Supplementary Information

Multi-year high time resolution measurements of fine PM at 13 sites of the French Operational Network (CARA program): Data processing and chemical composition

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Table S1: Description of the measurement stations from the CARA program used in this paper. A detailed description of these sites is presented at the end of SI, section "Sites description".

Operator	Station name	City	Airbase ID	Altitude (m a.s.l)	Latitude	Longitude	Site type
IMT Nord Europe	ATOLL	Lille	-	70	50.6111	3.1404	Suburban
LSCE & Ineris	SIRTA	Greater Paris	-	163	48.71181	2.14818	Suburban
Airparif	Gennevilliers	Greater Paris	FR04002	28	48.9298083	2.2946194	Urban background
Airparif	Paris Les Halles	Paris	FR04055	35	48.8627083	2.3446972	Urban background
Airparif	Paris BPEst	Paris	FR04329	49	48.8385167	2.4126242	Urban Traffic
Air Breizh	Rennes Pays-Bas	Rennes	FR19017	45	48.08965	-1.65911	Urban background
Atmo AuRA	Lyon Centre	Lyon	FR20062	160	45.75779	4.85422	Urban background
Atmo Grand Est	Metz Borny	Metz	FR01012	204	49.1102806	6.2233361	Urban background
Atmo Grand Est	Strasbourg Danube	Strasbourg	FR42010	135	48.5062222	7.7511806	Urban background
Atmo Hauts-de-France	Creil Faïencerie	Creil	FR18043	31	49.2597222	2.4744444	Urban background
AtmoSud & LCE	Marseille Longchamp	Marseille	FR03043	73	43.3052889	5.3947056	Urban background
Atmo Nouvelle-Aquitaine	Poitiers Augouard	Poitiers	FR09404	105	46.5839885	0.3455967	Urban background
Atmo Nouvelle-Aquitaine	Talence	Bordeaux	FR31002	23	44.800442	-0.5893941	Urban background

Table S2: Percentages of data that fell within the range of -3×DL to DL and data below -3×DL.

| | Pourcentages of data below -3×DL | | | | | | Percentages of data between -3×DL and DL | | | | | |
Station name	eBC	OA	NH4	SO4	NO3	Cl	eBC	OA	NH4	SO4	NO3	Cl
ATOLL	NaN	NaN	0.004	0.004	0.004	3.70	6.27	0.49	23	0.46	0.28	33
Paris BPEst	NaN	0.016	NaN	0.032	NaN	8.24	NaN	0.16	24	0.66	NaN	32
Creil	NaN	NaN	NaN	0.005	0.005	1.52	6.12	0.66	25	0.81	0.27	18
Gennevilliers	NaN	NaN	NaN	NaN	NaN	0.01	1.78	0.15	25	0.10	0.01	16
Lyon	NaN	NaN	NaN	0.002	NaN	0.00	1.67	0.04	31	0.40	0.02	26
Marseille	NaN	NaN	NaN	NaN	NaN	NaN	1.04	0.49	30	1.10	1.31	37
Metz	NaN	0.055	0.075	0.106	0.068	0.66	6.33	0.42	22	0.36	0.14	26
Paris Les Halles	NaN	NaN	NaN	0.283	NaN	0.87	1.06	0.19	41	3.44	NaN	35
Poitiers	NaN	0.045	0.003	0.154	0.008	4.81	7.35	1.50	33	2.09	0.36	25
Rennes	NaN	0.027	0.018	0.124	0.009	0.24	11.59	1.66	53	2.37	0.84	18
SIRTA	NaN	NaN	0.002	0.008	0.015	0.38	11.56	0.44	31	0.55	0.16	20
Strasbourg	NaN	NaN	NaN	0.526	NaN	0.15	2.18	0.51	40	2.69	0.13	32
Talence	NaN	NaN	NaN	0.036	NaN	5.95	7.37	1.12	36	1.45	0.34	26
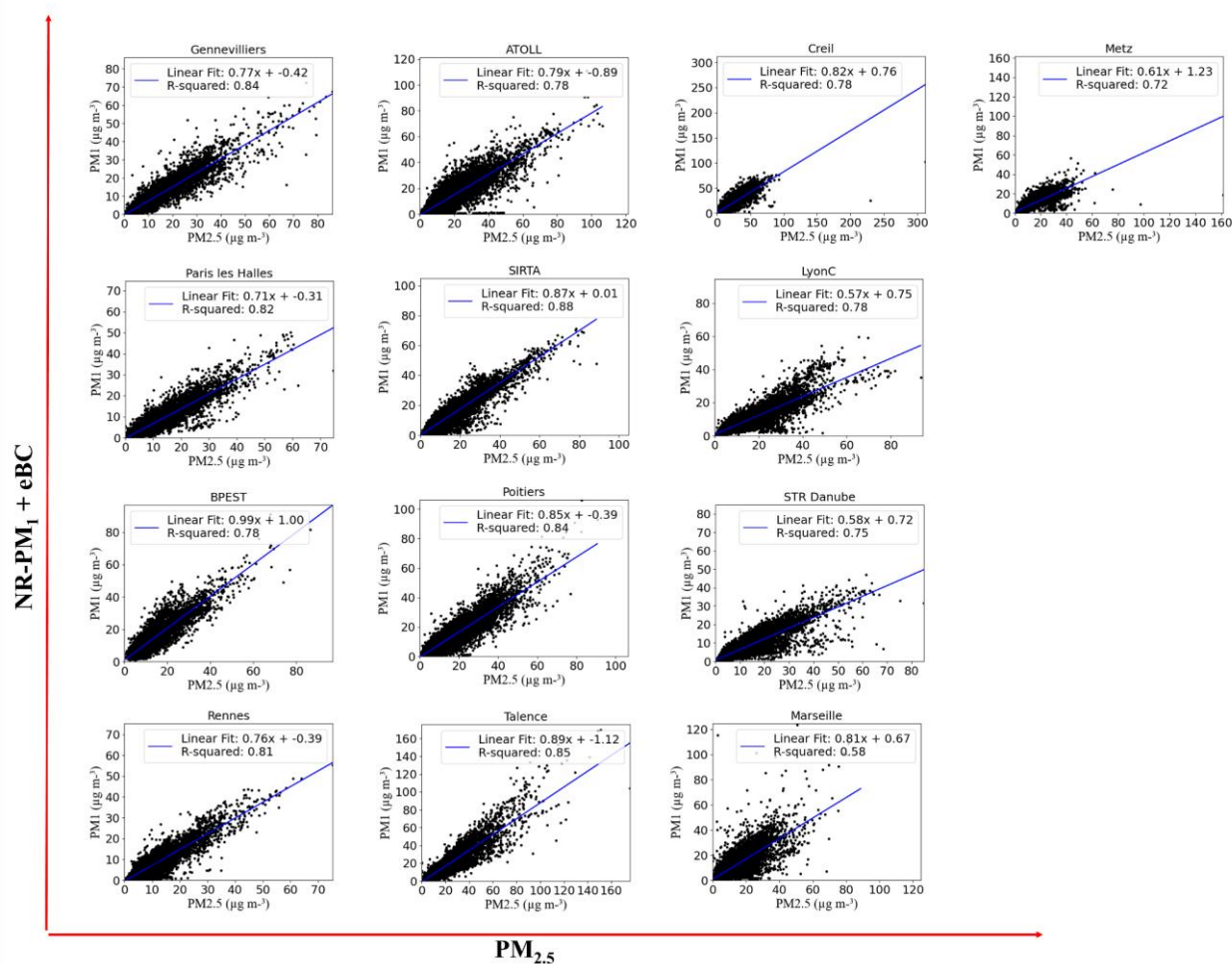
Figure S1: NR-PM$_1$+eBC vs. PM$_{2.5}$ for each site during the whole study period.
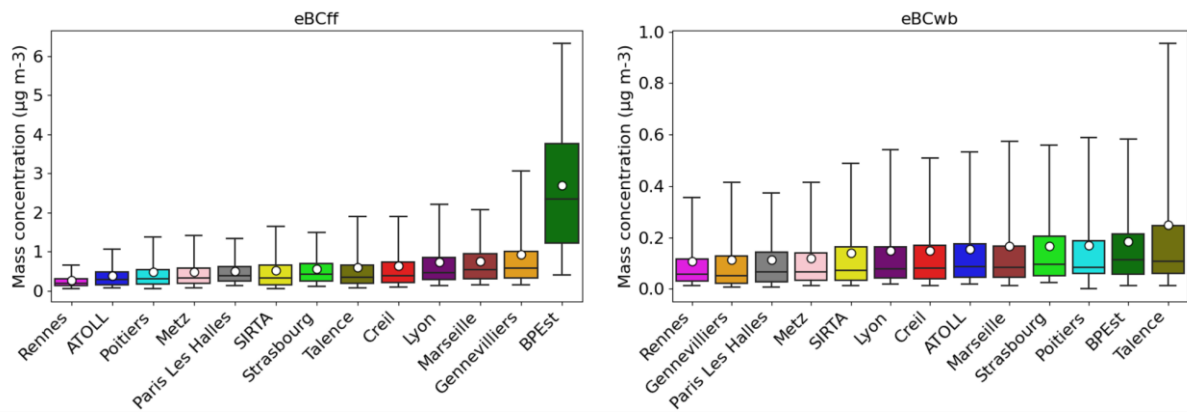
Figure S2: Box plots of statistical information (mean in circle, median, the percentiles 5, 25, 75, and 95th) of eBC$_{ff}$ and eBC$_{wb}$ for the 13 French sites.
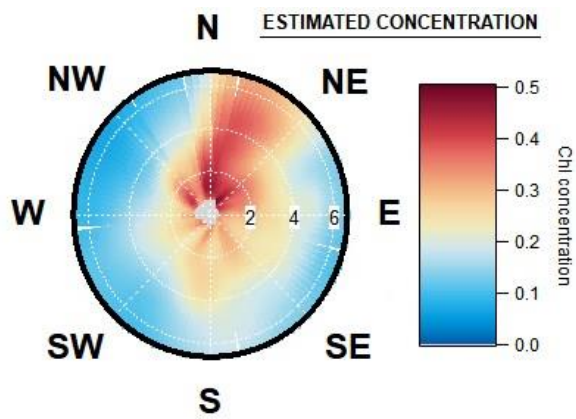
Figure S3: Pollution rose of Chloride at Creil site (Zefir).
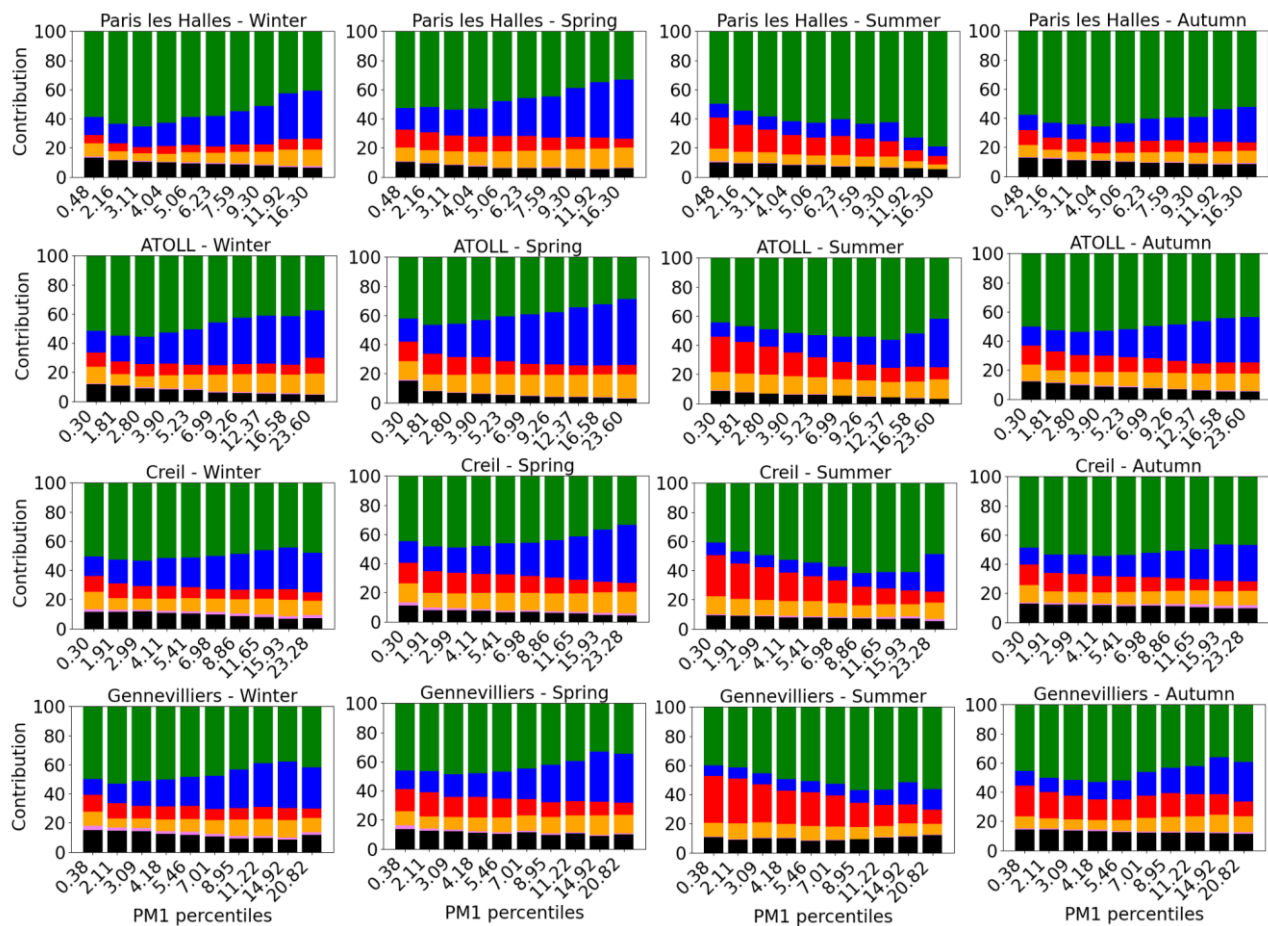
Figure S4: Relative contribution of chemical species as a function of PM$_1$ percentiles by season (continued)
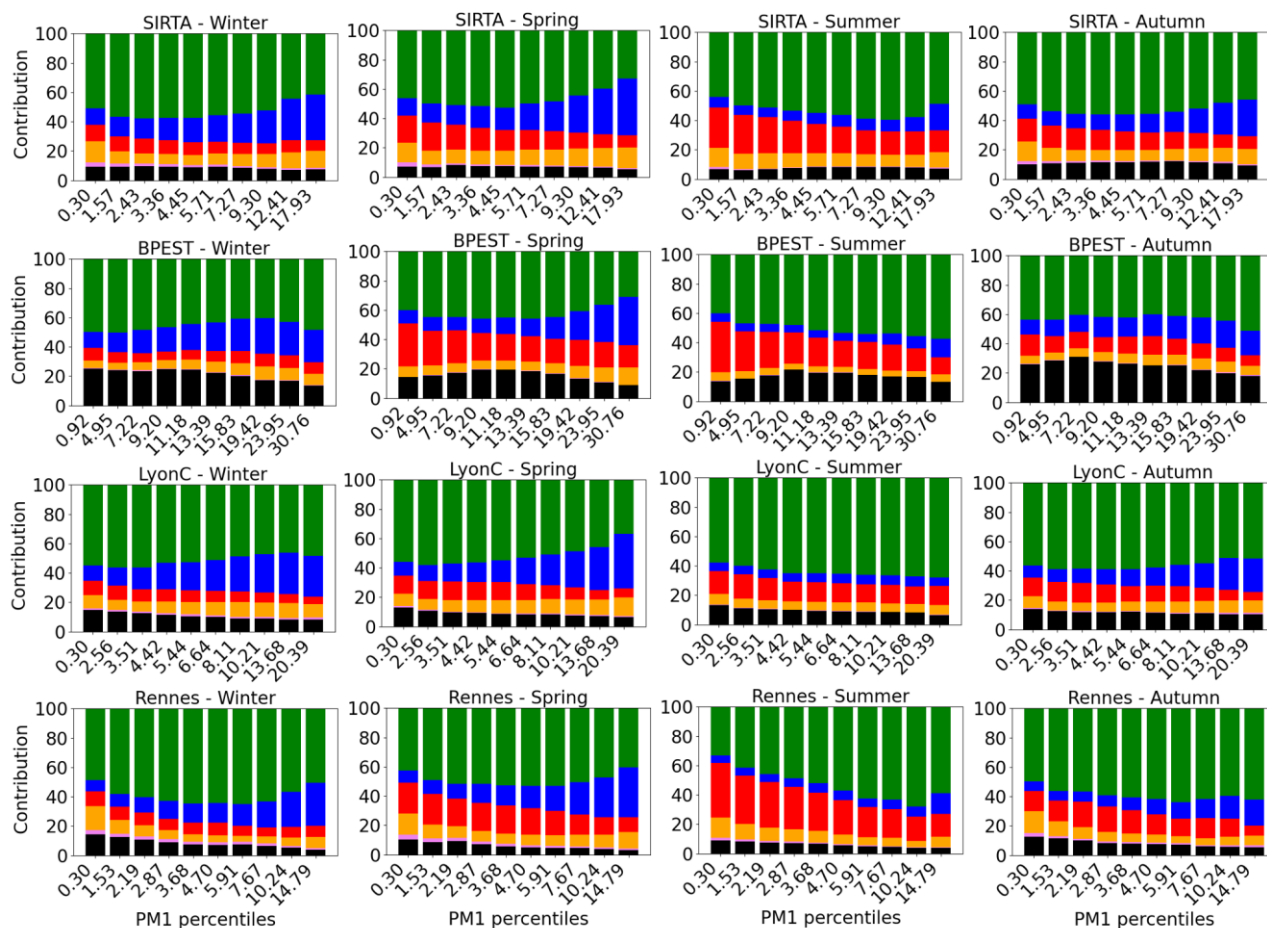
Figure S4: Relative contribution of chemical species as a function of PM$_1$ percentiles by season (continued).
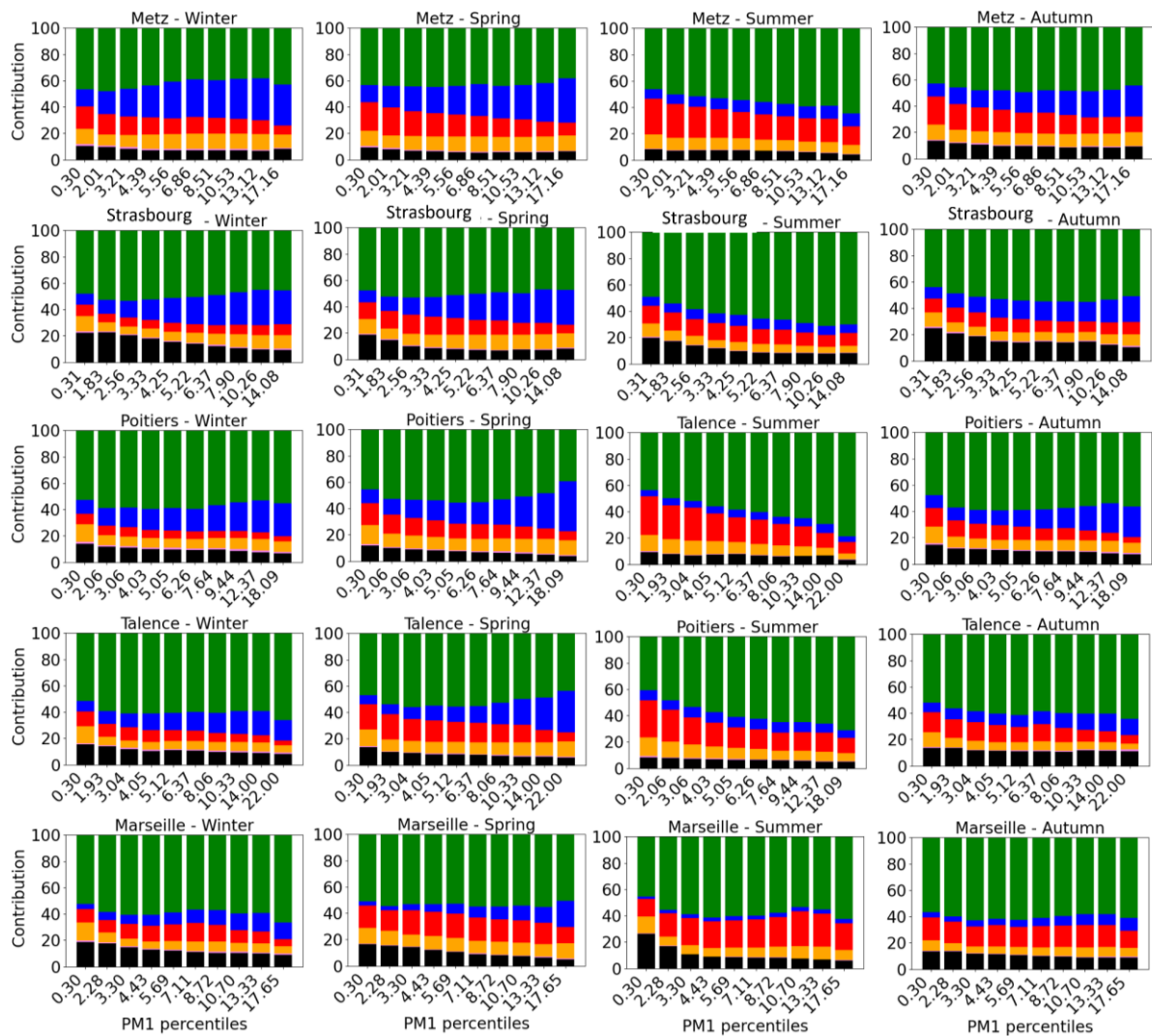
Figure S4: Relative contribution of chemical species as a function of PM$_1$ percentiles by season.
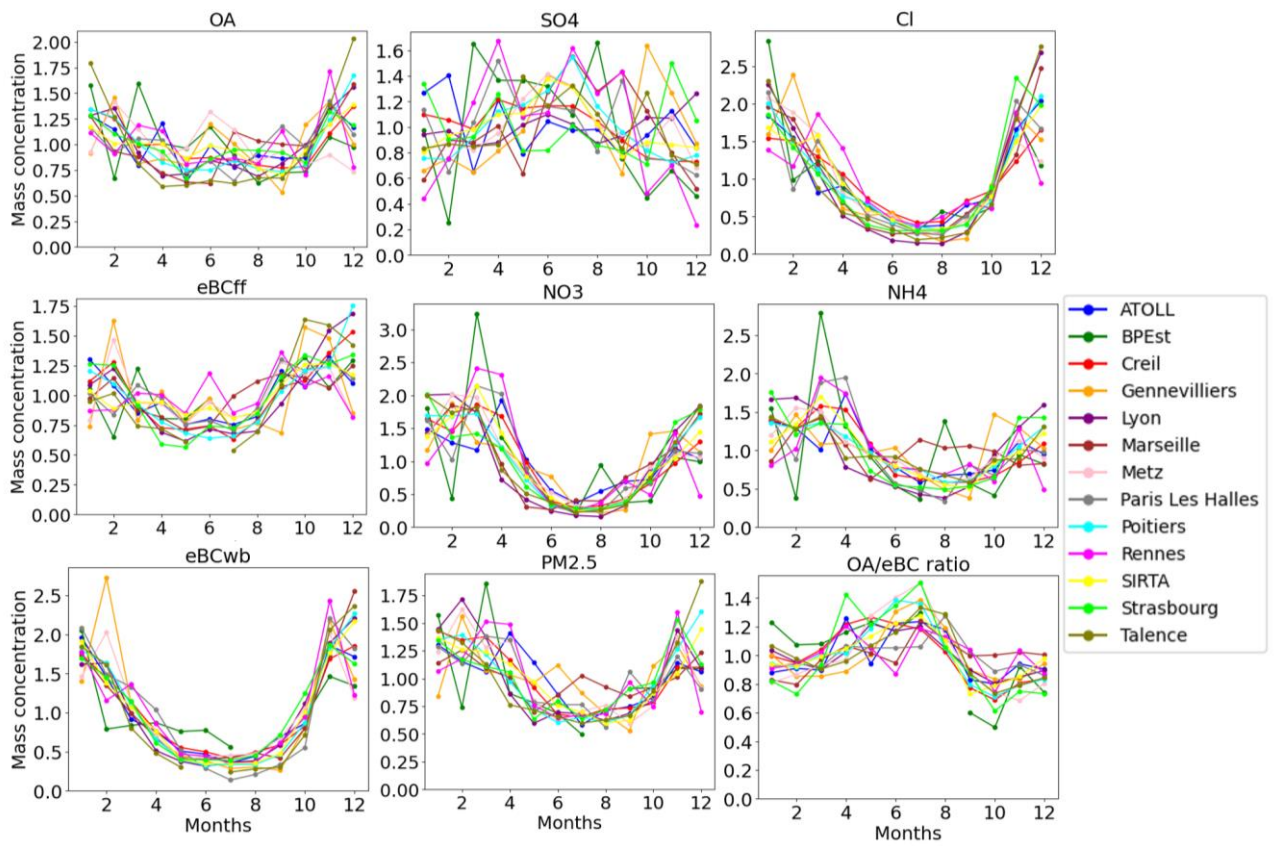
Figure S5: Monthly concentrations normalized by site-specific annual averages of the species studied here.
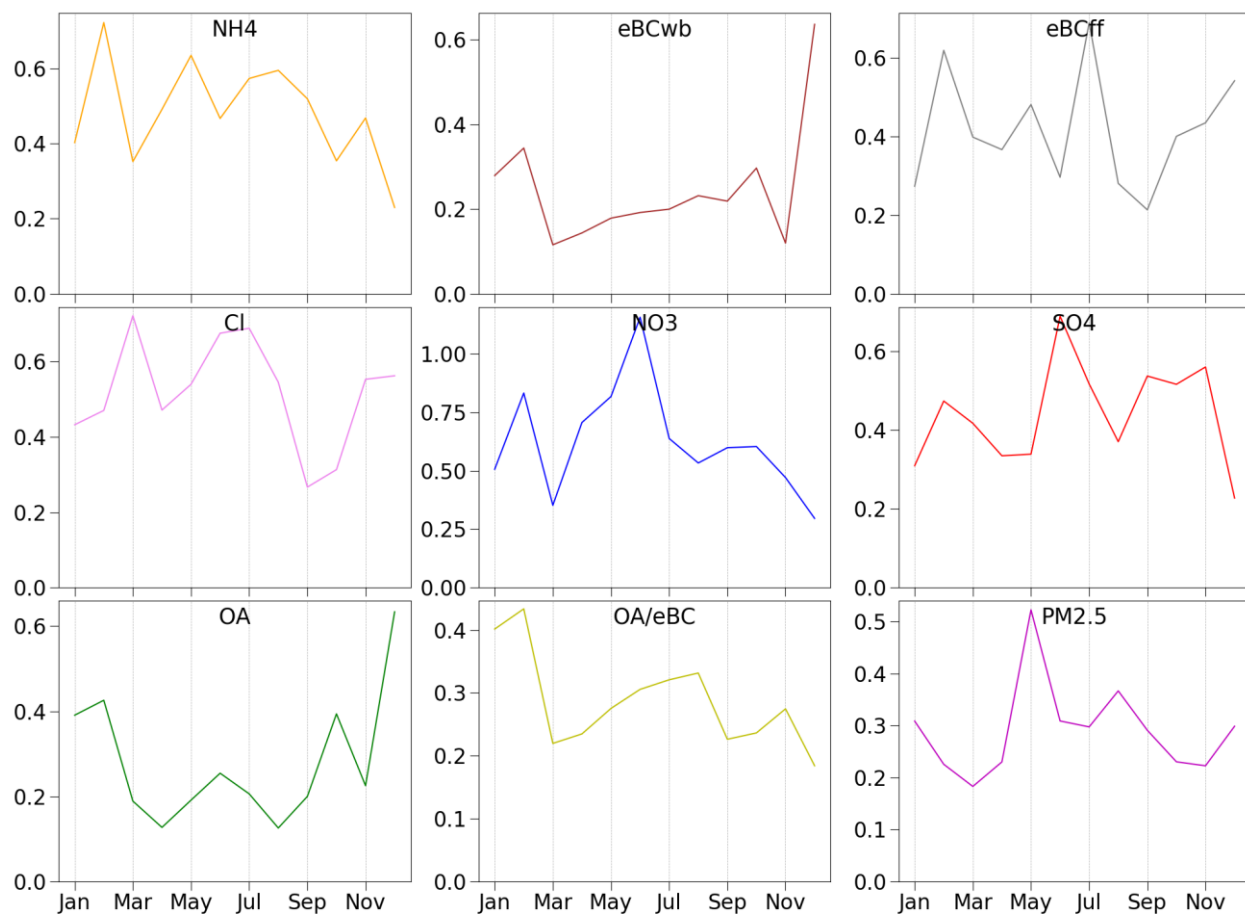
Figure S6: Monthly IQR/median ratios for each component from Fig. 4 from the main text.
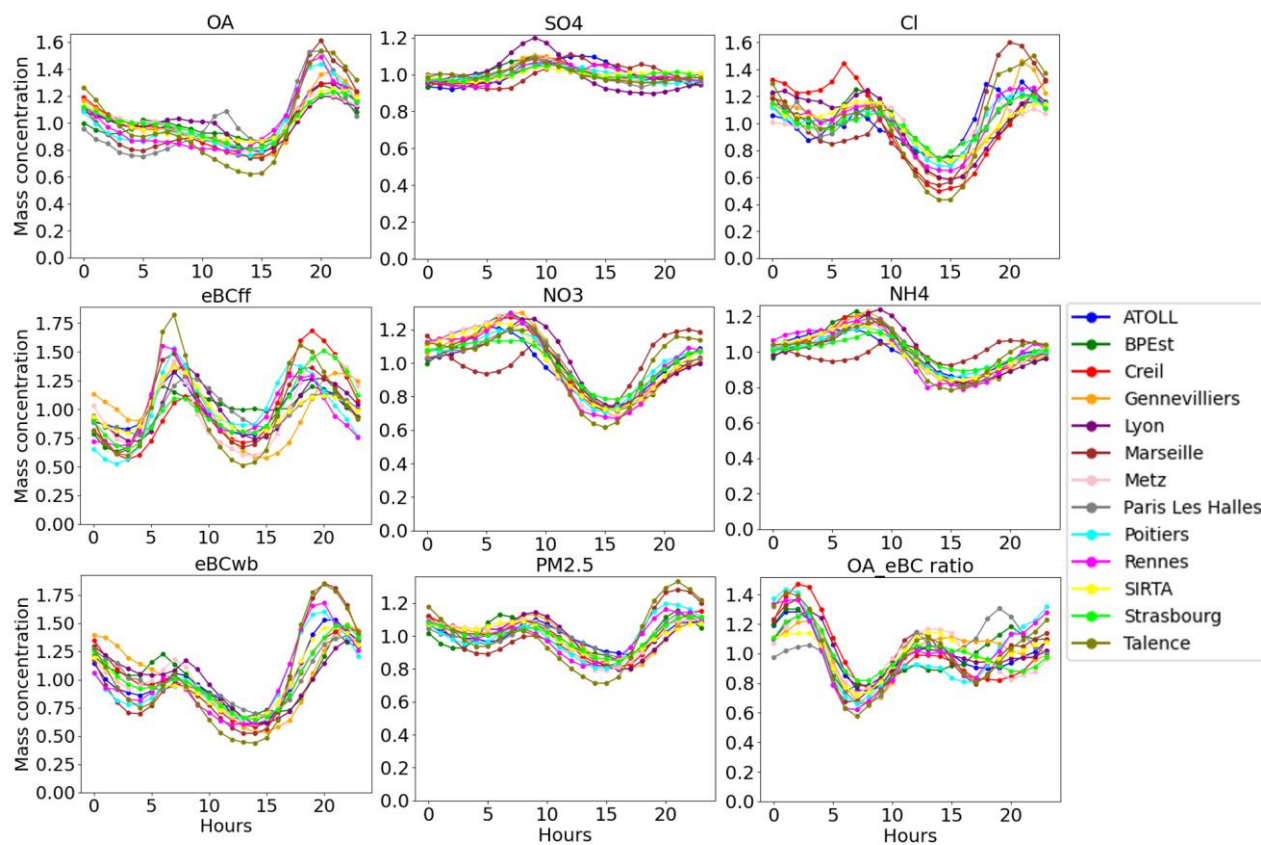
Figure S7: Diel concentration profiles, normalized by site-specific daily averages.
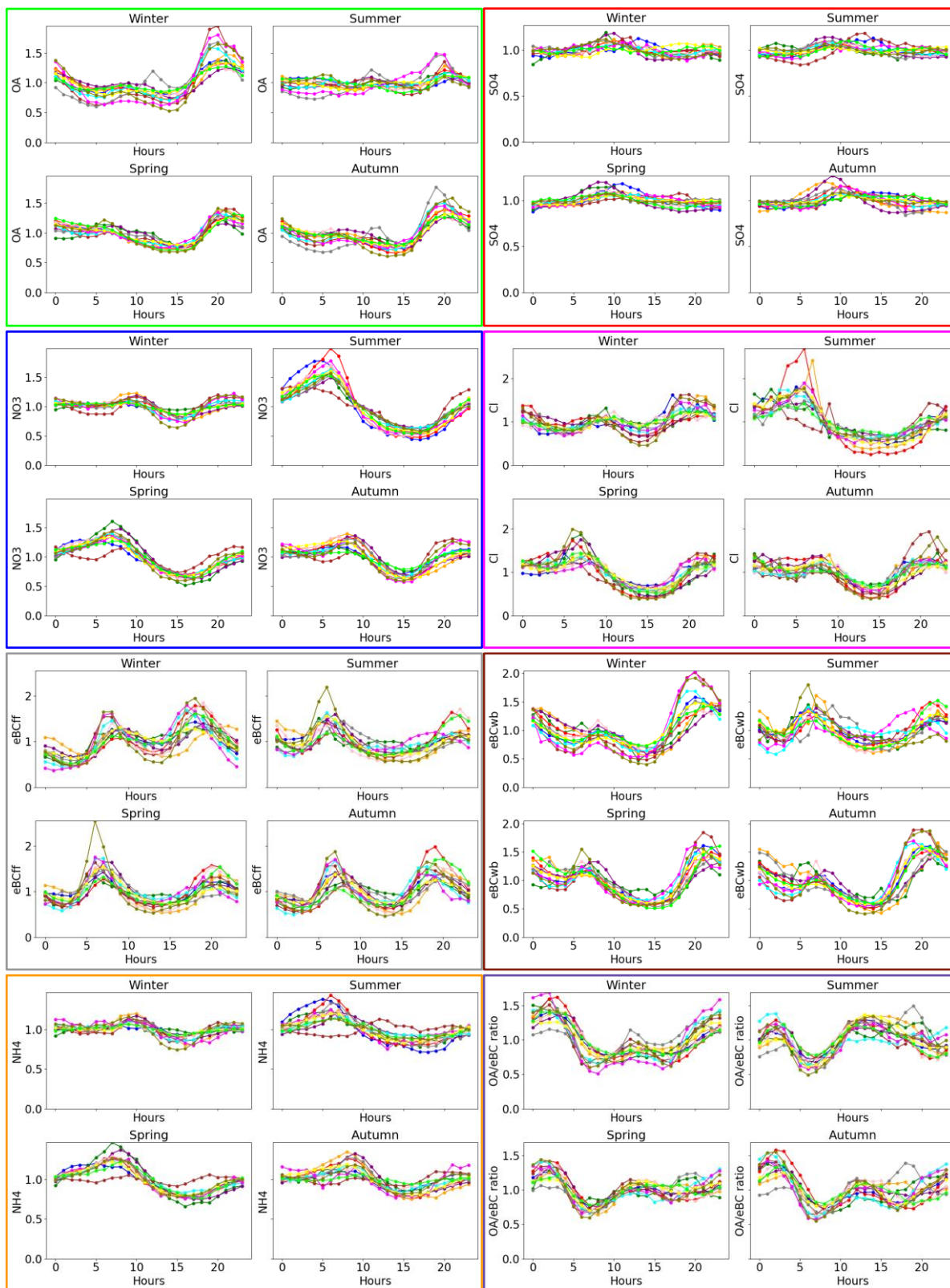
Figure S8: Seasonal diel concentration profiles, normalized by site-specific daily averages.
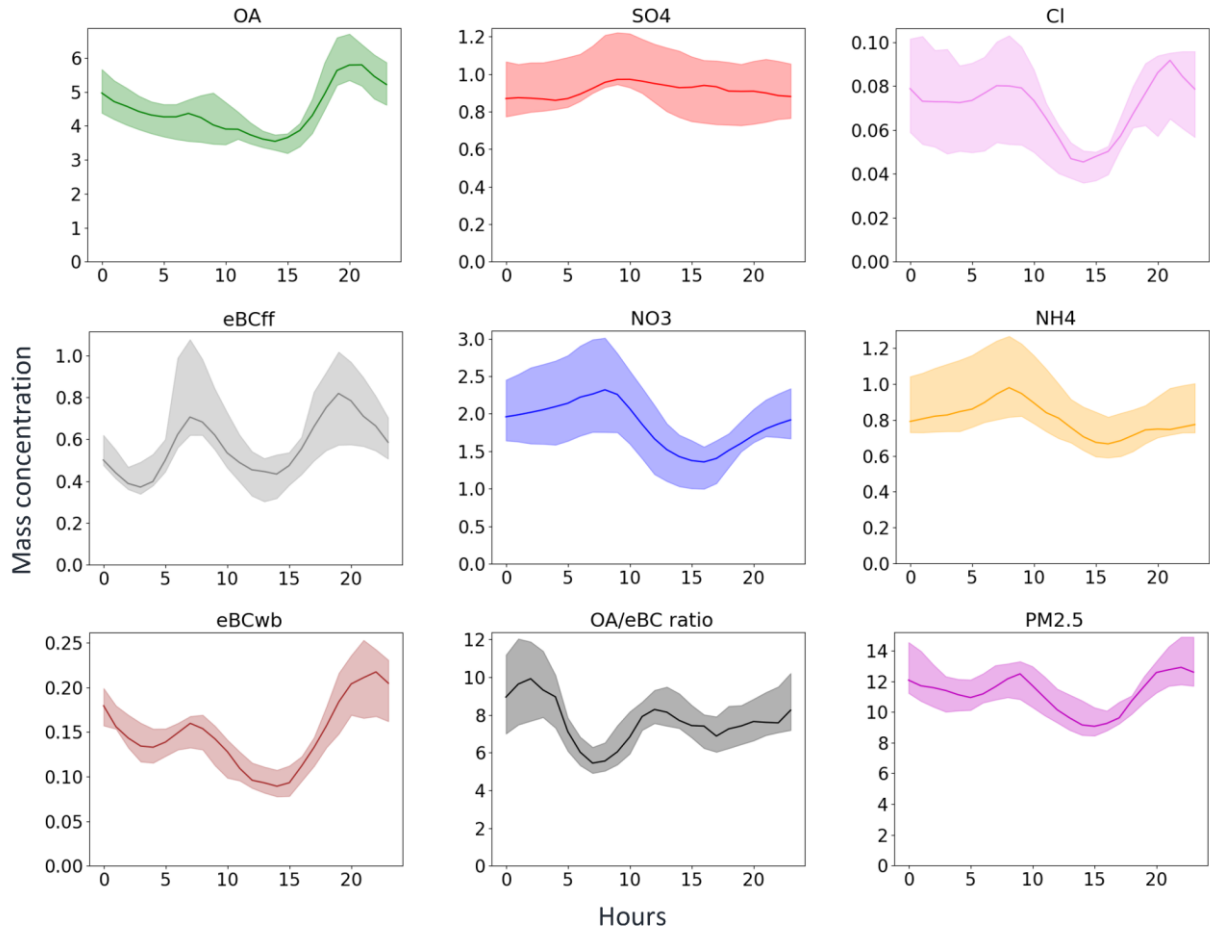
Figure S9: Diel median and IQR for each species across all sites.
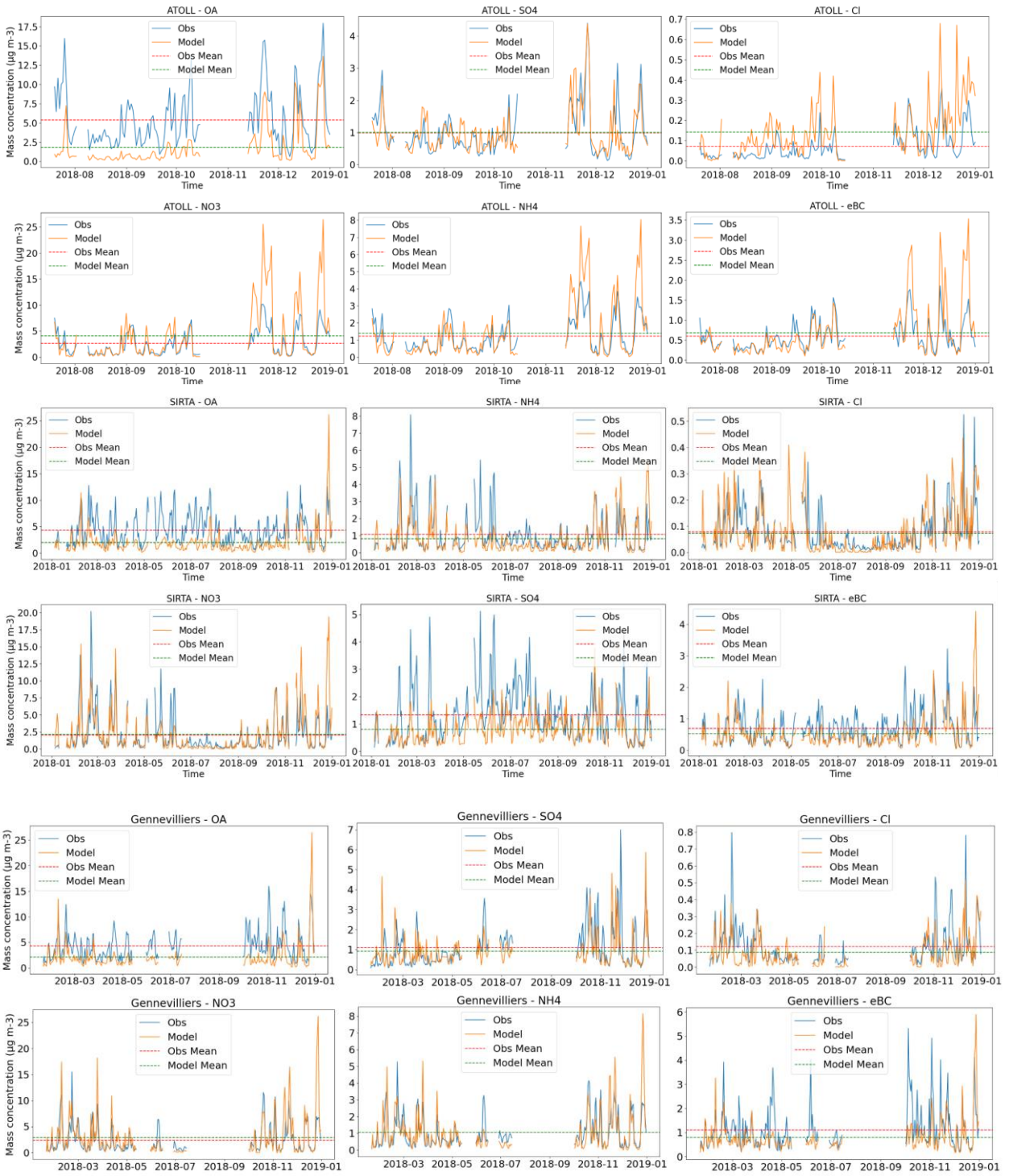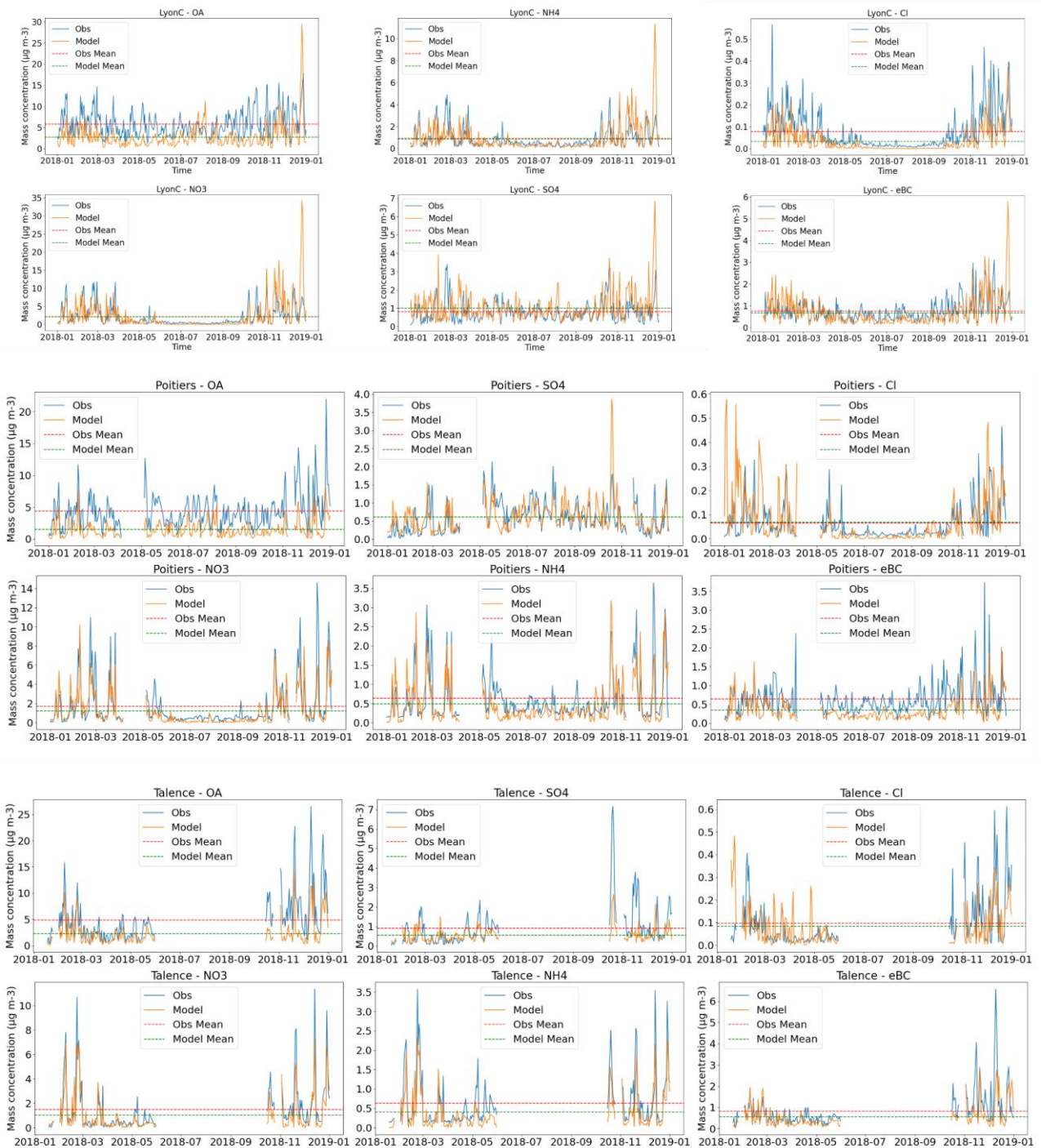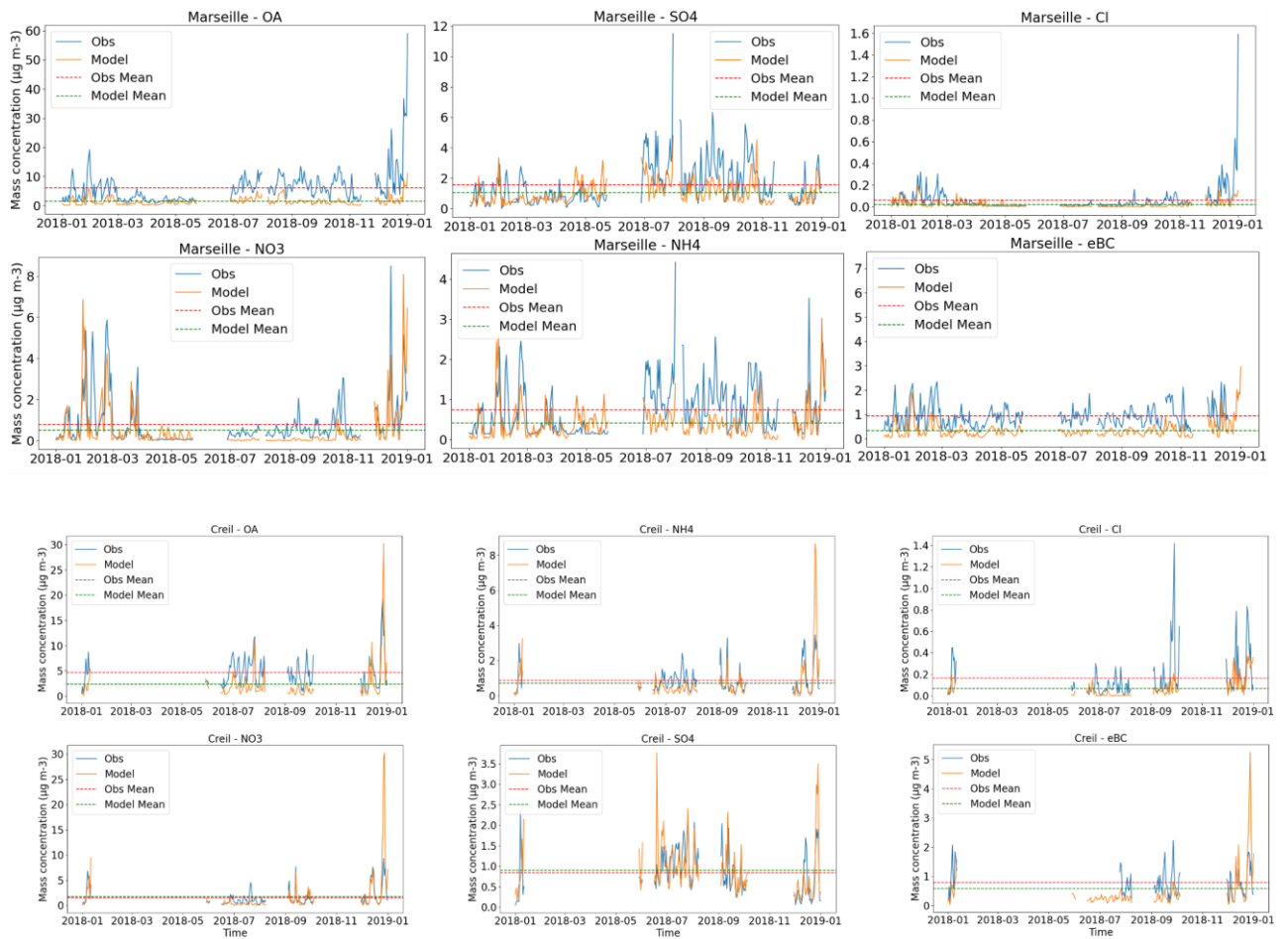
Figure S10: Temporal variability from simulations and observations for PM$_1$ chemical species at each site.
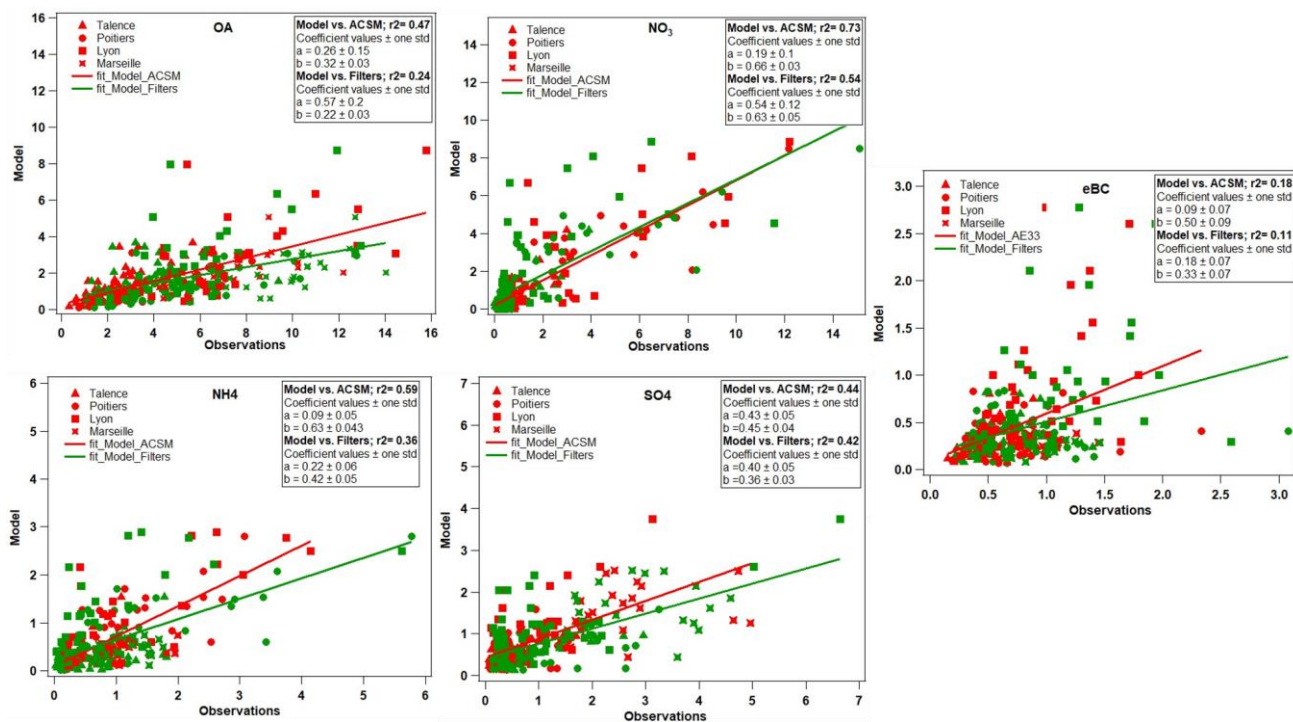
Figure S11: Scatterplots of comparison between daily averages of simulations and either online (in red; ACSM or AE33) or offline observations (in green; filter analyses) (in µg m^{-3}) for OA, NO$_3$, NH$_4$, SO$_4$, and eBC at four French urban sites (Talence, Poitiers, Lyon, and Marseille).

Sites description

A description of the sites discussed in this paper is presented below. For the ATOLL, SIRTA, and Marseille stations, their details can be found in Chebaicheb et al. 2023, Zhang et al. 2019, and Chazeau et al. 2021 et 2022, respectively.

1.   Paris Les Halles

The "Paris Les Halles" is an urban background station, located in the 1st district of Paris, 22 km from SIRTA. Les Halles, in the heart of Paris, is characterized by high local activity, with green spaces, shopping malls, restaurants, and numerous areas dedicated to leisure and culture, as well as the Châtelet - Les Halles RER train station, which is the largest underground station and provides access to the entire Paris region network.

The station is multi-instrumented, with permanent in-situ measurements since October 2019. Samples are taken at heights of between 1.55 and 2 m above ground level, with a 270° clearance to ensure optimum representativeness of measurements.

Figure S12: Map indicating the location of the Airparif Paris 1st-Les Halles station (top); photographs (credit: AirParif) of the sampling heads (bottom left) and the interior of the station (bottom right).

2. Boulevard Périphérique Est (BPEst)

The Boulevard Périphérique Est station, located in the 12th district of Paris, is an urban traffic station that has been in operation since January 2013. The Boulevard Périphérique surrounds the Paris city and is 35 km long. In general, it has four lanes in each direction. The largest traffic flows in the Paris region remain concentrated on the boulevard périphérique, with a traffic record of 180,000 to 250,000 vehicles per day according to the Atelier Parisien d'urbanisme (APUR) in 2019. This road generates significant emissions of gaseous and particulate pollutants into the air.

Samples are taken at heights ranging from 2.8 to 3.1 m above ground level. Sampling distances are 5 m to the road edge and 6.5 m to the center of the first traffic lane. The measurement axis covers 2×4 lanes with a total width of 34 m.

These measurements are used to monitor air quality in the vicinity of Paris's Boulevard Périphérique Est, assessing gaseous pollutants, fine particles, and aerosol levels. By focusing on an environment characterized by dense traffic, this station contributes to understanding the impact of road traffic-related pollution on air quality in this urban area.

Figure S13: Map detailing the location of the BPEST station (left) and a photograph (credit: AirParif) of the sampling heads at the edge of the ring road (right).

3. Gennevilliers

The Gennevilliers station is an urban background station, located 2.1 km northwest of Paris, and has been in operation since January 1986. Gennevilliers is a densely populated urban commune (49,880 inhabitants in 2020; 4,300 inhabitants/km^2). It lies at the crossroads of two freeways, the A15 and the A86, and covers an area of 1,200 hectares. Two-thirds of its surface area is devoted to economic and industrial activities. The commune is located in the Hauts-de-Seine department, a community rich in river transport.

Samples are taken at a height of around 15 m above ground level, on the roof of the Collège Louis Pasteur, to obtain representative ambient air samples. What's more, the station enjoys 360° clearance, ensuring unobstructed sampling around the site.

Figure S14: Map specifying the location of the Gennevilliers station (left) and a photograph (credit: AirParif) of the sampling heads on the roof of Louis Pasteur College (right).

4. Creil

The Creil monitoring station is an urban station located in the Oise department, in the Hauts-de-France region. It is specifically located in the center of the commune of Creil, which is the center of an urban unit comprising 22 communes and home to almost 120,000 inhabitants, making it the largest conurbation in the Oise region. Creil is close to major cities such as Paris, Beauvais, and Amiens, at distances of 45.35 and 72 km respectively. The town is crossed by the Oise River and is surrounded by two forests, the Halatte forest to the east and the Chantilly forest to the southeast.

The Creil measuring station is located in an urban environment influenced by both urban traffic and residential emissions. These measurements enable us to monitor air quality in the commune of Creil and assess the impact of emissions from road traffic, residential activities, and other local sources on air pollution in this urban area.
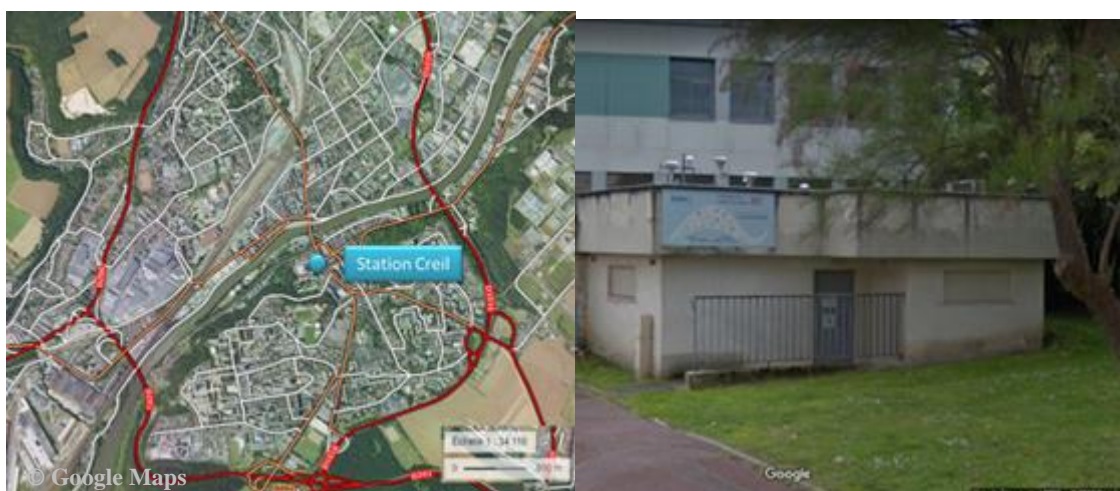
Figure S15: Map specifying the location of the Creil station (left) and a photograph (credit: Atmo Hauts-de-France) of the exterior of the station (right).

5. Lyon

The Lyon Centre urban background site, located in the Bassin Lyonnais/Nord Isère area, has been operational since January 5, 2007. Located in the heart of Lyon city, the monitoring station plays an essential role in collecting data on air quality in this densely populated agglomeration. It is France's third largest city, with 522,969 inhabitants

in 2019 (INSEE, 2019). Lyon is the capital of the Auvergne-Rhône-Alpes region, which covers an area of 69,711 km2. The city is known for its strong industrial activity, but also its agricultural and agri-food activities.

This site is representative of the Lyon population's exposure to atmospheric pollution; it characterizes the air breathed by all Lyon residents. In addition, the monitoring station is strategically positioned to capture pollution levels resulting from urban activities such as road traffic, industry, and domestic emissions. It thus provides crucial information for assessing the effectiveness of pollution reduction measures and supporting the implementation of environmental policies towards improving air quality in the region.
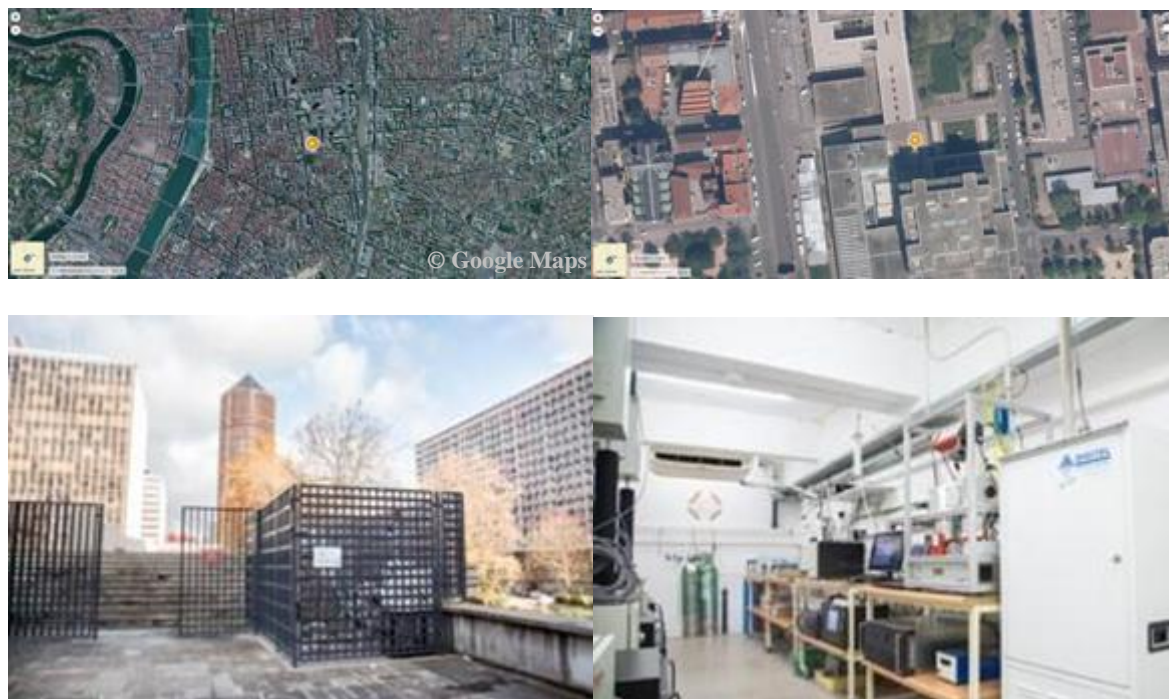
Figure S16: Satellite images pinpointing the location of the Lyon Centre station on a large scale (top left) and a small scale (top right), along with photographs (credit: Atmo AuRA) showing an exterior view (bottom left) and an interior view of the measurement station (bottom right).

6.   Metz

The Metz measurement station is located in the Borny district, which is situated in the southeast of the city center of Metz. The city is located halfway between Strasbourg (130 km) and Reims (155 km). It is 55 km east from the Paris region. Its population density is 2,866.3 inhabitants/km^2 in 2020 (120,211 inhabitants). It is known for its strong economic and industrial activity, notably metallurgy, petrochemicals, automotive, logistics, and commerce. This station is considered an urban background site and is located in a residential area. On the same street, there are mainly single-family homes and a nursery school, which means there is plenty of parking for school buses and parents. To the south of the station, there is also a shopping area with restaurants. These environmental features are important to consider when interpreting the measurement data, as they can influence air quality in this particular area. The proximity of homes, schools, and commercial activities can contribute to the exposure of the local population to air pollutants. For this reason, monitoring this urban background station is of particular importance in assessing the impact of human activities on air quality in this area.
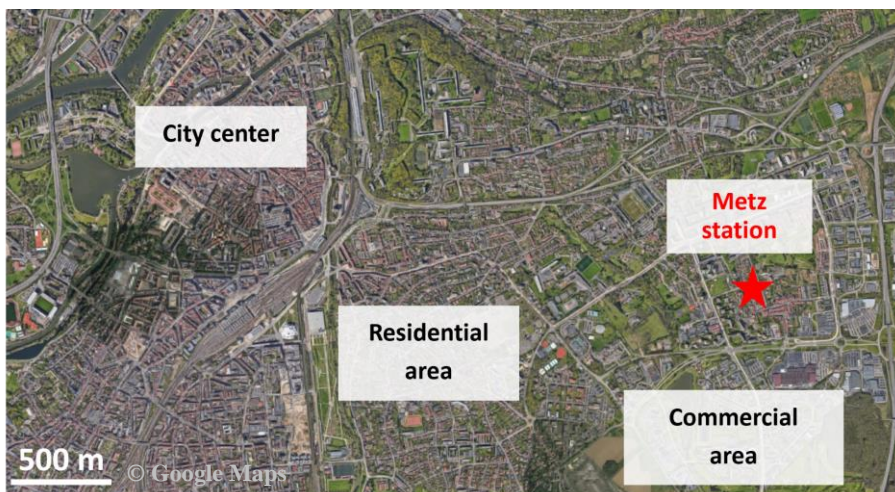
Figure S17: Map showing the location of Atmo Grand-Est's measuring station in Metz. (© Google Maps)

7. Strasbourg

The Danube station is located in the Neudorf district, south-east of Strasbourg, and has been in operation from December 2019 to the present day. The Neudorf district, where Danube station is located, is an eco-district currently under construction. It is surrounded by residential areas to the south and north, with a commercial zone including restaurants. To the east of the station, there is also a river port and a major thoroughfare (Avenue du Rhin) less than 100 m away.

Strasbourg is a predominantly urban agglomeration, representing 26% of the Strasbourg Urban Community (CUS), with a strong agricultural base covering 40% of the CUS. It also boasts five major industrial sites. The city is served by two major roads, the A35-A4 freeway (north/south axis) and the Rhine road (east/west axis). There are also rail links, with a TER station and a TGV station in Strasbourg, as well as an international airport in Entzheim and a river port in Strasbourg.

In terms of meteorology and topography, Strasbourg has a semi-continental climate, with low precipitation and limited sunshine. The preferred wind directions are south-southwest and north-northeast, and air masses are predominantly wind-driven, with some influence from Central European air masses.
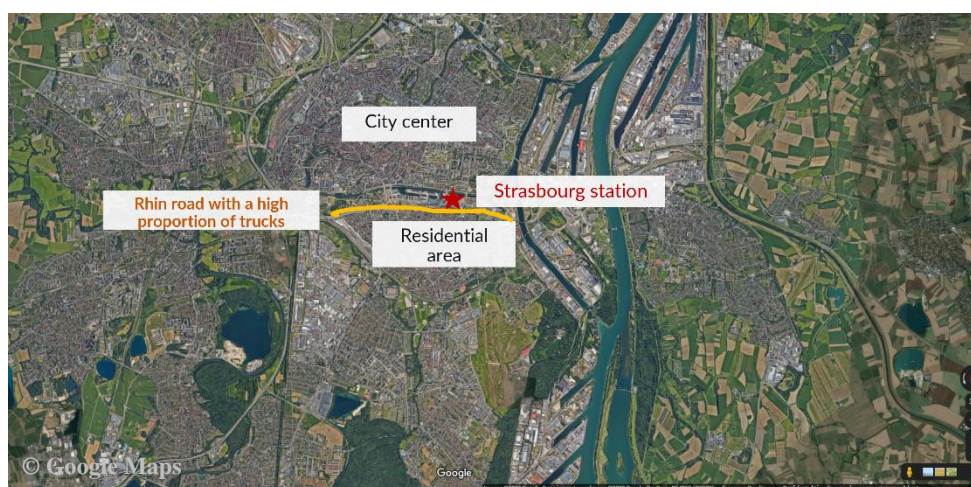
Figure S18: A map specifying the positions of the two Strasbourg measurement stations.

8.   Talence

The Talence station is an urban background station, set back from major traffic arteries. It is a reference station for monitoring particulate matter. Talence is part of the Bordeaux metropolitan area, which comprises 73 communes. It is one of the most densely populated communes in the region, with over 5,312.5 inhabitants/km² (44,359 inhabitants) in 2020. It is a highly urbanized city, with a dominant service sector. On the other hand, there is very little industrial or agricultural activity. It is surrounded by regional nature parks, notably the Landes de Gascogne forest to the southwest and the Parc du Médoc to the northwest.

Figure S19: A map and satellite image precisely indicating the location of the Talence station on a large scale (left) and a small scale (right)

9.   Poitiers

The Poitiers Augouard station is an urban background station located on rue Augouard in downtown Poitiers. The Poitiers agglomeration, located halfway between Paris and Bordeaux, is a densely populated urban area with 90,033 inhabitants in 2020. The measurement station plays an important role as a reference station for fine particulate monitoring in the region. It has been equipped with an AE33 since 2014 and an ACSM since 2015 to continuously analyze the chemical composition of fine particles in ambient air. In addition to these measurements, the station also carries out measurements of gaseous pollutants.

Figure S20: A map and satellite image providing precise details on the location of the Poitiers Augouard station on a large scale (left) and a small scale (right).

10. Rennes

The "Pays-Bas" station in Rennes is an urban background station that was established on August 30, 2012. Rennes is located in north-western France and is the capital of the Brittany region. It has a population of 354,000 in 2020. Rennes lies at the junction of the Channel-Atlantic link and is characterized by an oceanic climate. Within the Rennes metropolitan area, road transport and industry make smaller contributions. On the other hand, the agricultural and residential sectors play a greater role in PM_{10} and $PM_{2.5}$ emissions (AASQA, 2022).

The station is located in the south of Rennes, in a residential area served by the metro, and includes several apartment buildings, some of which are connected to the biomass heating network. Near the station, there is an unpaved footpath and a parking lot to the southeast.
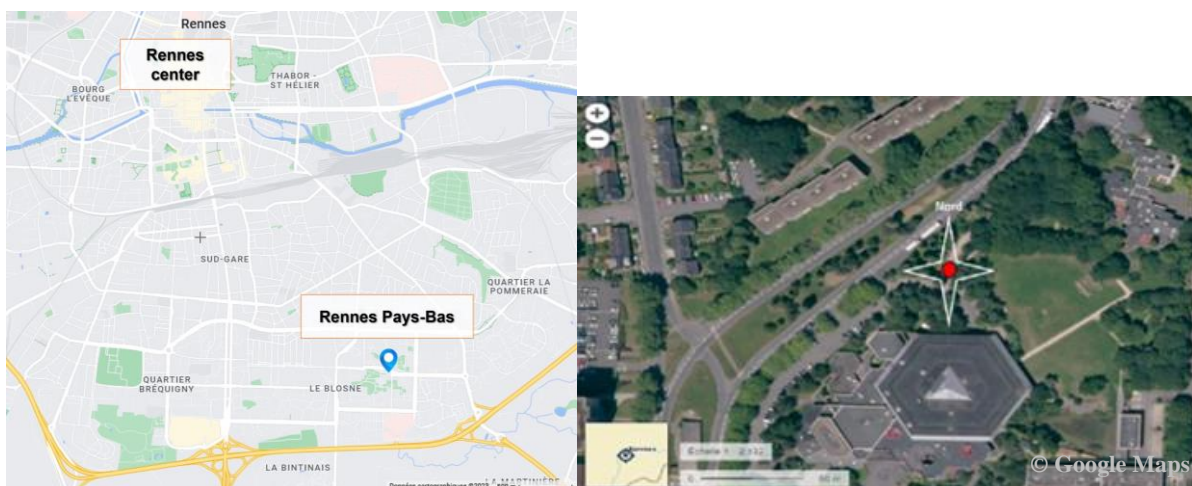
Figure S21: Satellite images providing precise location details of the Rennes Pays-Bas station on a large scale (left) and a small scale (right).

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