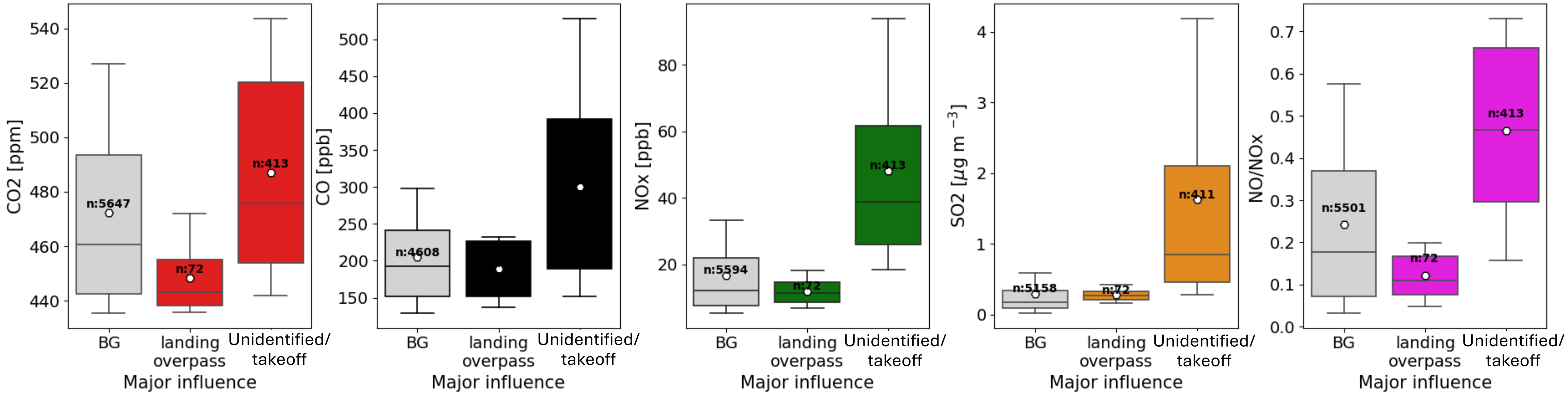
2) Can the UFP/gas properties be used to distinguish between take-off and landing emissions?

Can we distinguish takeoff vs. Landing emissions with combustion gases ?

1) Selecting daytime data > 30 000 cm^{-3} and wind direction between West and North-East => aviation emission

2) Landing overpass : > 7 PM vs. Unidentified/takeoff : < 7 PM

Measured gases concentrations as a function of the major emission influence



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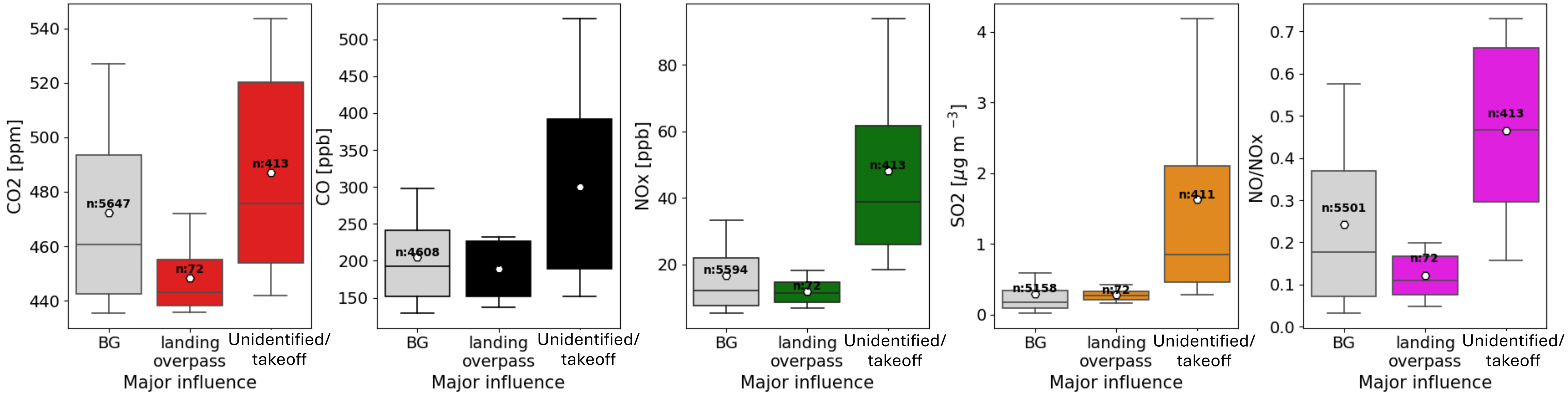

Those trace gases are not anymore enhanced by the time the down-mixed plume is detected

➔ gases such as SO_2 cannot be used as reliable predictor for UFP from aviation (many false negatives).

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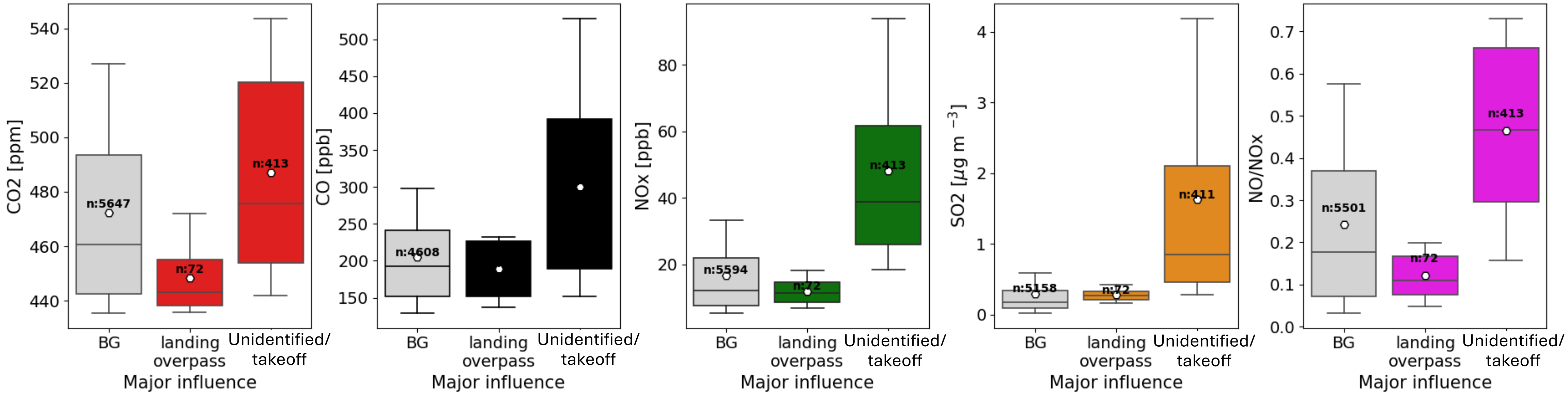

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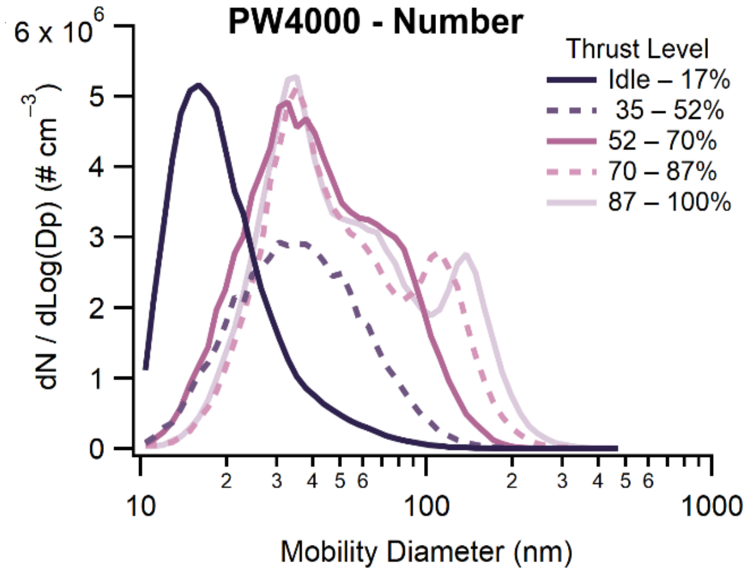
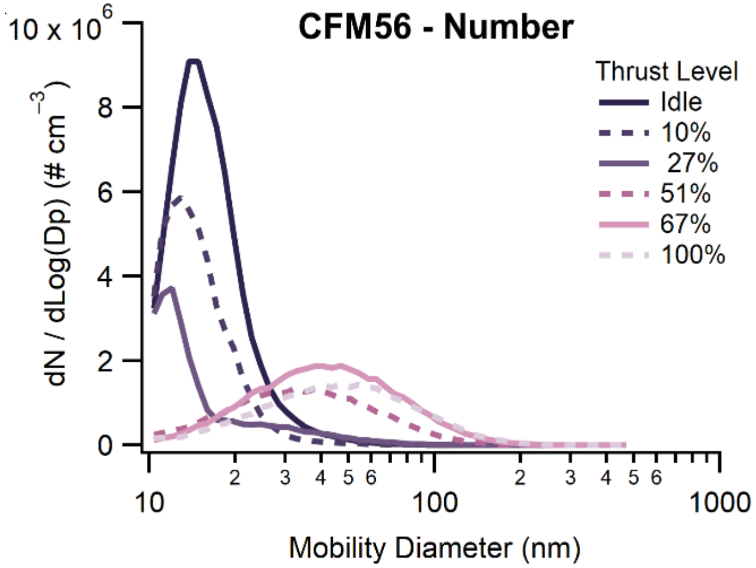
Use the UFPs properties to separate takeoff and landings ?

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., in prep.

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

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

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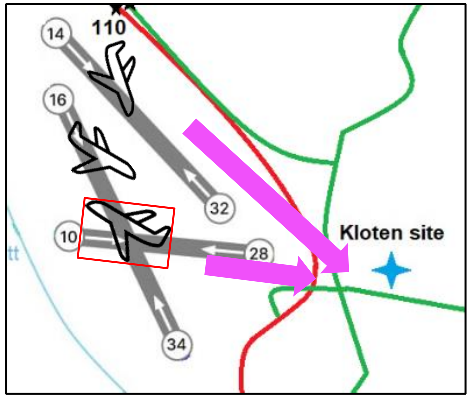
1) Selecting daytime data > 30 000 cm^{-3} and wind direction between West and North-East => aviation emission

2) Excluding landing overpass



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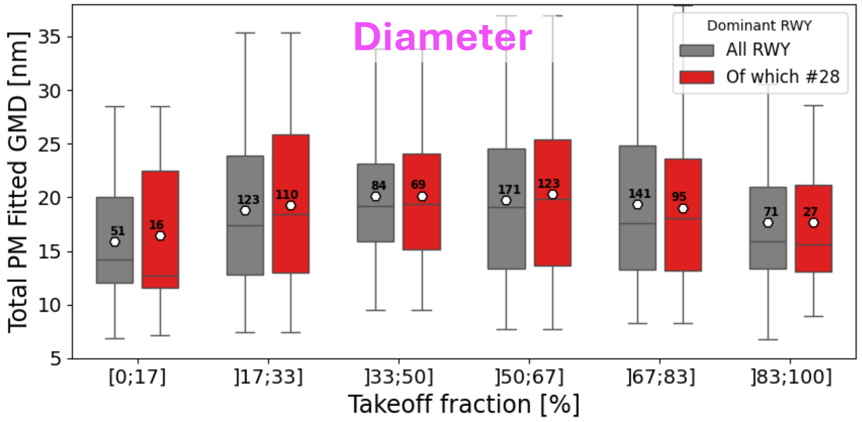
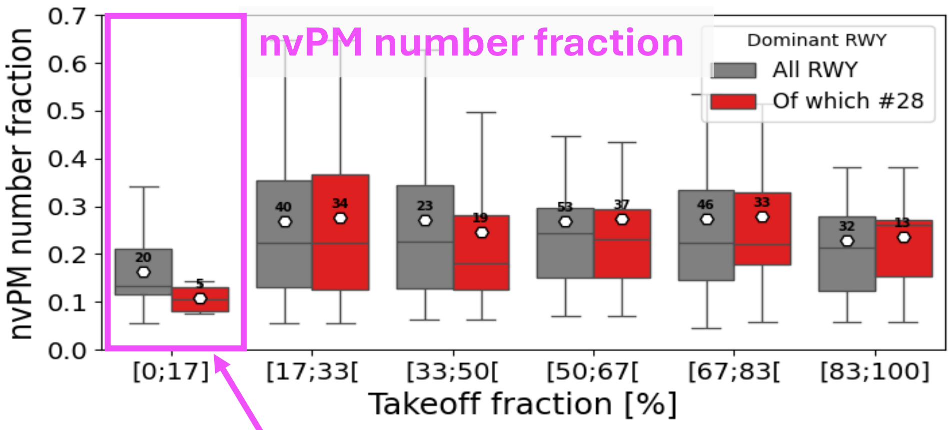
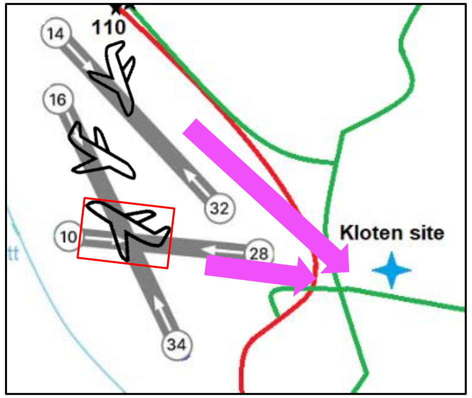




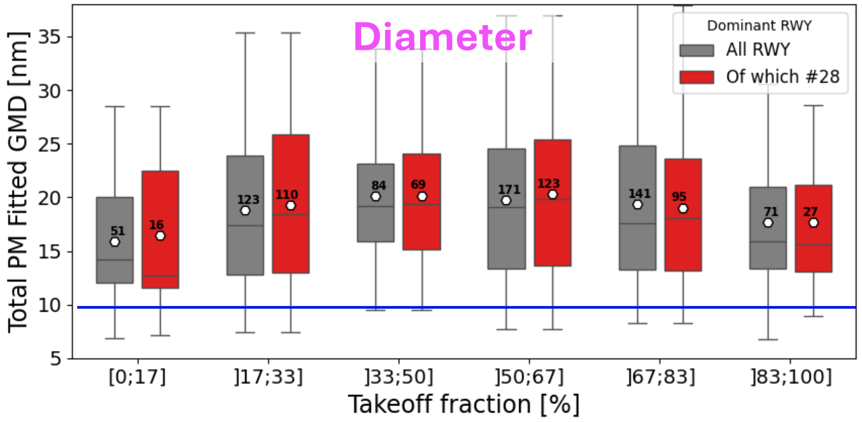
- Wide range of GMDs : 6 to 37 nm
- Neither GMD nor nvPM number fraction depend on take-off fraction (except without take-off)



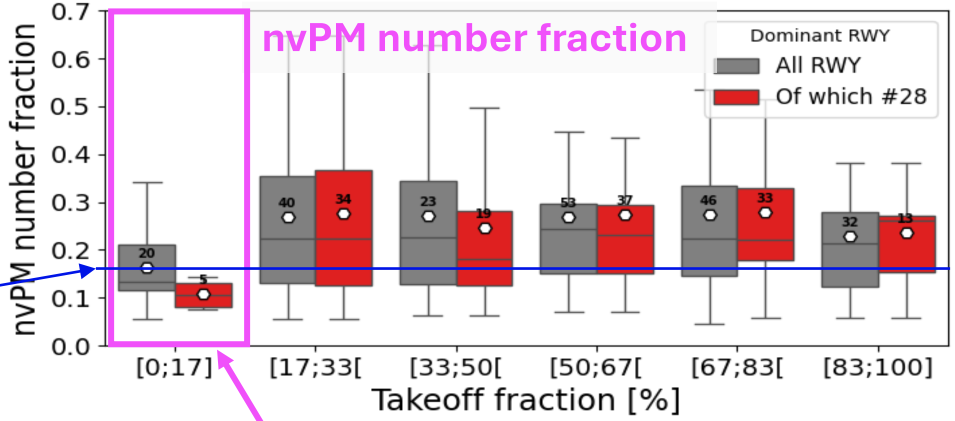
Can we distinguish takeoff vs. Landing emissions with UFPs properties ?

1) Selecting daytime data > 30 000 cm^{-3} and wind direction between West and North-East => aviation emission

2) Excluding landing overpass

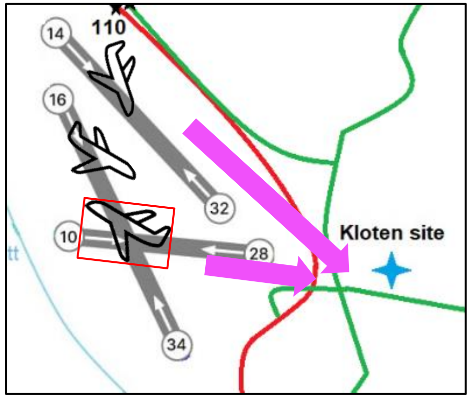


Landing overpass

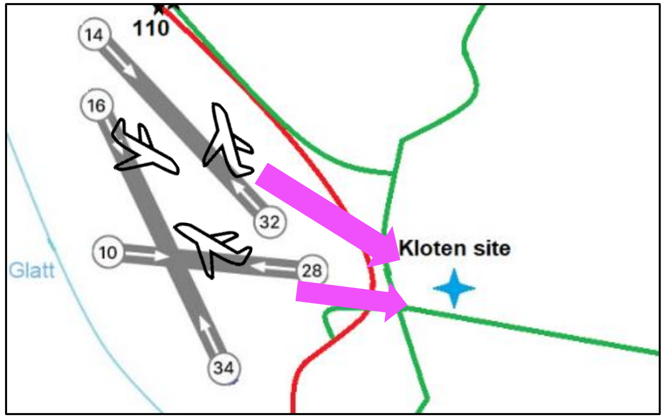


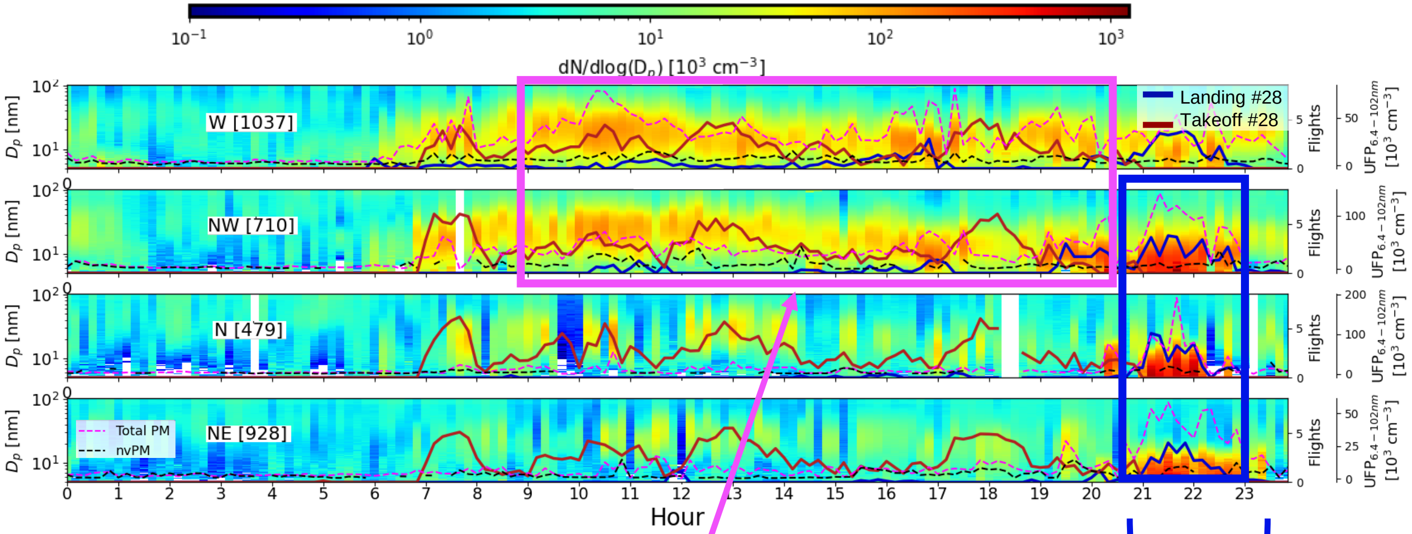
- Wide range of GMDs : 6 to 37 nm
- Neither GMD nor nvPM number fraction depend on take-off fraction (except without take-off)
- GMD and nvPM number fraction are higher than during landing overpass

➔ The vast majority of UFPs at the site originates from take-off (exception: downmixing of landing overpass).



UFPs measured at Kloten come principally from the Airport





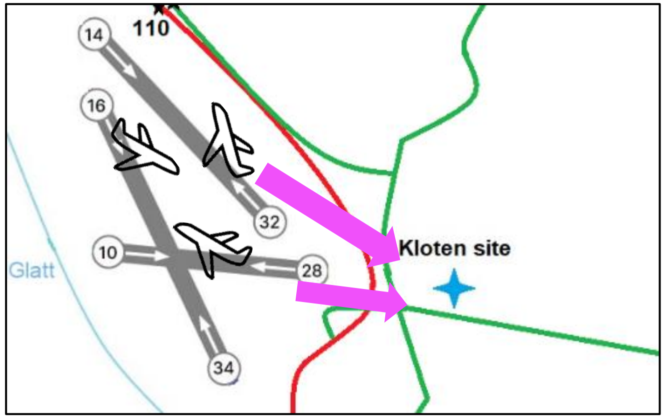
UFPs size distribution splitted by wind direction

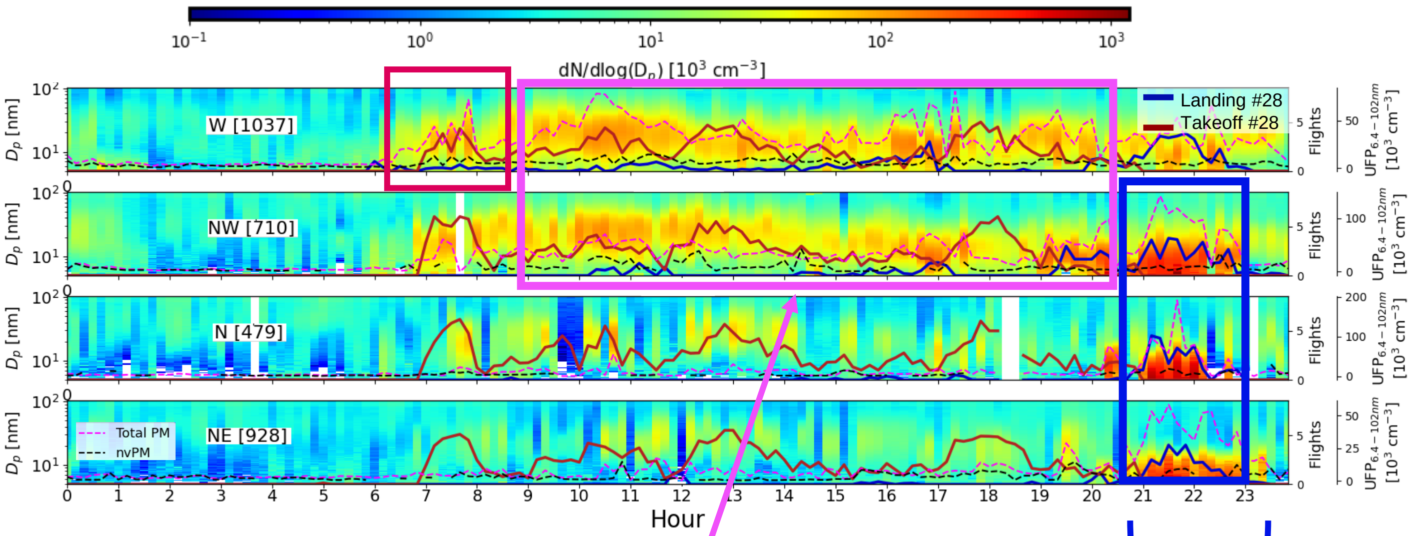
Dominant Takeoff emissions ?

Landing overpass: smallest GMD & highest number fraction of volatile particles

UFPs measured at Kloten come principally from the Airport

PSI

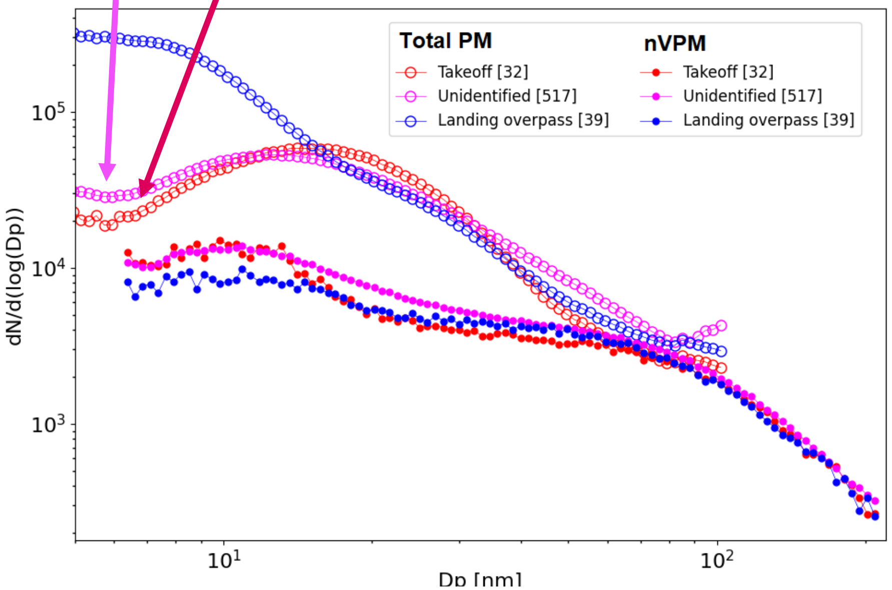




UFPs size distribution splitted by wind direction

take-off dominates: GMD and nvPM fraction dominate, but for the most part different from landing overpass

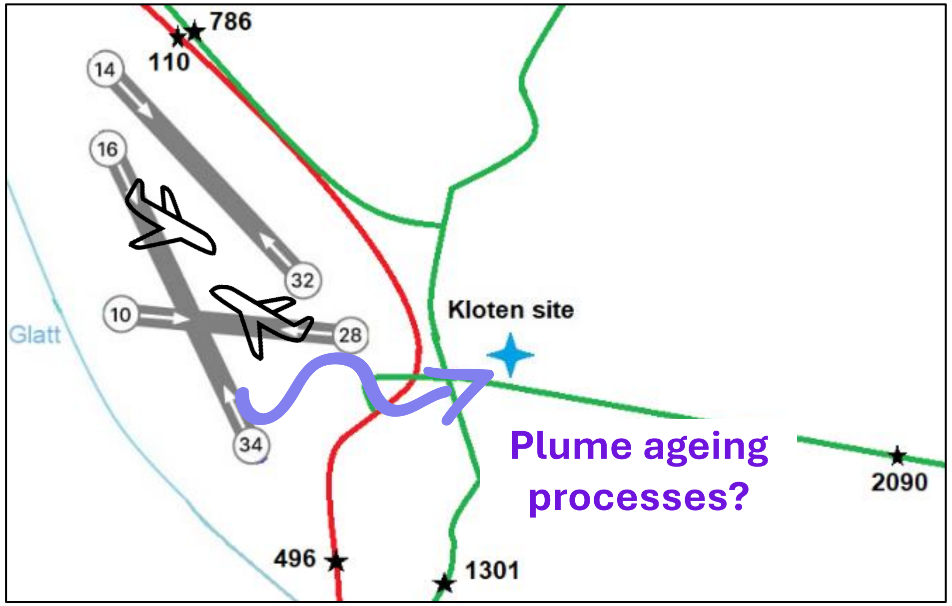
Landing overpass: smallest GMD & highest number fraction of volatile particles

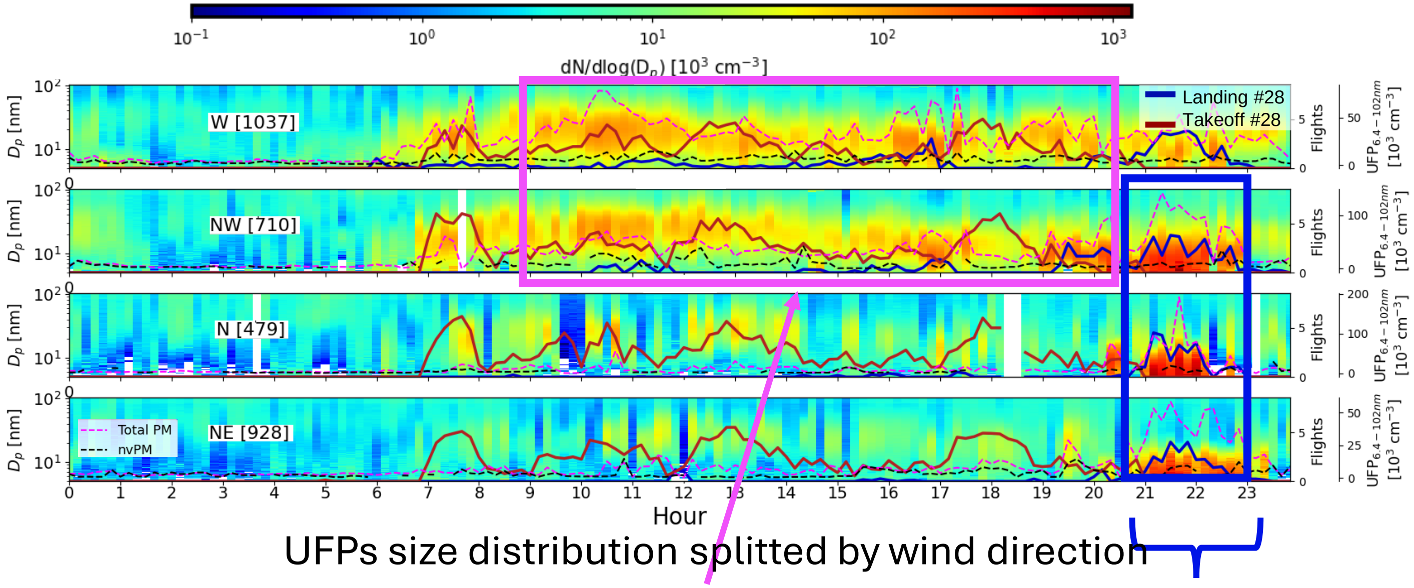


UFPs mean size distributions colored by periods and wind directions defined by the colored boxes

=> UFPs from morning Takeoffs are similar to UFPs emitted during daytime

UFPs measured at Kloten come principally from the Airport





UFPs size distribution splitted by wind direction

take-off dominates: GMD and nvPM fraction dominate, but for the most part different from landing overpass

Landing overpass: smallest GMD & highest number fraction of volatile particles

3) Can ageing processes be responsible for the wide diversity of the takeoff emissions ?

Can ageing processes be responsible for the wide diversity of the takeoff emissions ?

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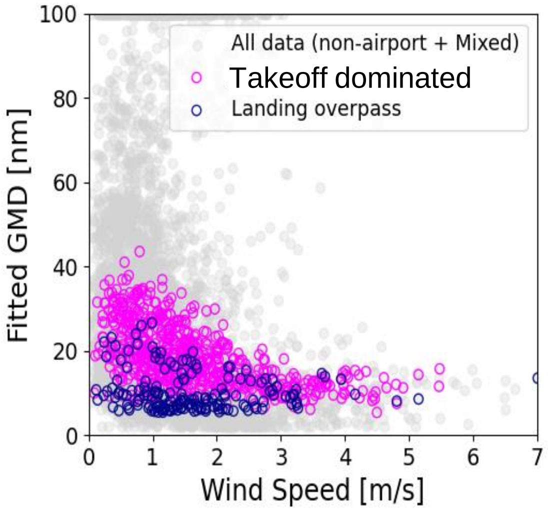
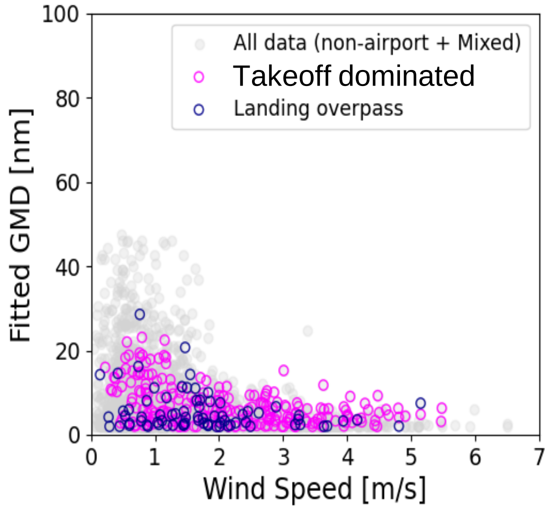
Total PM



~17 min ~2 min

Transport time
Airport-Site

nvPM



~17 min ~2 min

Transport time
Airport-Site

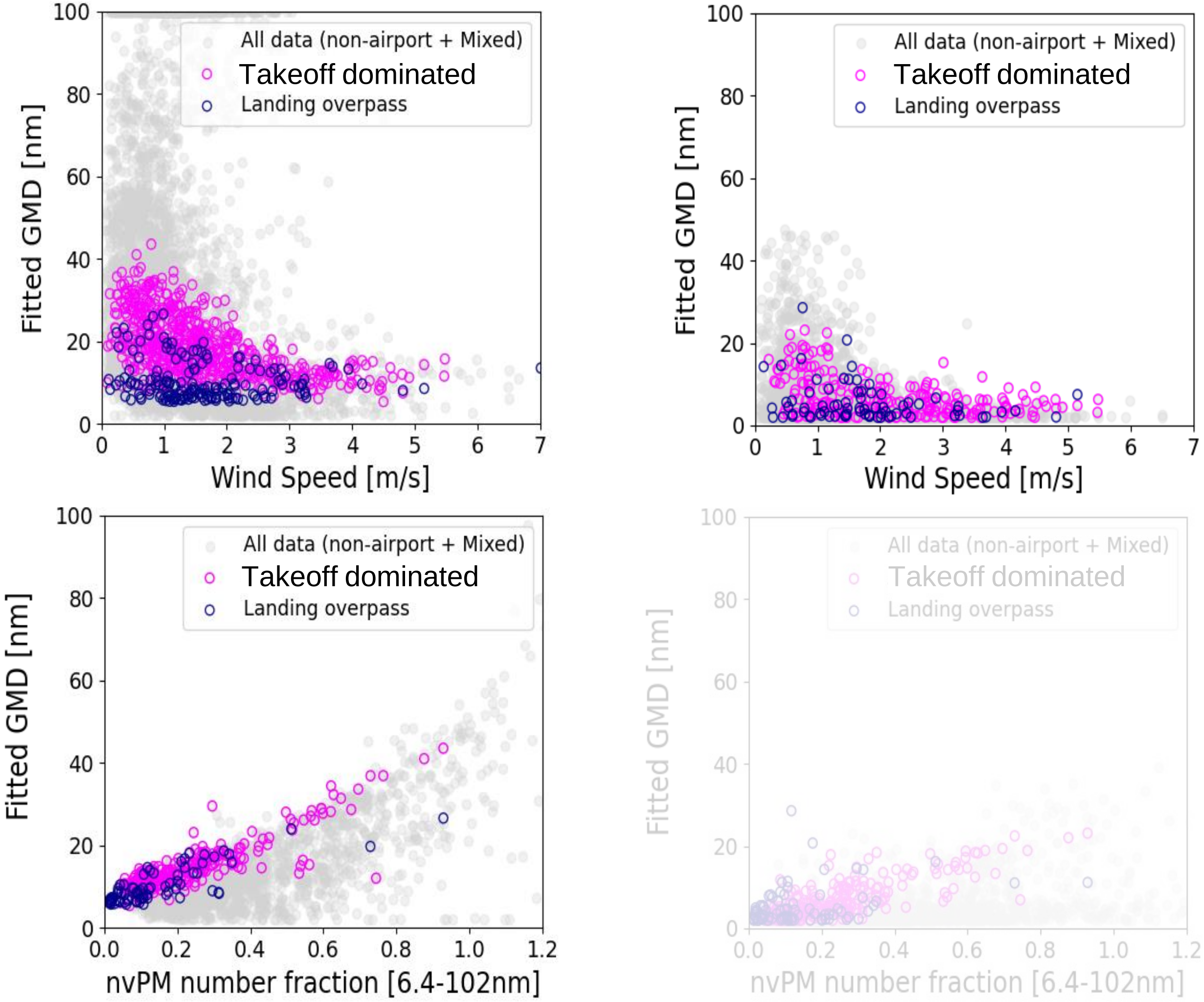
UFPs Geometric Mean Diameter vs. Wind speed

- Increase of nvPM number fraction **AND** total PM GMD with transport time
  => **Condensation and coagulation**

Can ageing processes be responsible for the wide diversity of the takeoff emissions ?

PSI

Total PM **nvPM**



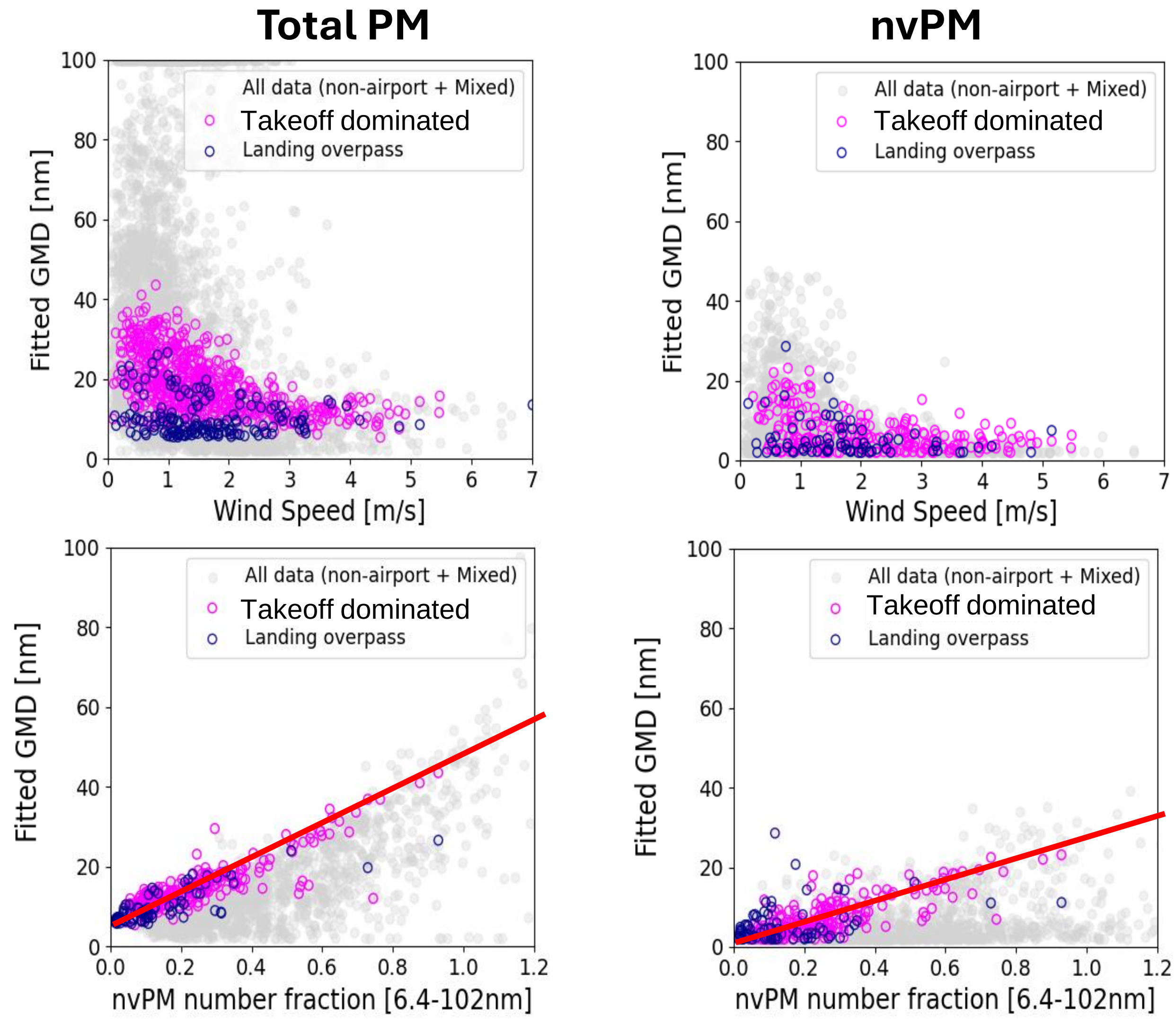
UFPs Geometric Mean Diameter vs. Wind speed and nvPM number fraction

- Increase of nvPM number fraction **AND** total PM GMD with transport time
  => **Condensation and coagulation**

- The smallest UFPs are the more volatile

Can ageing processes be responsible for the wide diversity of the takeoff emissions ?

PSI



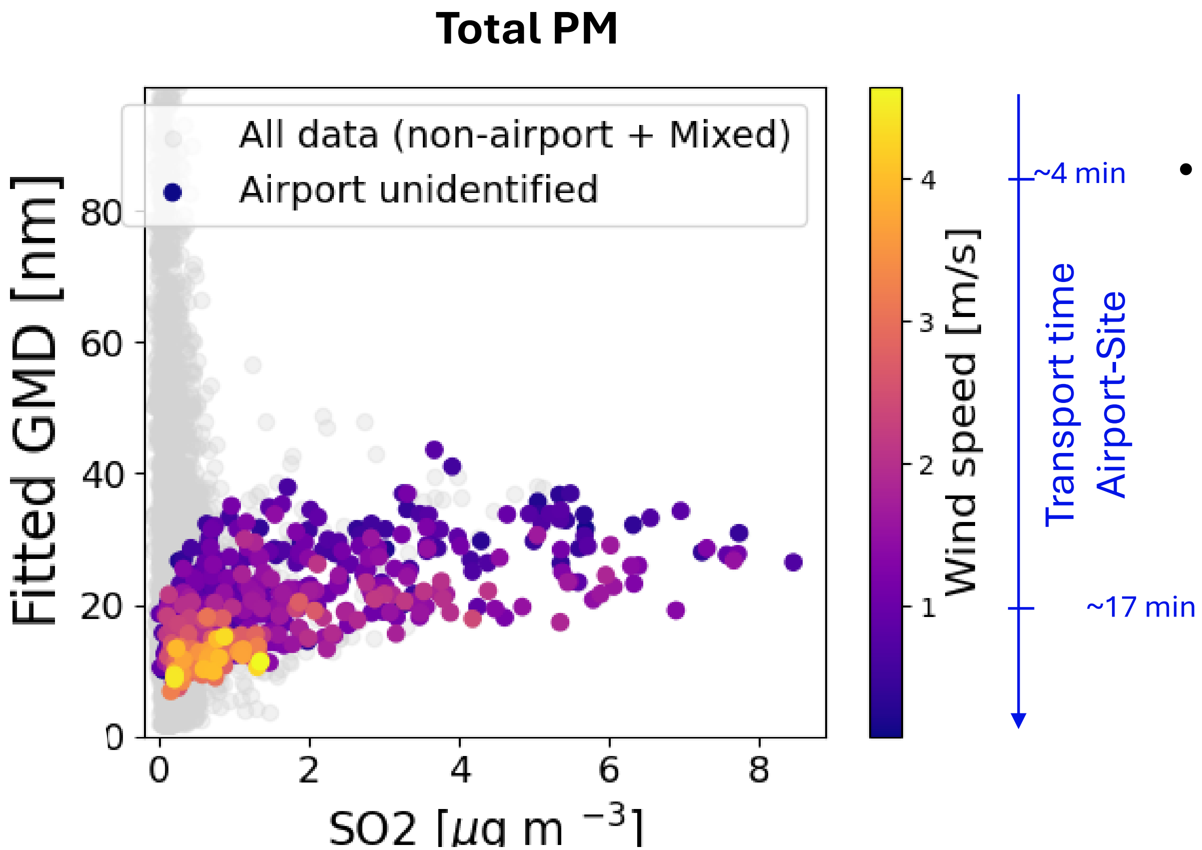
UFPs Geometric Mean Diameter vs. Wind speed and nvPM number fraction

- Increase of nvPM number fraction **AND** total PM GMD with transport time
  => **Condensation and coagulation**

- The smallest UFPs are the more volatile

- Catalytic stripper also reduces GMD when nvPM number fraction is high
  ➔ this suggests **coated nvPM particles**

Can ageing processes be responsible for the wide diversity of the takeoff emissions ?

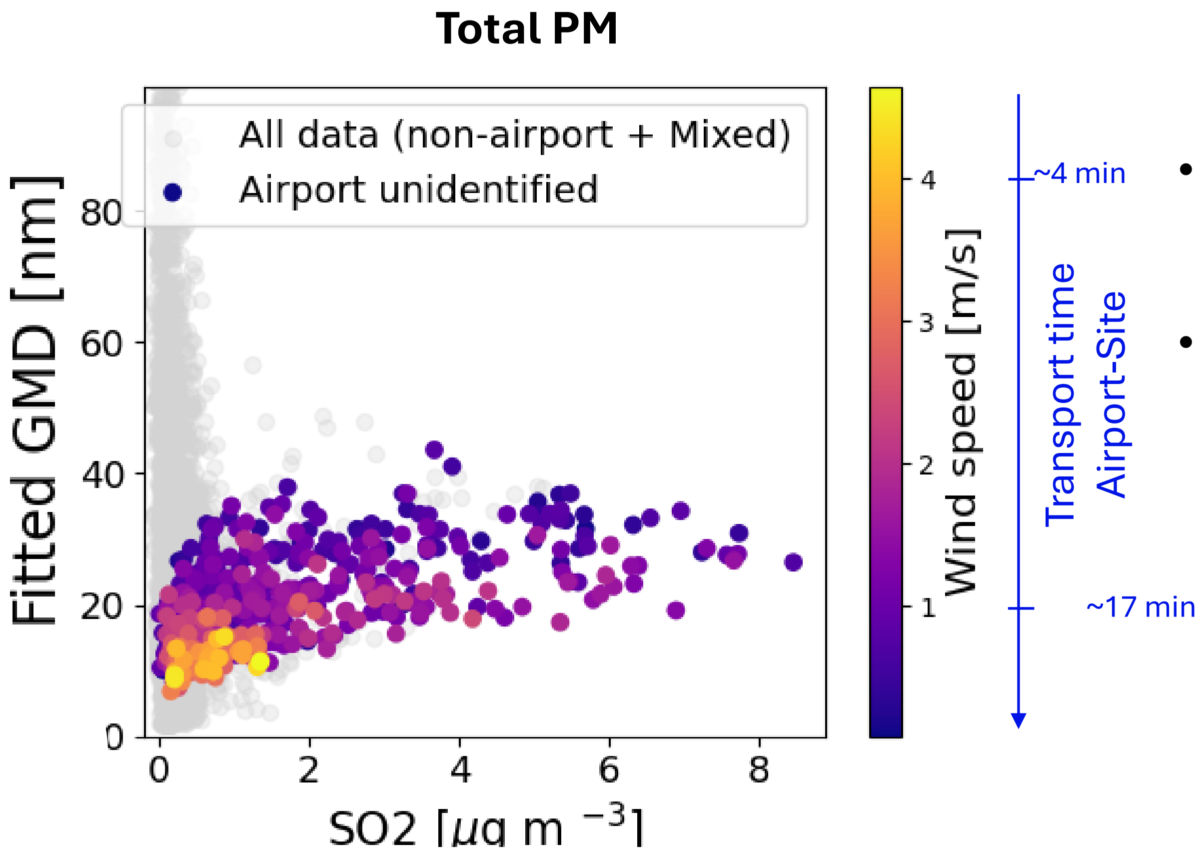


UFPs Geometric Mean Diameter vs. Sulfur dioxide and wind speed, landing overpass excluded

- SO_2 = Crude indicator of the amount of **consensable vapors emitted by aircraft** (sulfuric acid, lub oil…)

Can ageing processes be responsible for the wide diversity of the takeoff emissions ?

PSI



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

- SO_2 = Crude indicator of the amount of **consensable vapors emitted by aircraft** (sulfuric acid, lub oil...)
- GMD and SO_2 are positively related, and both are inversely related to wind speed.

➔ low wind speed = less dilution of exhaust plumes (SO_2 as an indicator) and longer transport time

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

Conclusion

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- Near the Zürich airport, UFPs properties are **dominated by airport emissions (high concentration > 30000 cm^{-3} and small diameters (17.5 nm))**
- **Takeoff emissions are largely dominant** over the landings emissions
- UFPs from landing overpass are **smaller and more volatile** than the one from takeoff
- Low **wind speed** and high **condensable vapors** concentrations favor **condensation and/or coagulation processes, leading to higher GMDs**

What's next ?

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

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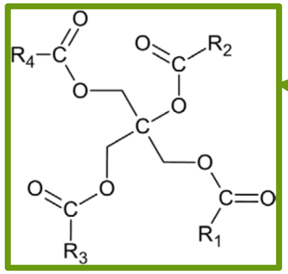
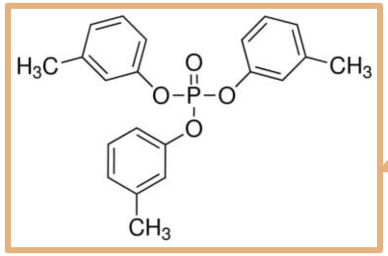
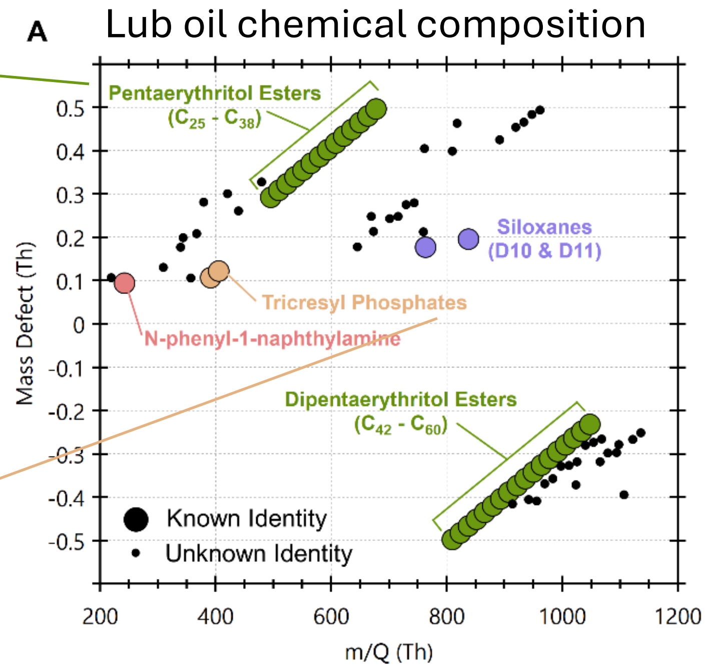
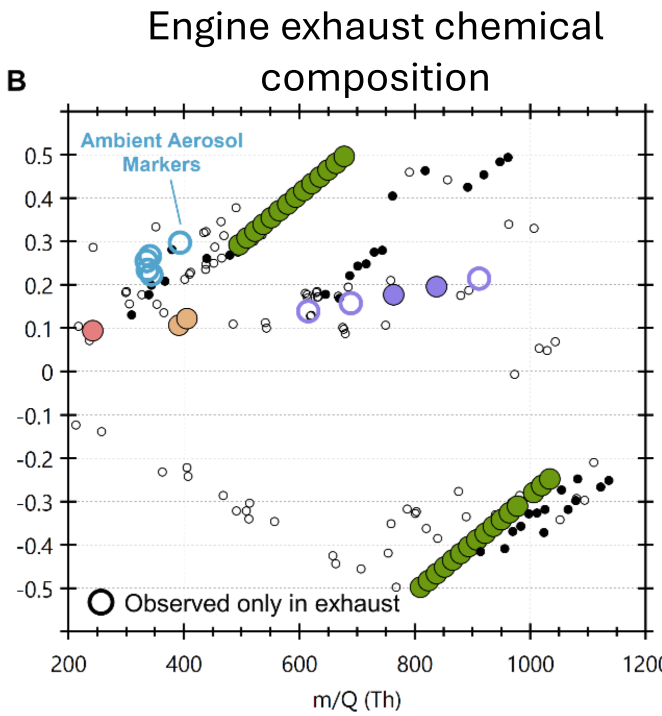








Z. C. J. Decker et al., in prep.

Can we retrieve the lub oil presence in the UFPs sampled on the field ?

➔ 2nd Field campaign (08/2024) to 1) **Confirm the current results and 2)** Obtain a **volatility resolved chemical composition of UFPs**

PSI Center for Energy and Environmental Sciences

A warm thank to all the collaborators

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

Stadt Kloten
WELTOFFEN UND BÜRGERNAH

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

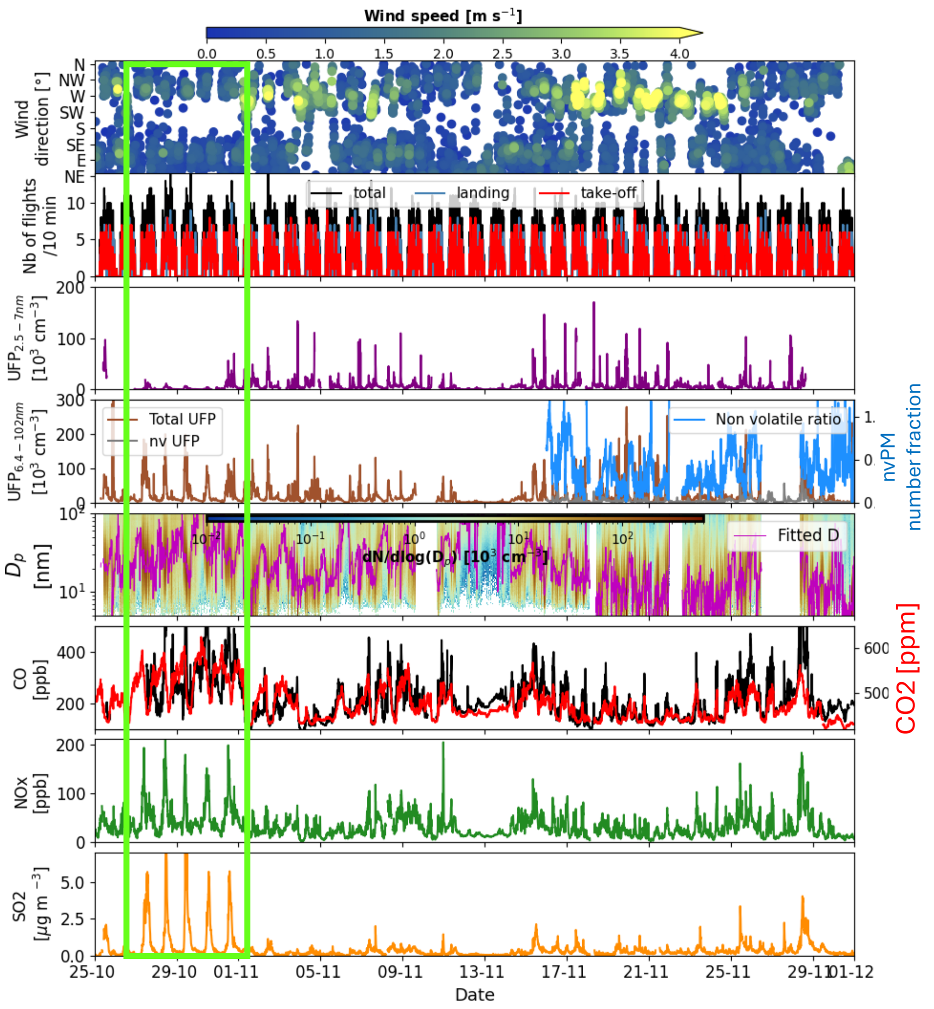
SR Technics

Swiss Federal Office of Civil Aviation (FOCA) SFLV 2020-080 Aviation Plume PROPeRtIes AT point of Exposure (APPROPRIATE) and AGEAIR 2 (SFLV 2018-048).

Deutsche Forschungsgemeinschaft (DFG; German Research Foundation) (grant no. 428312742 (TRR 301))

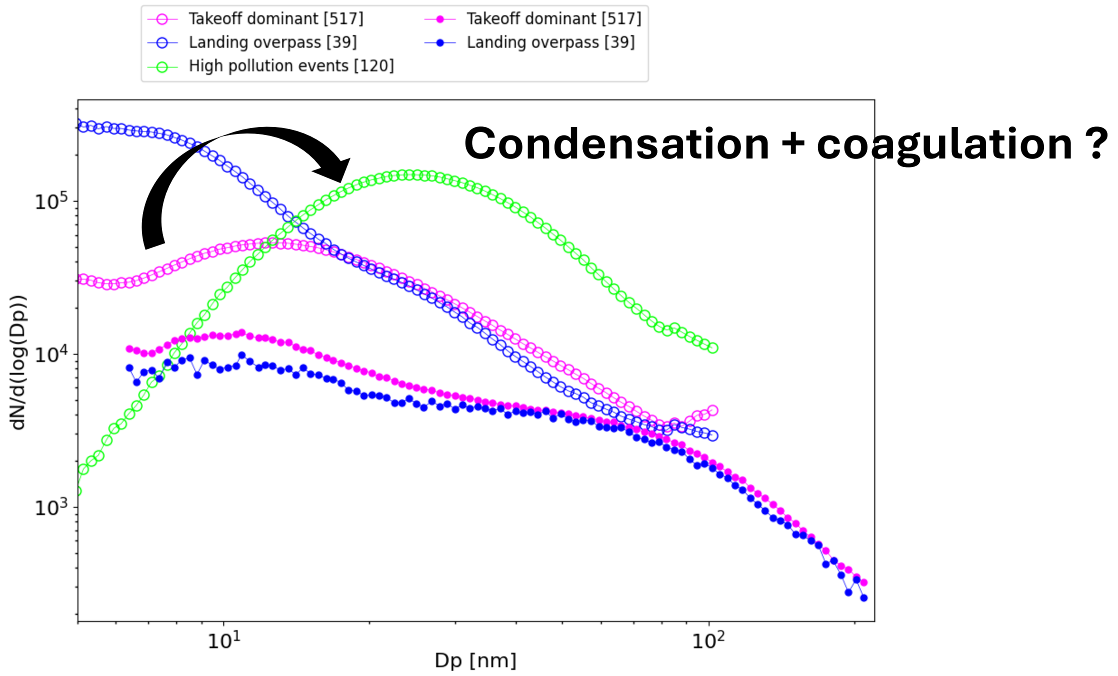
Contact: sarah.tinorua@psi.ch

A specific case of potential UFPs ageing



From October 27 to 31 :

- Very **low wind speeds** < 2 m s^{-1}
- High UFPs loading but **GMD >35 nm**
- **High SO_2,** NO_x and CO concentrations



=> Need more volatility measurements

Air quality standards on gases and PM atmospheric levels

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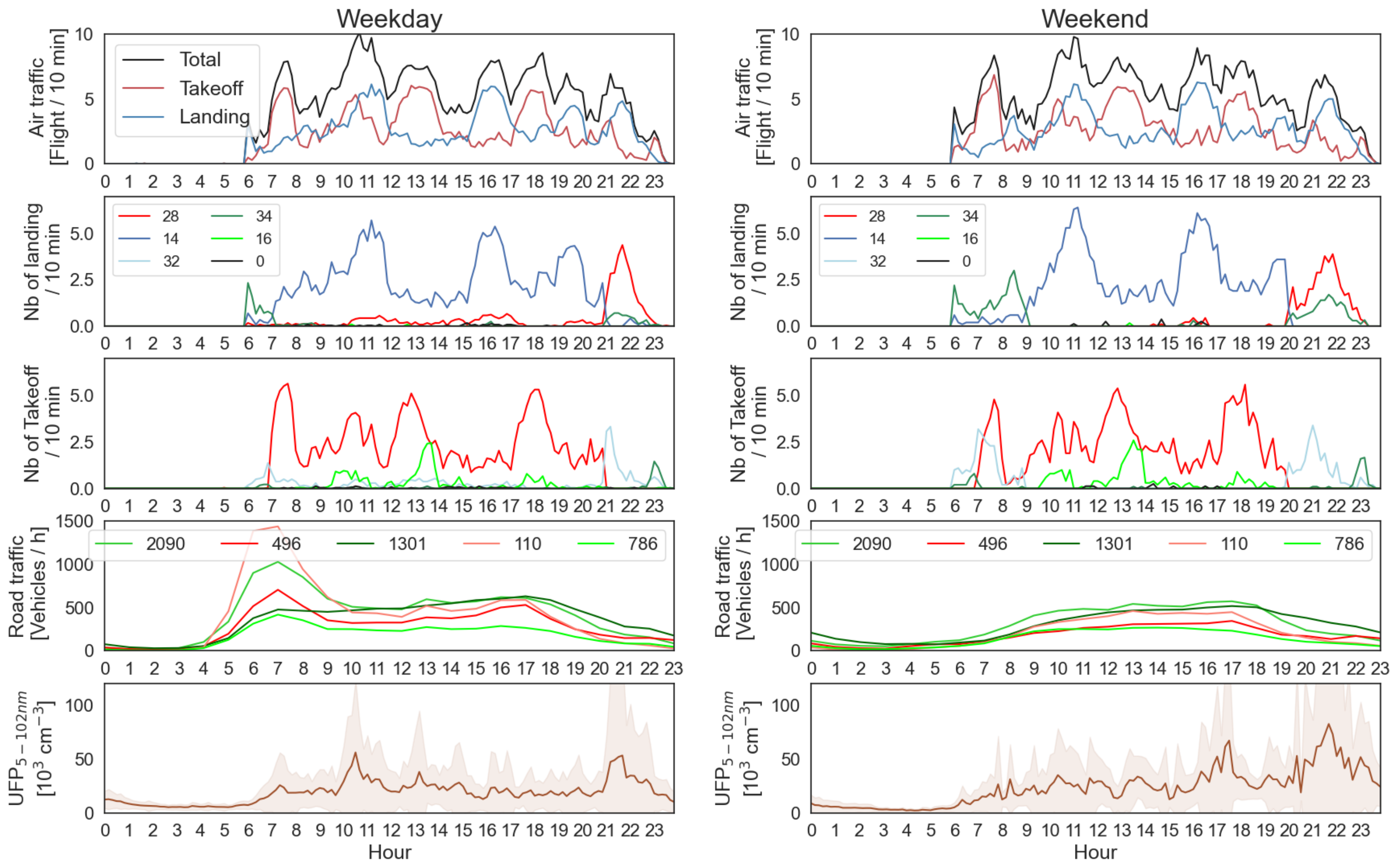
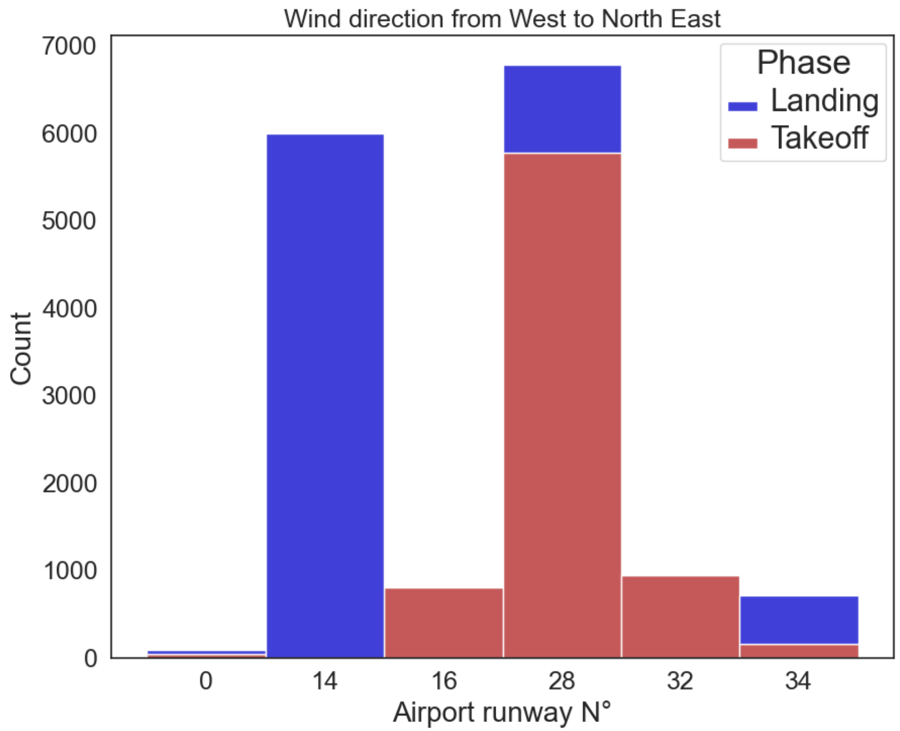
Pollutant	Concentration	Averaging period	Legal nature	Permitted exceedences each year
Fine particles ($PM_{2.5}$)	25 µg/m^3	1 year	Target value to be met as of 1.1.2010 Limit value to be met as of 1.1.2015	n/a
Fine particles ($PM_{2.5}$)	20 µg/m^3	1 year	Stage 2 limit value to be met as of 1.1.2020 ***	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





Source apportionment using the positive matrix factorization(PMF)

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Temporal size distributions matrix X

date	D1	D2	…	Df
t1	$C_{t1,D1}$	$C_{t1,D2}$	…	$C_{t1,Df}$
t2	$C_{t2,D1}$	$C_{t2,D2}$	…	$C_{t2,Df}$
…	…	…	…	…
tf	$C_{tf,D1}$	$C_{tf,D2}$	…	$C_{tf,Df}$

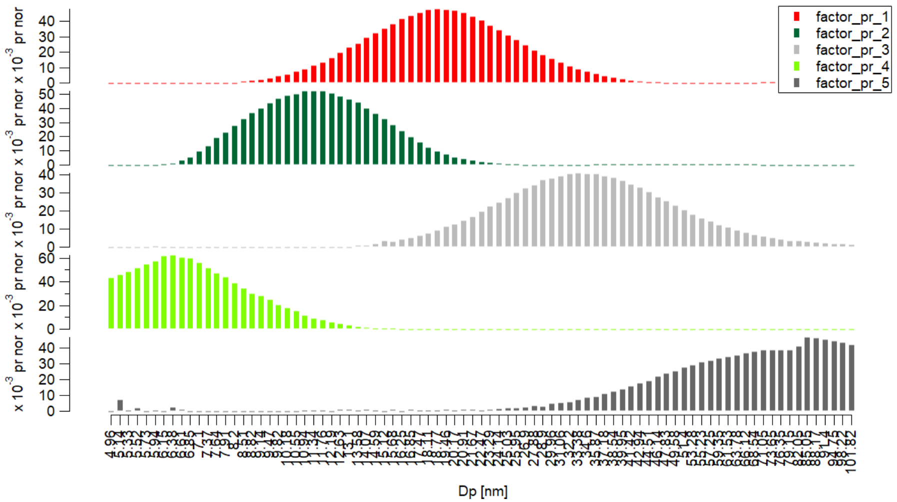
PMF[1] decomposes X into G and F, E are the residuals:

$$x_{t,D}=\sum_{s=1}^{5} g_{t,s}\, f_{s,D}+e_{t,D}$$

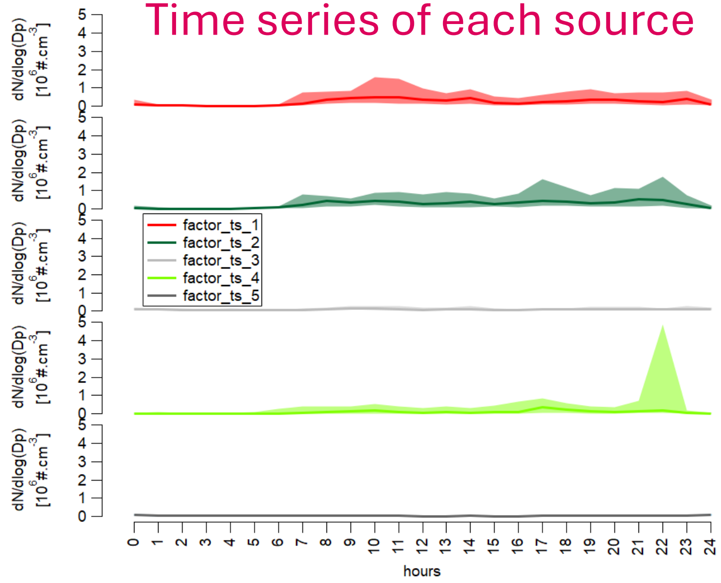
Source profiles

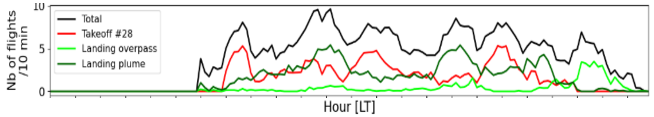
Source contributions

Source profile = Size distribution of each source



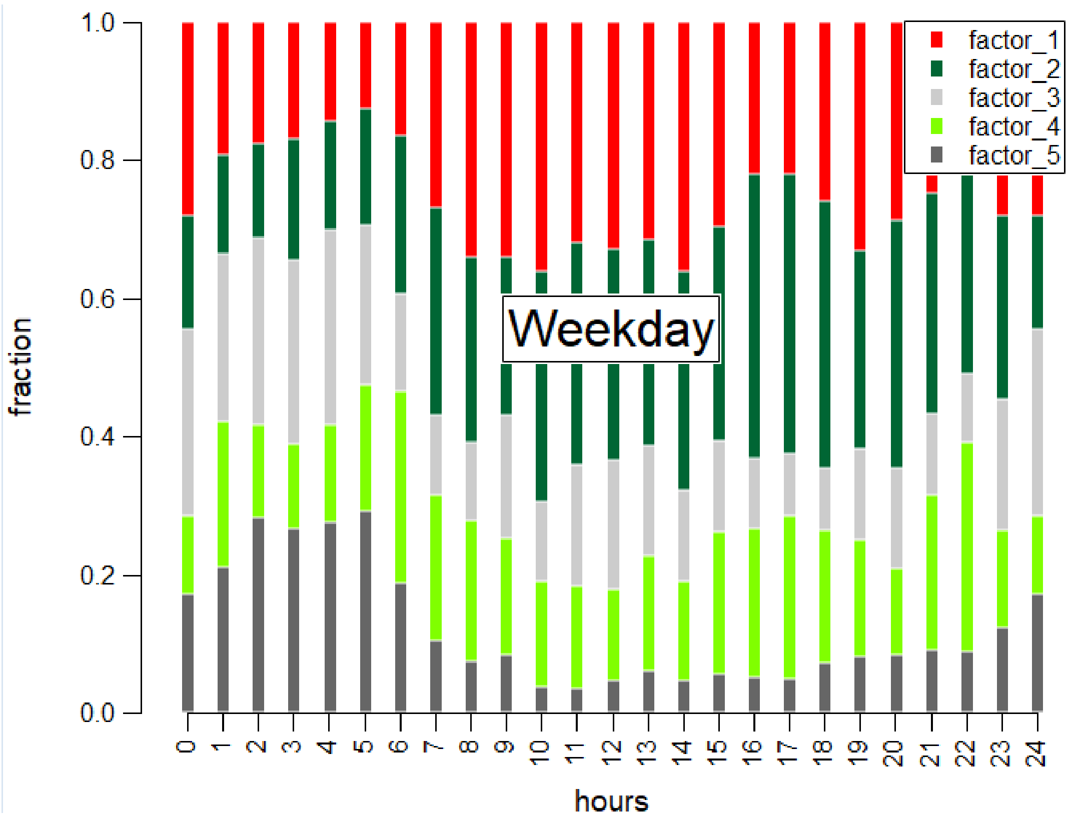
Time series of each source

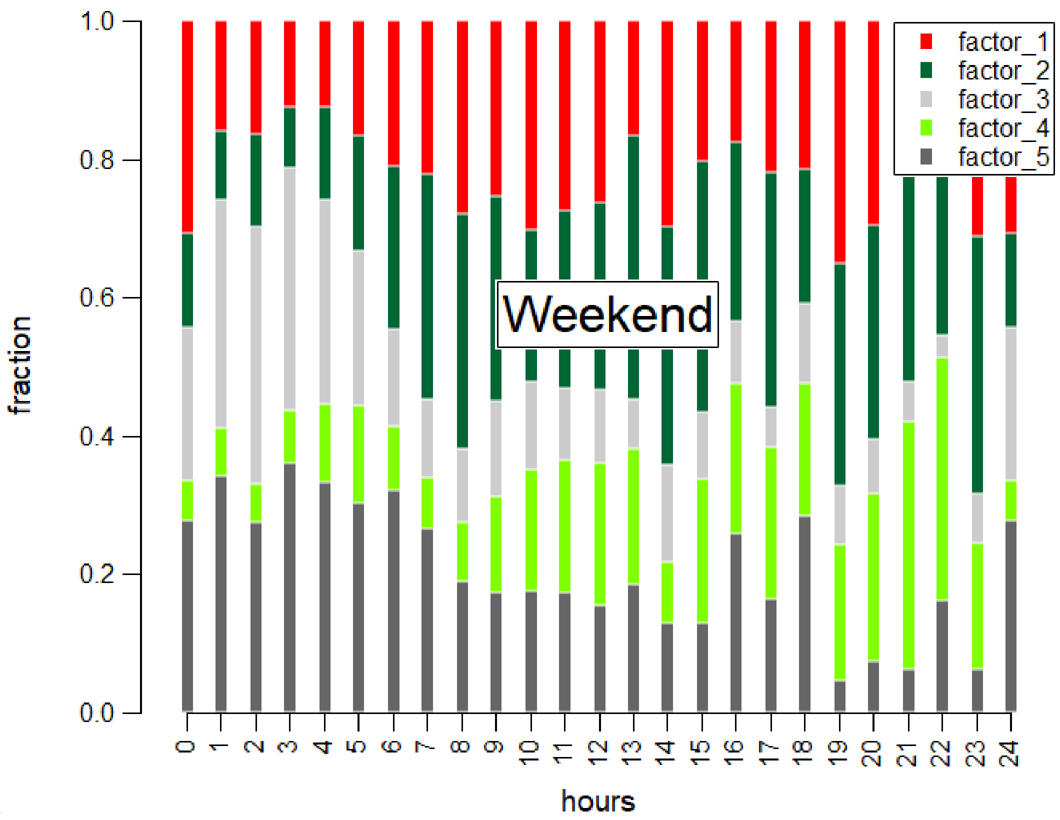




[1]Paatero, P. and Tapper, U., Environmetrics, 5, 111–126, 199

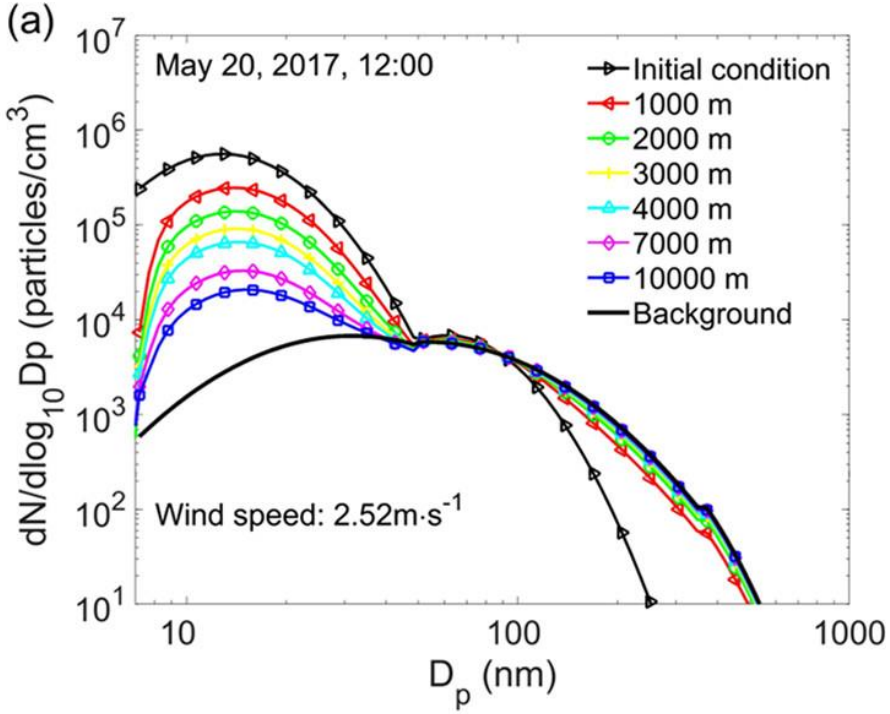
Daily cycle of factor's contribution calculated with PMF



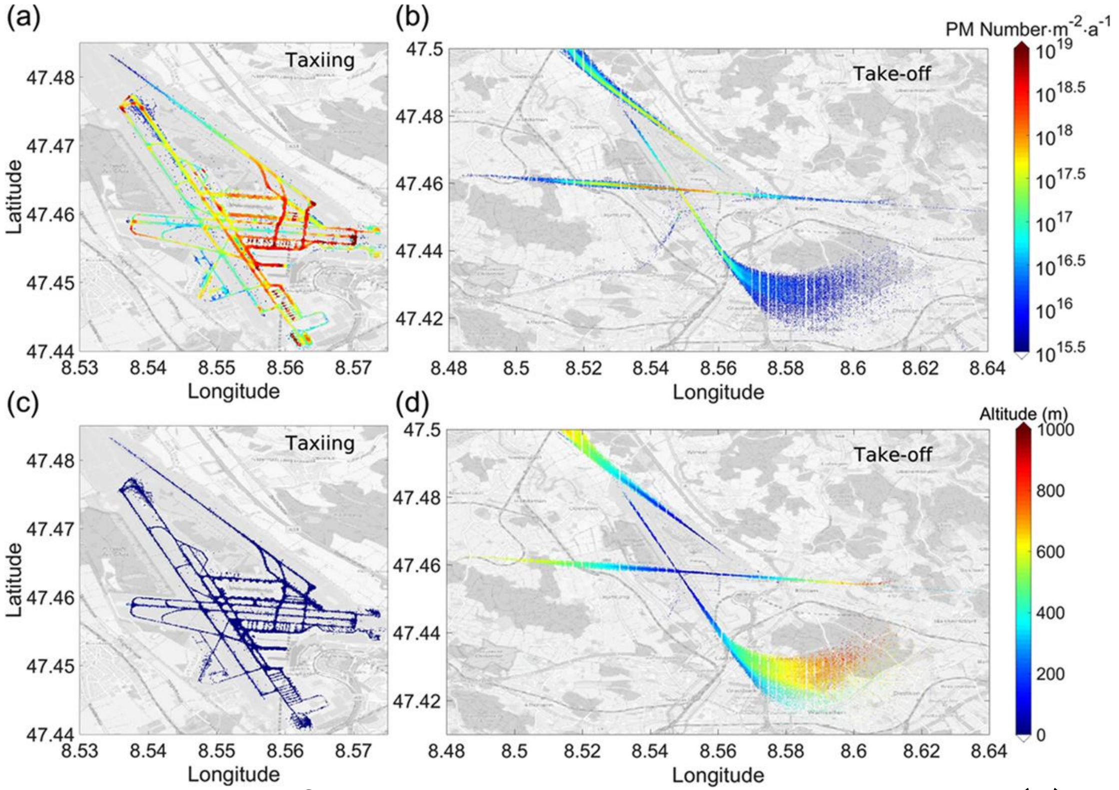


Plurimodal size distribution of UFPs emitted by aviation and spatial distribution along the runways

PSI



Evolution of the particle size distributions from 1 to 10 km for a typical plume at 12:00 on May 20, 2017.

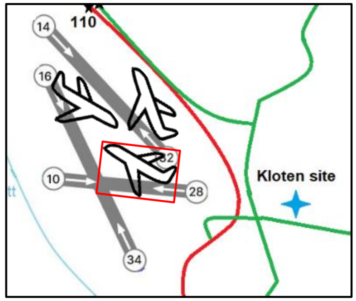


Spatial distributions of the particle number emission during (a) taxi and (b) takeoff phases at Zurich Airport and the corresponding altitudes of (c) taxi emission and (d) takeoff emission.

Zhang, X.; Karl, M.; Zhang, L.; Wang, J. Influence of Aviation Emission on the Particle Number Concentration near Zurich Airport. *Environ. Sci. Technol.* **2020**, *54* (22), 14161–14171. https://doi.org/10.1021/acs.est.0c02249.

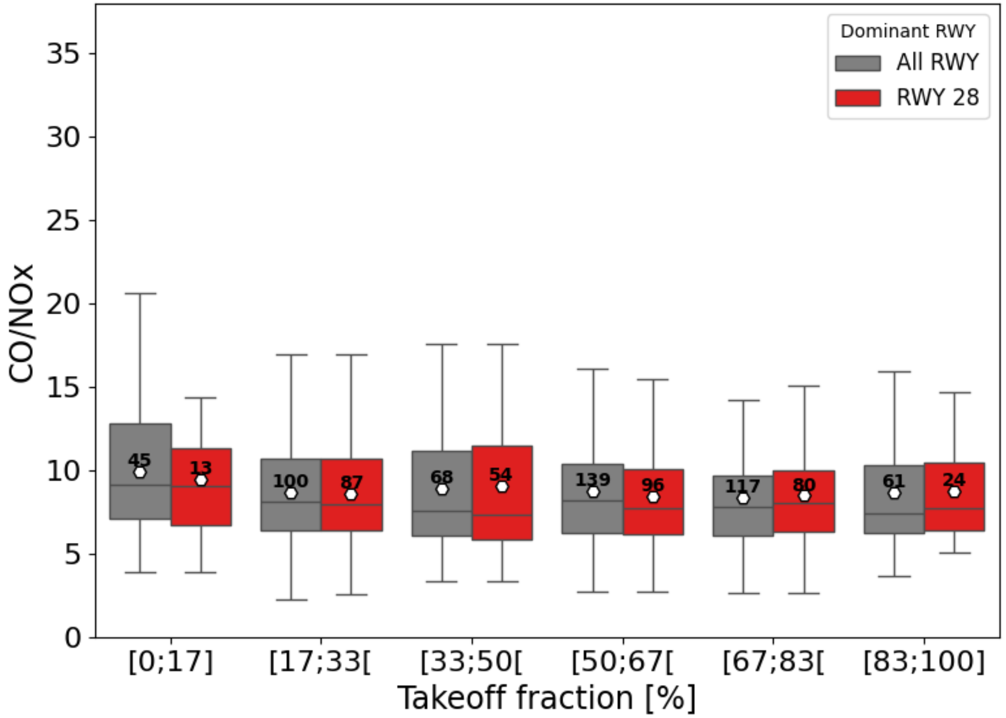
Can we distinguish takeoff vs. Landing emissions with UFPs/gases properties ? CO/NOx criteria

PSI



When **Thrust** ↗ : - combustion efficiency ↗ => **CO emissions** ↘
- combustion temperature ↗ => **NOx emissions** ↗[1]

CO/Nox = f (thrust)



CO/NOx ratio as a function of the takeoff fraction on airport emissions, excluding landing overpass

Both CO and NOx have other sources resulting in variable contributions

➔ we cannot properly determine ΔCO/ΔNOx associated with aviation emissions
➔ no reliable distinction between landing vs takeoff being dominant.

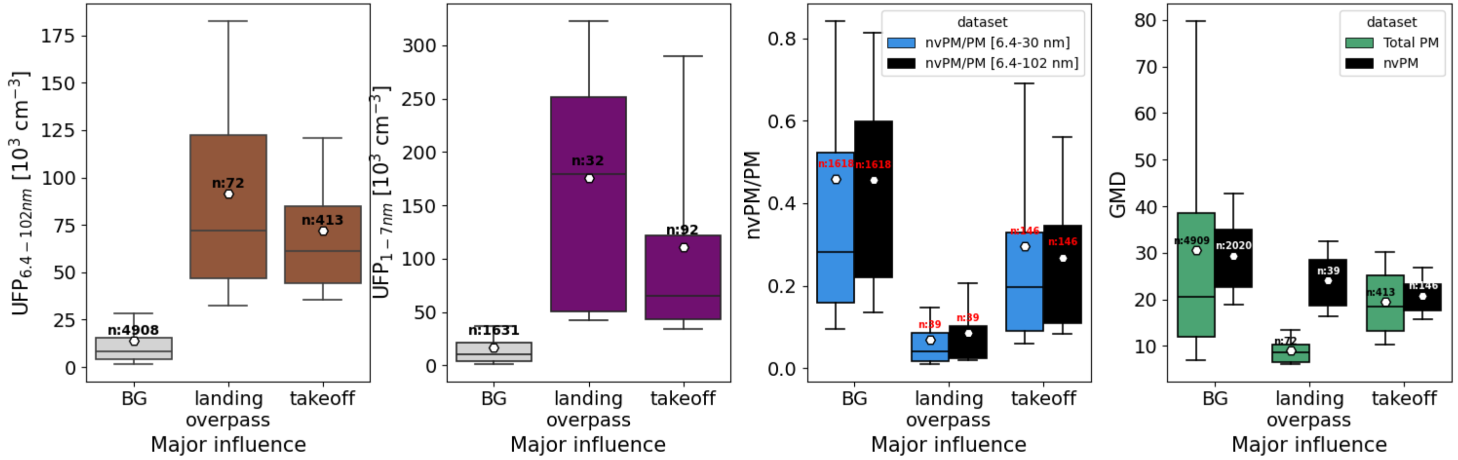
Use the other gases from engine combustion to separate takeoff and landings ?

[1]Timko, M. T. et al. *J. Eng. Gas Turbines Power* **2010**, *132* (061504).

UFPs characteristics of aircraft emissions are depending on the dominant thrust engine

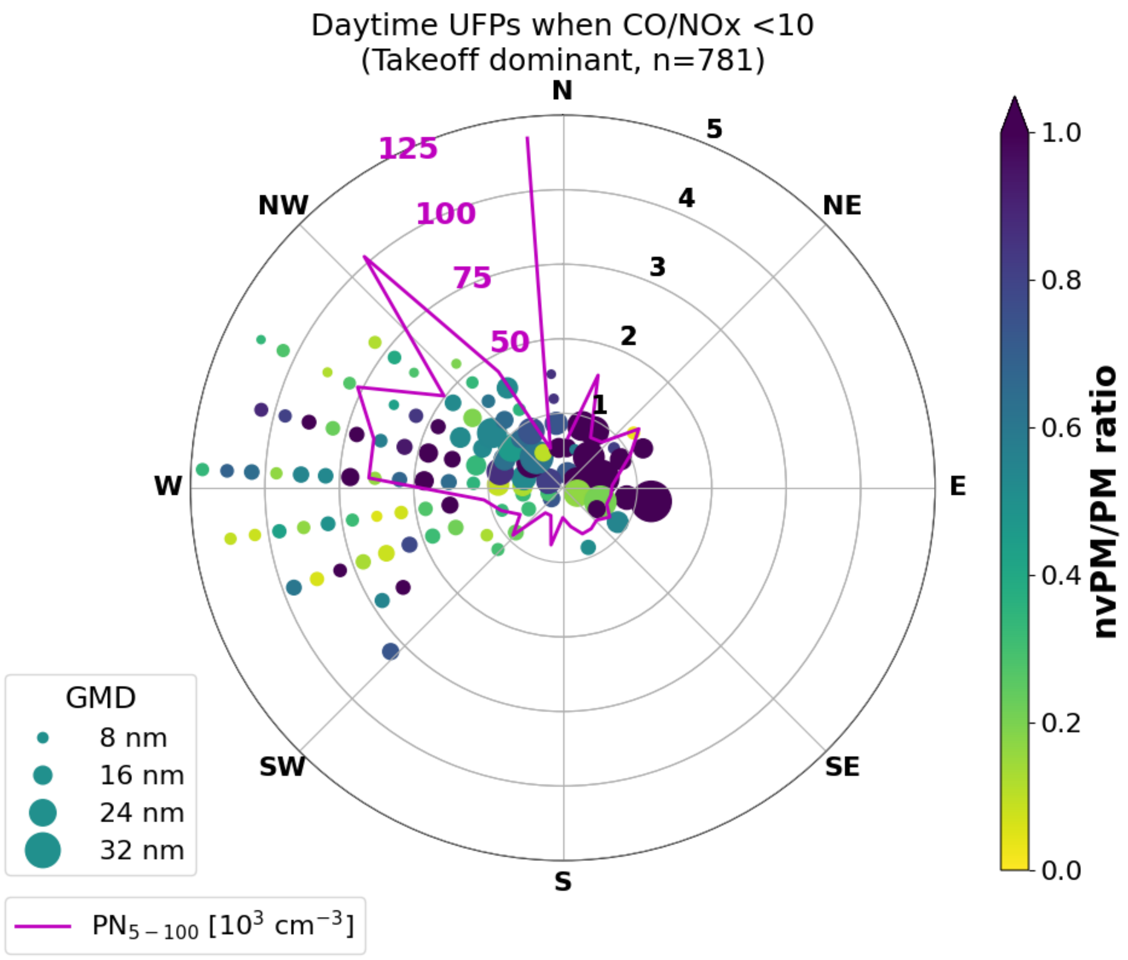
1) Selecting daytime data > 30 000 cm^{-3} and wind direction between West and North-East => aviation emission

2) Look at the UFPs measured properties depending on the landing/takeoff predominance



• Aircraft emissions characterized by a high concentration of very small UFPs > 50 .10^3 cm^{-3} and 5 < GMD < 30 n

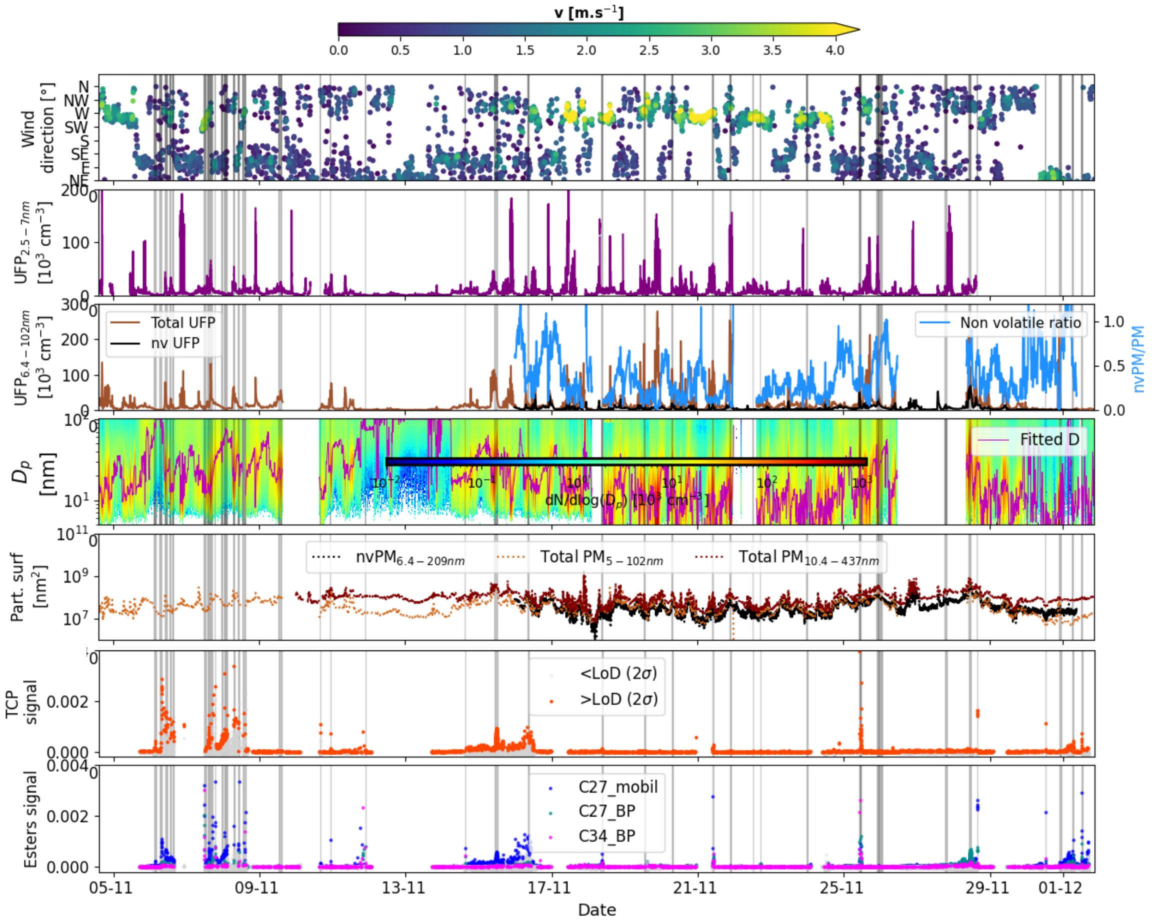
An other representation of UFPs from takeoff suggests condensation growth of nvPM



Polarplot of UFPs concentration, diameter and volatility during takeoff-influenced periods

- Increase of D when transport time is longer
- Increase of UFPs volatility along one wind direction

Preliminary results : Using the EESI measurements to find a unique signature of aviation emission



- Tricresyl Phosphate TCP are part of lubrication oils as antiwear additives.
- They have been measured by the EESI
- TCP peaks are present in 13% of the aviation emission events detected by UFPs concentration and wind direction.

=> Other aviation and road- specific components still need to be related to aviation events

Increasing attention to Ultrafine Particles (UFPs) from aviation

National Institute for Public Health and the Environment
Ministry of Health, Welfare and Sport

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Ultrafine particles in the vicinity of Schiphol Airport affect health

Publication date 27-06-2019 | 15:30

ELSEVIER
Environment International
Volume 141, August 2020, 105779

Effects of short-term exposures to ultrafine particles near an airport in healthy subjects

A. Lammers [a], N.A.H. Janssen [b], A.J.F. Boere [b], M. Berger [a], C. Longo [a], S.J.H. Vijverberg [a], A.H. Neerincx [a], A.H. Maitland - van der Zee [a], F.R. Cassee [b c]

Open Access Article

Environmental Exposure to Ultrafine Particles inside and nearby a Military Airport

by Marcello Campagna [1,*], Andrea Frattolillo [2], Sergio Pili [1], Gabriele Marcias [1], Natalia Angius [1], Costantino Carlo Mastino [2], Pierluigi Cocco [1] and Giorgio Buonanno [3,4]

[1] Department of Medical Sciences and Public Health, University of Cagliari, SS 554 bivio per Sestu km 4.500, Monserrato 09042, Cagliari, Italy
[2] Department of Civil and Environmental Engineering and Architecture, University of Cagliari, SS 554 bivio per Sestu km 4.500, Monserrato 09042, Cagliari, Italy
Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, Cassino 03043, Italy
Queensland University of Technology, Brisbane 4001, Australia
Author to whom correspondence should be addressed.

osphere **2016**, *7*(10), 138; https://doi.org/10.3390/atmos7100138

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Review | Open access | Published: 06 February 2021

A review of health effects associated with exposure to jet engine emissions in and around airports

Katja M. Bendtsen, Elizabeth Bengtsen, Anne T. Saber & Ulla Vogel

Environmental Health **20**, Article number: 10 (2021) | Cite this article

Pollutionwatch: fine particles affect lungs of those near airports

Trial finds reduced lung function and heart changes in young people who exercised near Schiphol

Extinction Rebellion activists protesting against climate pollution at Schiphol airport in the Netherlands. Photograph: Nacho Calonge/Getty