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ULTRAFINE PARTICLE DISPERSION MODELLING AT AND AROUND FRANKFURT AIRPORT (FRA), GERMANY

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Abstract: Air pollutant emissions represent a significant hazard to human health. In addition to the air pollutants regulated in the Air Quality Directive (EU Directive 2008/50/EC), there are other air pollutants in the scientific discussion in view of possible health effects. Here in particular ultrafine particles (UFP) have attracted considerable attention. In recent studies, airports have been identified as a source of increased atmospheric UFP number concentrations and there is a need to further understand the airport contribution to ambient near-ground UFP concentration by means of measuring and modelling. The German Environmental Agency funded the project “Influence of a major airport on temporal and spatial distributions of outdoor air concentrations of ultrafine dust <100 nm to describe the potential exposure in the vicinity - including other air pollutants [soot, nitrogen oxides and particulate matter (PM2.5 and PM10)]”, FE 3716 52 200 0. In this project, total UFP number concentration was estimated using a combination of well-established small-scale (LASAT, LASPORT) and large-scale modelling (EURAD, MADE). Emissions were determined for aircraft traffic, road traffic, airport ground services and regional/mesoscale background using standard national and international inventories (HBEFA, ICAO, GRETA) and specific data obtained from the airport. The dispersion results (series of 3-dimensional hourly mean concentrations apportioned to aircraft, airport, motor traffic and background) were compared to measurements carried out in the vicinity of the airport.

The model results suggest that aircraft main engines are the dominant emission source of UFP number at the airport. Long-time averages of UFP number concentration are dominated by the background going further away from the airport, while the airport contribution to hourly mean concentrations can be more pronounced. An important aim of the project was to identify shortcomings of current state-of-the-art emission and concentration modelling of UFP in the context of airports. Here, inconsistent UFP diameter ranges in the applied data bases, models and measurements are of relevance, likewise differences in the considered UFP constituents, in particular volatile versus non-volatile.

The results of the modeling show that the airport’s impact on the annual average of the total number concentration of ultrafine particles decreases considerably as the distance from the airport increases and is subject to the main wind direction. The modeling indicated that around 1 km north of the airport, approximately 25% of the total load originated from the airport, and this dropped to less than 10% at a distance of 2.5 km from the airport.

Key words: *Ultrafine particles, airport, aircraft, LASAT, LASPORT, EURAD, MADE.*

INTRODUCTION

Deposits from air pollutants pose a significant risk to human health. In addition to the air pollutants already regulated by the Air Quality Directive (EU Directive 2008/50/EC), other airborne trace substances which could be harmful to human health are the focus of scientific discussion. These substances include black carbon, which long-term cohort studies [1] have shown to have an impact on mortality, and ultrafine particles (UFP), which are associated with a range of negative effects, including on the brain [2]. More recent studies [3], [4] have held airports responsible for the increase in the UFP concentration in ambient air. In initial preliminary studies by the FEA, over 1 million particles per cubic centimeter of air were recorded for a short period of time (averaging time less than 30 seconds) at very low flight altitudes below the approach path in the immediate vicinity of Frankfurt Airport, with background levels of 10,000 particles per cubic centimeter [5].

Using Frankfurt Airport as an example, the aim of the project was to determine the impact a major airport has on increased concentrations of the following airborne trace substances: ultrafine particles, black carbon, NO_2, PM_{10} and $PM_{2.5}$. The project focused on the number concentration of ultrafine particles. To this end, model calculations were used to calculate temporally and spatially differentiated concentrations in the area surrounding the major airport up to distances of approximately 30 km.

Emissions from aircraft, ground-level sources at the airport site, road traffic and the background area (long-distance transportation, industry and domestic heating) were considered as sources.

A key objective of the study was to highlight the current state of technology in modeling for loads caused by ultrafine particles and to identify weaknesses and problems in the data sources and modeling. In addition, modeling different source groups separately made it possible to draw conclusions about the airport's relative share in relation to the total load.

To corroborate the model results, they were then compared with existing measurements, drawing on series of measurements taken in the area around Frankfurt Airport. In addition, measurement and modeling strategy recommendations were made to improve the quantification of the airport and aircraft share in the total air pollution.

Looking ahead, recommendations were made for future model studies with extended modeling approaches.

The project content is structured according to the following areas of activity: literature study, modeling, and a comparison of the measurement results with the modeled data.

LITERATURE STUDY

Relevant studies of UFP emissions from the main engines and auxiliary power units of airplanes, from the *ground support equipment* (GSE) and from vehicles have been compiled in the literature study. Studies on UFP measurement campaigns and UFP dispersion modeling were also identified. All references have been categorized and compiled in a summary table.

MODELING

The concentration of ultrafine particles across the area of the airport and its vicinity was calculated using a modeling system which draws on different dispersion models, each with their own strengths. The Chemistry Transport Model EURAD and the Lagrangian dispersion models LASAT and LASPORT are standard procedure in Germany for advice and licensing, as well as for tackling scientific questions.

The principal combination of the models employed used is depicted in Figure 1. EURAD, which simulates the particle formation with the *Modal Aerosol Dynamics model for Europe* (MADE), was used to calculate the background load. The concentrations originating from car traffic emissions outside the airport were calculated with LASAT. The modeling system LASPORT was used to determine the emissions and concentrations from the airport and aircraft movements. While EURAD is designed for transregional dispersion calculations, LASAT and LASPORT can be used for both regional and high-resolution dispersion calculations on a microscale.

The total load was determined using the sum of the individual partial results, generating a value which can be compared with the results of the measurements.

The modeling was performed for the year 2015. Relevant meteorological and emission-related input data were processed and fed into the modeling system. The modeling was carried out with a temporal resolution of one hour.

The area around Frankfurt Airport was defined as the model area, covering 35 km by 35 km (see Figure 2). Located within the model area are the UFP measurement sites of Langen (operated by the UBA), Raunheim (operated by the FEA at the station of the Hessian Agency for Nature Conservation, Environment and Geology, HLNUG) and the station at Frankfurt-Schwanheim (HLNUG), which was set up at the end of 2017.

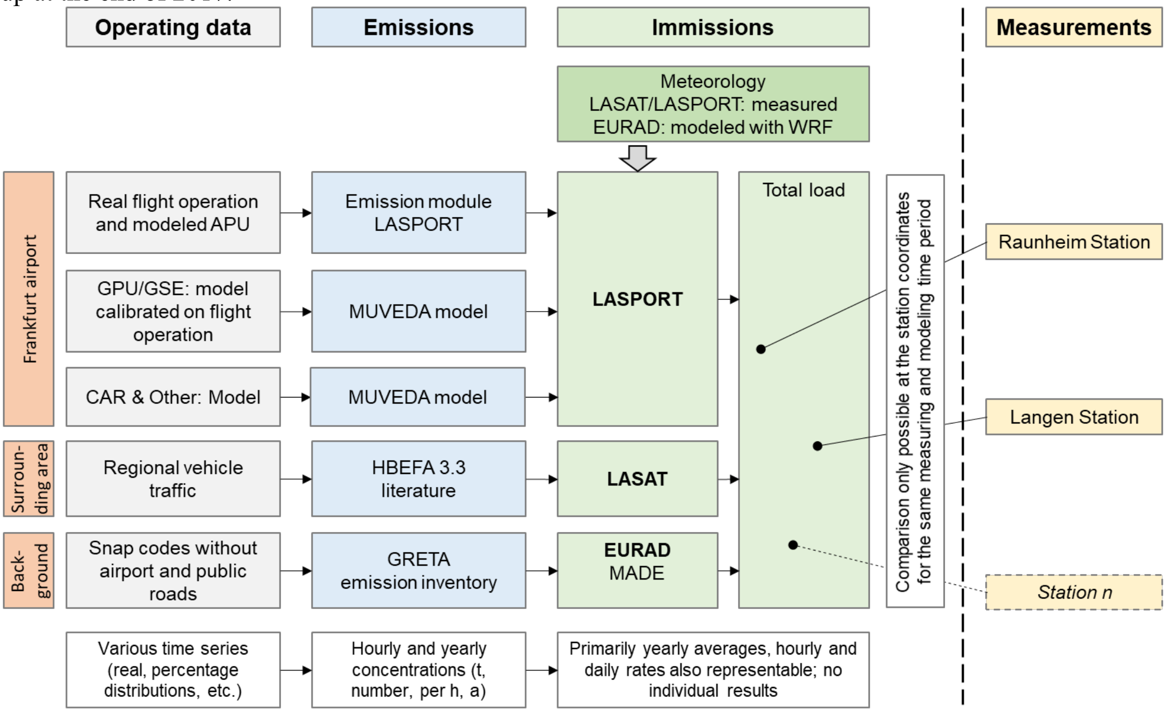

Figure 1: Overview of the model system used.

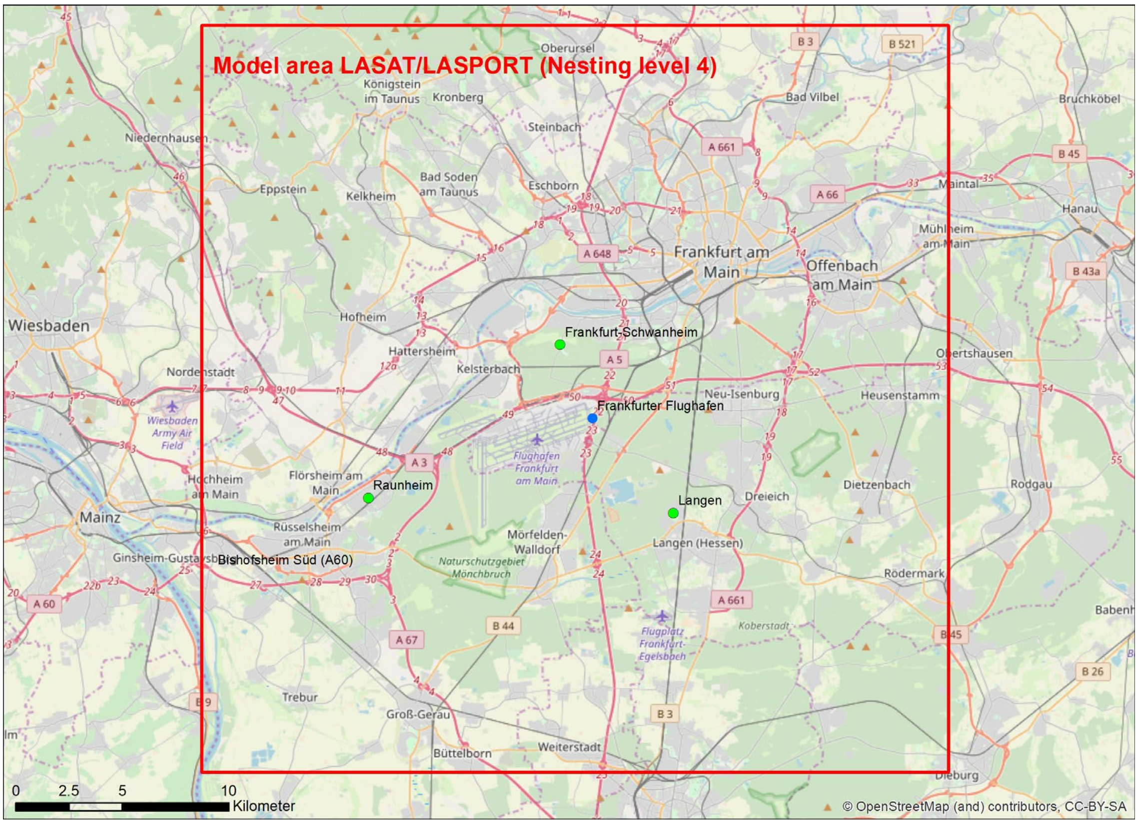

Figure 2: Inner model area

In order to incorporate the impact of international long-distance transportation in the background load modeling with EURAD, a significantly larger model area covering the whole of Europe was selected (see Table 1). A modeling configuration was chosen which combines the models' varying scales using a nesting approach. The computational meshes and the horizontal resolutions used are depicted in Table 1 below. In the following, the term "nesting level" derived from said nesting approach is used to refer to the area enclosed by the computational mesh and its horizontal resolution.

Table 1: Nesting levels for the different model calculations.

	Model	**Region**	**Area (km)**	**Horizontal resolution**	**Vertical resolution**
Nesting level 0	EURAD	Europe	6250 x 5500	62.5 km	0–16 km (100 hPa), 23 layers, 15 less than 3 km, lowest layer 0–36 m
Nesting level 1	EURAD	Central Europe	3325 x 2575	12.5 km	
Nesting level 2	EURAD	Germany	765 x 965	2.5 km	
Nesting level 3	EURAD	Frankfurt Airport	50 x 50	500 m	
Nesting level 4	LASPORT	Frankfurt Airport	35 x 35	200 m	0–2 km, 19 layers, lowest layer 0–3 m
	LASAT (vehicles)	Frankfurt Airport	35 x 35	100 m	

Simulation results from the meteorological model WRF, which is run using data from the *Global Forecast System* (GFS) of the *U.S. National Centers for Environmental Prediction* (NCEP) (NCEP-GFS data), ftp://ftp.ncep.noaa.gov/pub/data/nccf/com/gfs/prod), were used as meteorological input data for the EURAD model. The time series (hourly average) for wind direction, wind velocity and cloud coverage measured by the German Weather Service on the eastern edge of Frankfurt Airport at ground-level (10 m above the ground) were used for the dispersion calculations with LASAT and LASPORT and were accepted as representative for the model area observed.

CALCULATION OF THE BACKGROUND LOAD

The emissions for nesting levels 0 and 1 were calculated from the data in the emissions database TNO-CAMS [*Copernicus Atmosphere Monitoring Service* (CAMS), maintained by the *Netherlands Organisation for Applied Scientific Research* TNO, https://topas.tno.nl/emissions]. The FEA provided the 2015 emissions data for the nesting levels 2 and 3 from the GRETA database (*Gridding Emission Tool* for ArcGIS, https://www.umweltbundesamt.de/sites/default/files/medien/1968/publikationen/2016-11-09_griddingtool_greta_langfassung_final.pdf). As the GRETA data is only available for the Federal Republic of Germany, values from the TNO-CAMS emission data set were used for all the grid cells outside of Germany.

Emissions from road traffic, from the Frankfurt Airport and from air traffic were not included in the calculation of the background load in nesting level 4, which encloses the model area for LASAT and LASPORT, as these sources were already part of model calculations on smaller scales.

The configuration of the aerosol components in the EURAD model took place under the premise that each representation of particles must be consistent both with observations of particles and with a numerical efficiency of the mathematical representation in the software program. As a result, an approach was taken in accordance with Whitby [6], modeling the particles as the overlaying of lognormal sub-distributions known as modes. If the standard deviation of the modes is kept constant, as is the case in EURAD, only two integral properties have to be predicted in each mode, namely the particle number concentration and the mass concentration of the individual chemical components.

To model the UFP, the Modal Aerosol Dynamics model for Europe (MADE) was integrated in the EURAD model [7]. MADE was developed from the *Regional Particulate Model* (RPM) [8]. The particles were divided into two groups: fine particles and coarse particles (see Figure 3).

MOTOR VEHICLE EMISSIONS IN THE SURROUNDING AREA

The emissions from public road traffic were calculated based on route-specific traffic volumes, which were provided by the State of Hesse and checked against count data from the German Federal Road Research Institute (BASt). The emission factors for particle numbers as well as the other pollutant components observed were obtained from database 3.3 of the Handbook Emission Factors for Road Transport (HBEFA) [9]. Depending on the data situation, the temporal patterns were determined on the basis of route-specific or standardized daily cycles or hourly count data.

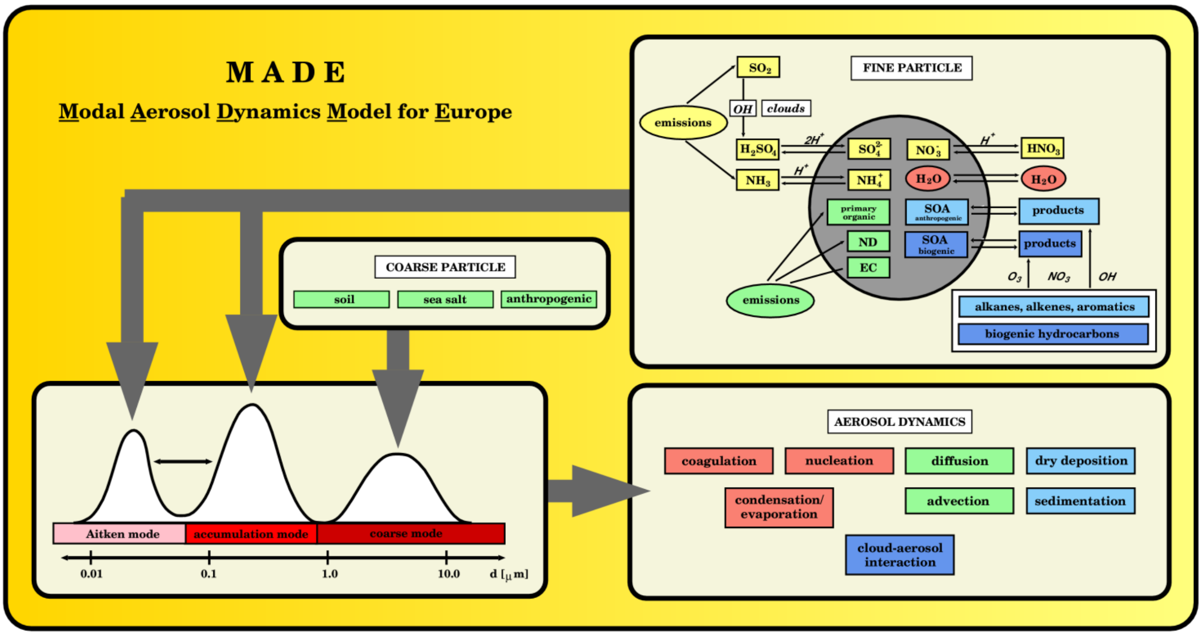

Figure 3: Schematic overview of the Modal Aerosol Dynamics model for Europe (MADE).

GROUND-LEVEL EMISSIONS AT THE AIRPORT

The emission sources of an airport are diverse and not limited to aircraft engines. Figure 4 depicts the most significant emission sources of an airport, which itself can be divided into three areas based on access restrictions: the surrounding area (publicly accessible), the airport site (access generally permitted with authorization) and the airport apron (access strictly regulated).

Filling stations, solvent applications, tank farms and aircraft fueling are not considered relevant for direct ultrafine particle pollution, as they emit hydrocarbons but no solid particles, and are therefore not the subject of this study.

The emission sources are broken down into line sources (public streets, service roads, airport aprons, towing routes), plane sources (parking lots, position areas), volume sources (multi-story above and below ground parking garages) and point sources (emergency power systems, gas and oil heating).

The emissions from car traffic as part of a line source were calculated based on the road geometry, route-related activity data and route-related emission factors (based on HBEFA 3.3).

The emissions from aircraft ground handling were distributed across the position areas. They were also calculated directly in the LASPORT database using the aircraft movements listed in the flight log.

Emissions from the *ground power units* (GPU), which supply power to parked aircraft when there is no other ground power available, have been handled separately.

The activity data on aircraft towing operations was derived from the air traffic database. The activity data was expressed as time in minutes derived from the points in time when an aircraft left one position and arrived at another. To model the emissions in LASPORT, the times were distributed along the towing routes and used to calculate the traffic volumes in conjunction with the average speed of traffic and the length of the route. A similar procedure was followed with the idle times of aircraft tractors during coupling and decoupling in parked positions.

For all other emission sources, previously measured emissions were fed into LASPORT instead of activity data. In the case of emission sources at Frankfurt Airport which did not stem from engines, the activity data could not be derived from the flight log and were therefore obtained from the airport's emissions inventory.

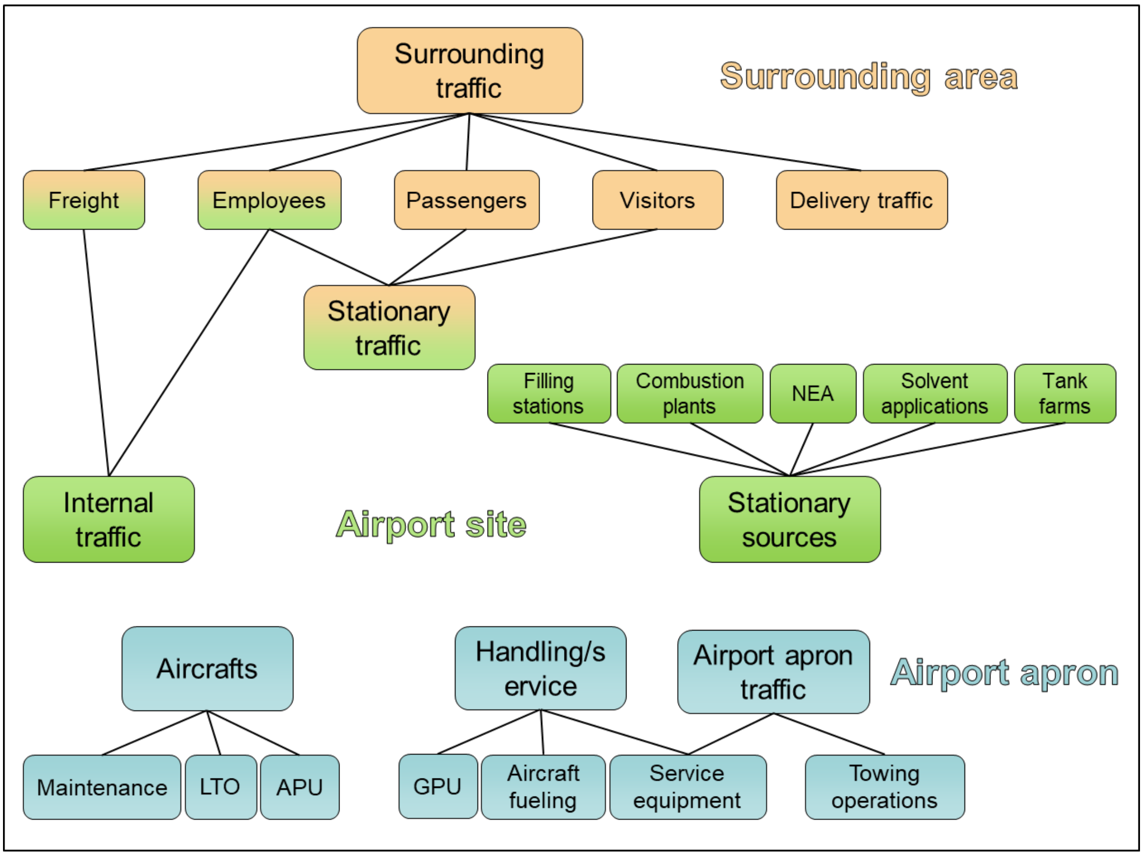

Figure 4: Airport-related emission sources.

AIRCRAFT ENGINE EMISSIONS

Aircraft emit pollutants from their main engines and auxiliary power units. While the *auxiliary power units* (APU) are generally only required after landing and prior to startup for supplying energy inside the airplane and for starting the main engine, the main engines are in operation in different load stages during the entire *landing and take-off cycle* (LTO).

For the main engines of jet planes with a static thrust greater than 26.7 kN, the fuel consumption and *emission indices* (EI) — i.e. the pollutant amount released per unit of fuel burned — are found in the *ICAO Engine Emission Databank* (EEDB). The current version, Issue 24, was used in this project.

For APUs, ICAO Document 9889 lists the fuel consumption and emission rates of NO_x, HC and CO for 6 APU categories and various load conditions: *start-up and stabilization* (auxiliary power unit startup, SS/NL), *high load* (main engine startup, HL/MES), *normal running* (aircraft preparation and boarding, NR/ECS). An average emission rate of approximately 30 g/h is specified for PM_{10}. Additionally, an emission index of 0.8 g/kg was taken as a basis for SO_x as was previously done with the main engines.

In this project, simplifying assumptions were made for aircraft and helicopters with turboprop or piston engines as their contribution to the total emissions from air traffic at Frankfurt Airport is significantly less than 1%.

SHARES OF THE SOURCE GROUPS AND TOTAL LOAD

To obtain a total load value which could be compared with the measurement results, the results of the dispersion calculations of all emitter groups observed were added together. In Figure 5, the ground-level annual averages of the UFP concentrations of the modeled emission sources are represented separately and as an accumulated total load.

The results of the modeling show that the airport's impact on the annual average of the total number concentration of ultrafine particles decreases considerably as the distance from the airport increases and is subject to the main wind direction. Around 1 km north of the airport, approximately 25% of the total load stems from the airport. This figure drops to less than 10% at a distance of 2.5 km from the airport.

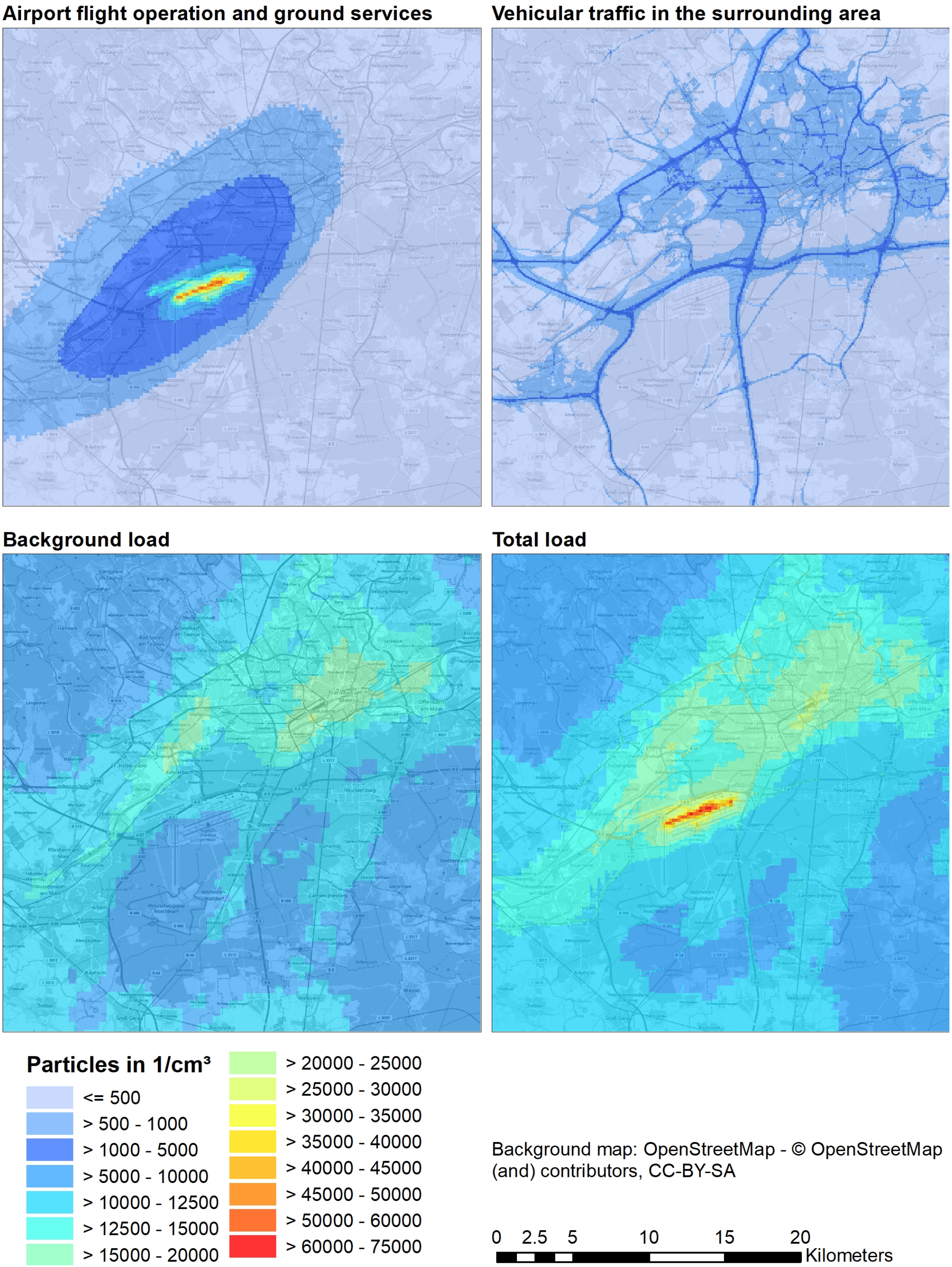

Figure 5: The 2015 annual average for the ground-level number concentration of ultrafine particles (UFP) in 1/cm³ for these source groups: flight operations and ground support, car traffic in the surrounding area, background load and total load.

CONCLUSION

One of the project's main objectives was to show the extent to which the total concentration of ultrafine particles in the area surrounding a major airport can be calculated using currently available emissions databases and dispersion models, indicate emergent technical and fundamental problems and illustrate how the modeled results compare to measurements.

Separating the model calculations into different spatial scales proved to be a sensible and practical approach for recording the background load on a large scale as well as presenting the immission condition at the airport in the greatest possible detail. The division into spatial scales and source groups also made it possible to incorporate existing emissions databases into the modeling without having to make significant compromises. On the basis of hourly averages, the results of the different partial calculations could be uniformly grouped into one time series of the total load. At the same time, detailed results from each individual setting emerged from this approach, making it possible to investigate the impact of different source groups.

In the course of the project, it became clear that the databases and models use divergent definitions of particle components, such that the combination of the partial results was not entirely consistent. Furthermore, the origin and relocation of the volatile components could not be addressed using the local standard models as none of the input parameters required for this (for example, empirical relocation rates) are available. One such observation was only possible with the large-scale EURAD/MADE model, though it is not designed to provide suitable results on a smaller spatial scale. However, such model results would be necessary in order to draw a comparison with measurements made in the vicinity of the airport.

Fundamental problems also emerged from the comparison of the model data with the measurements. In some cases, the measurements were based on varying definitions of particle components, particularly with regard to the diameter range observed. Furthermore, the measurements recorded the sum of the volatile and non-volatile components, while the modeling exclusively considered the non-volatile components except when it came to the background. From a technical perspective, the comparisons were further complicated by the fact that the modeling occurred in reference to 2015, however only the Langen measuring station had measured ultrafine particles in the investigation area throughout the entire year of 2015.

The model-measurement comparison for Raunheim depicts a satisfactory congruence for PM_{10} and NO_x. For the long-term average number concentration of ultrafine particles (several weeks in Raunheim and annual average in Langen), the model results had a maximum deviation of 45% in the same order of magnitude as the measured data, which is also satisfactory in light of the uncertainties specified in the emission data. The statistic correlation between the wind direction and the hourly average of the number concentration of ultrafine particles at the Raunheim station and stemming from the airport is consistent with the measurements. The measurements and the model results both show Frankfurt Airport to be an emission source depending on the wind direction.

The yearly cycle of the modeled number concentration of ultrafine particles is dominated by the background load calculated using EURAD/MADE and exhibits the highest values in the winter months and the lowest values during the summer months. The measured concentration tends to demonstrate the opposite trend in its yearly cycle. The yearly cycle with the highest values occurring in the summer appears in the measurements particularly in smaller particles less than 50 nm in size. The causes for these opposing tendencies could not be explained within the scope of this project.

The temporal resolution of the modeling was 1 hour. It was therefore not possible to draw conclusions from the model results for shorter periods of time, for example in regard to individual aircraft movements. Concentration modeling for time periods of single minutes or shorter would require considerably greater accuracy in determining the local meteorological relationships and the current and local relevant traffic and emission volumes. Such data are not generally available. Even when observing hourly averages, there are some considerable uncertainties in the input data. Therefore, for average periods of time such as individual hours or days, only a statistical comparison with appropriate measurement evaluations is conclusive, not a direct comparison of the measured and modeled concentration time series.

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