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COMBINATION OF COUNTS AND MODELLING FOR ESTIMATING AIRCRAFT ULTRAFINE PARTICLE EMISSIONS AT TREVISO AIRPORT

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Abstract: As part of the Environmental Monitoring Plan at Treviso Airport (Italy), an experimental study has been carried out to investigate the relationship between flight activity and local ultrafine particles (UFPs) concentrations. This is crucial, given the significant health risks associated with UFPs, with an aerodynamic diameter smaller than 1 µm. Two monitoring stations were installed for continuous UFPs and meteorological data collection over a 6-month period, with Station A located 150 meters from the runway and Station B about 1500 meters away. Concentration data measured near the runway (at 5 minutes frequency) showed distinct peaks in UFPs concentrations following aircraft landings or takeoffs. Consequently, the objective was to estimate the UFPs emission from aircraft, assuming they are the primary sources infuencing concentrations at station A. The method involved selecting real events and reproducing peak occurrences generated by the movement of individual aircraft on the runway through detailed dispersion modeling simulations. This approach used a 3D Lagrangian particle model running at 1-minute time resolution, and addressed aircraft emissions with a normalized UFPs emission factor, represeanting a first attempt to set a raw emission value. The ratio of modeled to measured peak concentrations then allowed to derive the specific UFPs emission factor for the aircraft under study. Emissions were characterized using flight registry data, which includes precise timestamps for landings and takeoffs accurate to the minute, along with 3D radar tracks used to reconstruct flight paths. The emission factor calculated using this approach (~10^{16} particles/second) aligns with reported literature ranges. A single emission factor was derived for both takeoffs and landings due to negligible observed differences. Further validation of this result involved a Lagrangian dispersion simulation to assess the impact of UFPs emissions from the entire air traffic over a broader domain for a three-month period. The analysis confirmed the good agreement between calculated and measured UFPs concentrations at station A and a minor contribution of airport activities to ambient UFPs concentrations at station B, where contribution from other activities (heating, road traffic...) may arise.

Key words: *UFPs, aircraft, Lagrangian particle model, PM1, SPRAY****.***

INTRODUCTION

The Environmental Monitoring Project at the "Antonio Canova" Airport in Treviso (Italy) aims to plan and optimize strategies until 2030 to address specific environmental issues related to the air quality. The Regional Agency for Environmental Protection (ARPAV) requested a specialized monitoring of ultrafine particles (UFPs) emitted due to aircraft operations, taking into account that particles in this size range are not regulated by the current legislation. Indeed, the relevance of UFPs is significant due to the health hazards associated with potential deposition on lung alveoli and subsequent transportation into the bloodstream to organs external to the respiratory system (Gongbo et al., 2017). The airport operator thus started a measurement campaign with two monitoring stations, one located 150 meters from the runway (station A) and the other in Quinto di Treviso (station B), about 1500 meters away. The location of the monitoring stations is shown in Figure 1.

Figure 1. Aerial view of Treviso Airport and location of the two UFPs monitoring stations indicated by yellow markers.

The measurement instruments installed for monitoring UFPs included Universal Scanning Mobility Particle Sizers (Palas U-SMPS), which classify particles based on their electrical mobility, thereby providing detailed size distribution data. Condensation Particle Counters (CPCs) were used for measuring particle size class concentrations, enabling the quantification of particle number per unit volume. Concentration data were provided at a frequency of 5 minutes, covering 77 particle size classes ranging from 4 nm to 1 µm. The monitoring stations were also equipped with meteorological sensors, providing data (wind speed and direction, temperature, atmospheric pressure, relative humidity, precipitation and solar radiation) with a frequency of 1 minute. The data used in this study are those measured starting from October 22nd, 2022, for a period of approximately 6 months.

Concentration measurements of UFPs from station A, located near the runway, exhibited distinc peaks following aircraft takeoffs or landings. These events, characterized by a peak concentration significantly higher than the preceding and subsequent background levels, typically lasted for no more than 20 minutes. Subsequently, a methodology was developed to estimate the emission factor of UFPs smaller than 1 µm from aircraft. This methodology relied on dispersion simulations of specific episodes, defined by the passage of individual aircraft over the runway during either landing or takeoff. The simulations aimed to replicate the concentration peaks observed in the measurements.

Simulations of specific episodes were conducted using the Lagrangian particle dispersion model SPRAY (Tinarelli, 2019). This model accurately represents the dispersion of pollutants in the atmosphere by employing computational particles that collectively form plumes emitted from a source. These particles follow the atmospheric motion, providing a detailed understanding of pollutant dispersion dynamics. Even if simplified conditions of horizontal homogeneity were assumed, SPRAY enables to consider emissions tracking the aircraft motion both horizontally and vertically at a high frequency (1s). Additionally, it incorporates vertical profiles to describe mean wind and turbulence.

GENERAL METHODOLOGY AND EPISODE SELECTION

Several episodic simulations were performed using the Lagrangian particle model SPRAY to replicate UFPs peak concentrations at station A, caused by the passage of individual aircraft over the runway during either takeoff or landing. This approach therefore assumed that the concentrations measured at station A were influenced only by the contribution of aircraft. The study specifically addressed the total measured concentrations of particles ranging from 4 nm to 1 µm.

The episodes to be simulated were specifically selected ensuring that station A was situated downwind of the runway and excluding instances of calm wind conditions, based on the meteorological data provided by the station itself. A normalized constant emission flux of 10^9 particles/second was attributed to the aircraft to address the lack of prior knowledge regarding the emission factor.

For each simulation, the ratio between the peak concentration simulated at station A and that measured at the station following the passage of the aircraft was calculated. The average ratio derived through a significant number of episodes allowed for the estimation of the coefficient to be applied to the normalized emissive flux, thus providing the actual flux that would generate the measured concentrations of UFPs smaller than 1 µm. It is specified that the analysis was conducted by distinguishing between landings and takeoffs, under the assumption that the engines are stressed differently in the two situations, leading to different emission fluxes in turn.

SPECIFIC MODEL SETUP

Domain

The computational domain used for simulating the selected episodes was defined by selecting an area spanning 3.6 x 1.9 km^2 with a horizontal resolution of 25 meters, centered on the runway. Since the objective was to simulate peak concentrations near the runway, it was unnecessary to provide a detailed description of soil characteristics to account for inhomogeneities elsewhere. Therefore, simulations were conducted assuming flat terrain and uniform land use, characterized by grass with surface roughness of 0.03 m.

Meteorological data

For each event to be simulated, meteorological data (wind speed and direction, temperature, and solar radiation) measured near the runway at station A with a 1-minute frequency were used to drive the dispersion simulations. These data served as the meteorological input, assumed uniform across the domain. From wind speed and solar radiation measurements, Pasquill stability classes were calculated. Hence, from a meteorological point of view, a rather heterogeneous selection of episodes was made. In other words, landings and takeoffs at different times of the day were considered, thus in both stable and unstable or neutral cases.
Based on the meteorological data measured at station A, vertical stability-dependent wind speed profiles were then calculated. Equation (1) defines the wind speed U(z) at altitude z:

$$U(z) = U_0 \left(\frac{z}{z_0}\right)^{\alpha} \quad (1)$$

- U_0 is the wind speed measured at elevation z_0 of 10 m;
- α defines the variation of wind speed with altitude as a function of stability class and soil type.

The wind direction, instead, does not vary with altitude.
Scale variables for turbulence characterization, including friction velocity (u*), Planetary Boundary Layer height (H_{mix}), Monin-Obukhov length (L), and convective velocity scale (w*), were also estimated based on the meteorological data and soil type.

Emissions

In the selected episodes, precise timestamps for both landings and takeoffs accurate to the minute were available, based on the flight records provided by the operator of Treviso's "Antonio Canova" Airport.
Data from radar tracking was utilized to design distance-velocity and distance-altitude profiles for each aircraft, taking into account the specific direction of each operation. The trajectories were discretized within the Lagrangian particle model into segments of variable lengths, aligning with the speed of the aircraft. This ensured that each segment corresponded to a 1-second duration emission. The sum of these segments covered the entire trajectory of the plane in both time and space without discontinuity, providing a reasonable representation of the rapid dynamics of the phenomenon, where the position changes every second.
Not knowing a priori the emission factor of UFPs smaller than 1 µm from aircraft, whose determination is the objective of this study, a normalized emission flux of 10^9 particles along each 1-second segment of the trajectories was used, for both takeoffs and landings, assuming that all aircraft have the same emission. On average, it takes approximately 33 seconds for an aircraft to decelerate along the runway during the landing phase, starting from the moment the wheels make contact with the ground. Conversely, during the takeoff phase, the aircraft requires approximately 46 seconds of acceleration to attain the necessary speed before lifting off from the runway.

Radar tracks were also used to determine the precise takeoff direction, which can be either towards or away from the city of Treviso, while landings at Treviso airport consistently follow a predetermined route directed towards Treviso.

Simulation setup

Ground level concentration fields of UFPs, expressed in particles/m^3, were calculated and averaged over five-minute intervals to align with the measurement standards. As an example, Figure 2 illustrates the ground level concentration fields of UFPs during a landing episode, represented as 5-minute averages over successive time steps. The rapid dynamic impact of aircraft passage is evident: within 10 minutes, the aircraft-generated plume is no longer visible within the calculation domain.

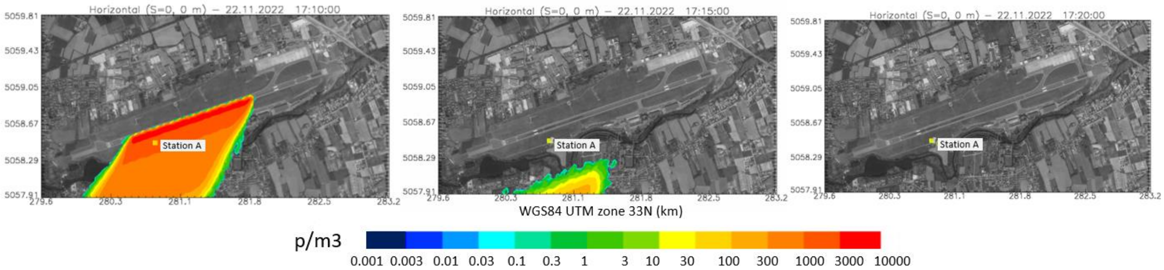

Figure 2. Concentration fields of UFPs (particles/m^3) calculated by SPRAY as 5-minute averages over successive calculation time steps during a landing episode.

Each 5-minute concentration average was constructed by sampling particle plumes occurring at a fixed frequency of 5 seconds. Specifically, the concentration calculated by the model at station A was extracted for comparison with the measurements. In order to compare peak concentrations due to the aircraft passage, the contribution of the background levels were subtracted from the measured peak concentrations.
Figure 3 shows instead the example of another landing episode, with the concentrations reproduced by the model at the point of station A, compared with those measured.

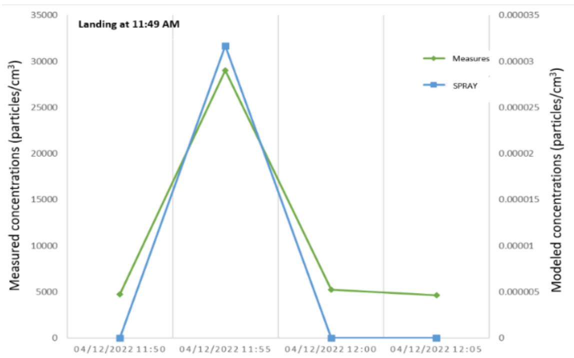

Figure 3. Comparison of measured concentrations at station A with estimated concentrations from SPRAY at the same location, considering normalized emissions, in particles/cm^3.

Since the time deviation between measured and modeled peas never exceeded 5 minutes, thus staying within the inherent uncertainty of the problem's representation, the ratio of simulated to measured peak concentrations was determined even if the peaks were not perfectly aligned.

RESULTS

A total of 42 events were analyzed for this study, distinguished between 20 landings and 22 takeoffs. The coefficients, determined by the ratio of SPRAY-estimated concentrations to those measured at station A, exhibited variations within one order of magnitude for takeoffs, while coefficients derived from simulating landings displayed a wider range of variation. Outliers and episodes where the model fails to reproduce the impact were excluded in both takeoffs and landings. The sample was then reduced to 20 cases for takeoffs and 15 cases for landings.

Average values of the coefficients were computed separately for takeoffs and landings. However, the difference observed between these two operational phases was not considered to be significant (Austin et al., 2021).

Therefore, based on the observed similarity between takeoffs and landings, a single coefficient was calculated and applied to the normalized emission factor. This resulted in an effective emission factor of $1.04 \cdot 10^{16}$ particles/seconds in the range of UFPs smaller than 1µm. The result obtained is reasonably close to some values available in literature (Shirmohammadi et al., 2017), which indicate aircraft emission factors ranging from 10^{14} to 10^{17} particles/(kg fuel), taking into account that an aircraft typically consumes approximately 1 kilogram of fuel per second.

Further validation of the results involved a Lagrangian dispersion simulation on an hourly basis to assess the impact of UFPs emissions from total air traffic over a larger domain for a three-month period, using the previously estimated emission factor. The simulation was driven by three-dimensional meteorological data provided by the Weather Research & Forecasting Model, WRF (Skamarock et al., 2021).

Over the analyzed period, the monitoring stations provided average UFPs concentrations of 15000 particles/cm^3 at station A and 10000 particles/cm^3 at station B. Specifically, the simulation conducted with SPRAY provided concentration values that accounted for approximately 30% of the total UFPs concentration measured at station A and 5% of that recorded at station B.

Thus, the analysis showed a rapid decline in the contribution of aircraft activity with distance and confirmed the presence of additional sources of UFPs in the surrounding area, not taken into account by the model simulation but detected by measurments for all the different wind directions. This background level gains greater significance in determining ambient UFPs concentrations at station B, where the influence of other activities such as heating, road traffic, and industrial operations becomes more apparent in comparison to airport activities.

CONCLUSIONS

The methodology outlined in this study, conducted as part of the Environmental Monitoring Project at "Antonio Canova" Airport in Treviso, Italy, involves the use of the Lagrangian particle model SPRAY. The model aimed to replicate peak concentrations of UFPs smaller than 1 µm measured by the monitoring station near the runway during numerous takeoff and landing episodes, using a normalized aircraft emission factor. The methodology was hence based on the assumption that the concentrations measured by that monitoring station are influenced by aircraft only. The study thus yielded an effective emission factor of $1.04 \cdot 10^{16}$ particles/seconds in the range of UFPs smaller than 1µm, which is consistent with the ranges reported in the literature. A further validation of the emission factor was conducted by comparing the results from a three-month modeling simulation over a broader domain with the corresponding measured data. This preliminary analysis confirmed the validity of the approach and suggested further investigation into contributions from other sources.

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