Allergic Pollen Detection Campaign 2026
MontAdapt Project

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Location: Grenoble, France

Campaign Period: February 2026 to October 2026

Summary

Airborne pollen is a major environmental health concern, and its dynamics are strongly influenced by climate and local environmental conditions. Within the MontAdapt project, a pollen monitoring campaign was conducted in the Grenoble region (France) between February and October 2026 to investigate the influence of altitude on pollen seasonality and allergenic exposure.

Measurements were carried out at three elevations ranging from the Grenoble valley to approximately 1,000 m above sea level using a combination of automated Aerōtape sensors and traditional Hirst and Sigma-2 (SLT) samplers. The Aerōtape system provided high-frequency observations and real-time processing through a deep-learning-based pollen recognition algorithm, enabling automated concentration estimation and data delivery via a dedicated pipeline. SLT samplers were used as reference methods and showed good overall agreement with Aerōtape measurements in capturing seasonal trends and major pollen peaks.

The study focused on eight allergenic pollen taxa: *Corylus*, *Alnus*, *Betula*, Cupressaceae, *Fraxinus*, *Quercus*, *Poaceae*, and *Ambrosia*. Results show a clear seasonal succession in Grenoble, from early tree pollen (*Corylus*, *Alnus*) through spring taxa (*Fraxinus*, *Quercus*, *Betula*) to summer grasses (*Poaceae*) and the late summer *Ambrosia* pollen. Comparison with historical pollen Hirst data (1991–2024; RNSA) indicates earlier pollen peaks in 2026 for several taxa, particularly *Corylus*, *Alnus*, *Fraxinus*, and *Quercus*, consistent with a shift in phenology potentially linked to climate warming.

Altitude affected pollen composition more than seasonal timing. Urban Grenoble showed higher concentrations of Cupressaceae, *Platanus*,

Populus and *Ambrosia*, while higher elevations were characterized by increased *Poaceae*, *Betula*, *Picea*, and *Salix*. Grass pollen dominated across all sites in late spring, with highest concentrations around 900–1,000 m.

Overall, the Aerōtape system showed good agreement with manual samplers, demonstrating the reliability of AI-based continuous pollen monitoring for environmental health applications and climate adaptation strategies.

1. Introduction

Airborne allergenic pollen represents a significant public health issue for millions of people living in both urban and rural environments. Exposure to pollen can trigger allergic rhinitis, asthma, and other respiratory symptoms in sensitive individuals. Different plant species release pollen at different times of the year, resulting in distinct seasonal allergy periods.

In central regions of France, the pollen season may begin as early as January with highly allergenic pollen from hazel (*Corylus*) and alder (*Alnus*). These early-season taxa are followed by ash (*Fraxinus*), oak (*Quercus*), and birch (*Betula*) during spring, typically until the end of May. During summer, grasses (*Poaceae*) become the dominant source of allergenic pollen and can maintain high pollen concentrations for several months. Pollen from the Cupressaceae family (cypress and juniper species) may also be present from January onward throughout much of the pollen season. Finally, ragweed (*Ambrosia*) can generate an additional peak of allergic risk during late summer and early autumn.

Individuals may be sensitized to one or several pollen taxa simultaneously, resulting in varying levels of allergic symptoms throughout the year.

In mountain regions, pollen occurrence and seasonality are strongly influenced by altitude. Lower temperatures, delayed vegetation development, and differences in land cover and ecosystem composition can lead to substantial variations in pollen exposure between valley and mountain locations.

Within the framework of the MontAdapt project, we investigated how altitude affects the occurrence and timing of major allergenic pollen species in the Grenoble region. Measurements were conducted at three elevations: within the Grenoble valley at 14m, in the Belledone Mountains at approximately 580 m and at approximately 1,000 m above sea level. The objective was to evaluate differences in pollen season onset, duration, and intensity across the altitudinal gradient and to contribute to a better understanding of climate-related health impacts in mountain environments.

2. Instrumentation and Methods

2.1 Monitoring Devices

The pollen monitoring campaign combined automated and manual sampling methods. Automated measurements were performed using Aerōtape devices (Oberon Sciences), while traditional Hirst and Sigma-2 (SLT) samplers were installed in parallel at selected locations for validation purposes.

The Aerōtape is an automated pollen monitoring instrument that samples air at a flow rate of approximately 17 L min^{-1} for 10 minutes. Airborne particles are deposited onto a sticky collection tape and subsequently imaged using an integrated optical system. Images are acquired automatically and processed by an artificial intelligence algorithm for pollen detection and classification. The instrument provides near real-time measurements with a temporal resolution of approximately 12 minutes, allowing continuous monitoring without human intervention.

The Hirst sampler is the reference method for pollen monitoring. It continuously pumps air at approximately 10 L min^{-1} onto a rotating adhesive tape over a seven-day period. Following collection, the tape is analysed manually by a trained palynologist. This method provides daily pollen concentration data but requires significant manual processing.

The Sigma-2 (SLT) sampler is a passive collection device that captures airborne particles on adhesive microscope slides without active air pumping. Slides are exposed for seven days before laboratory analysis. While simpler to deploy, the method provides only weekly resolution and also requires manual microscopic counting.

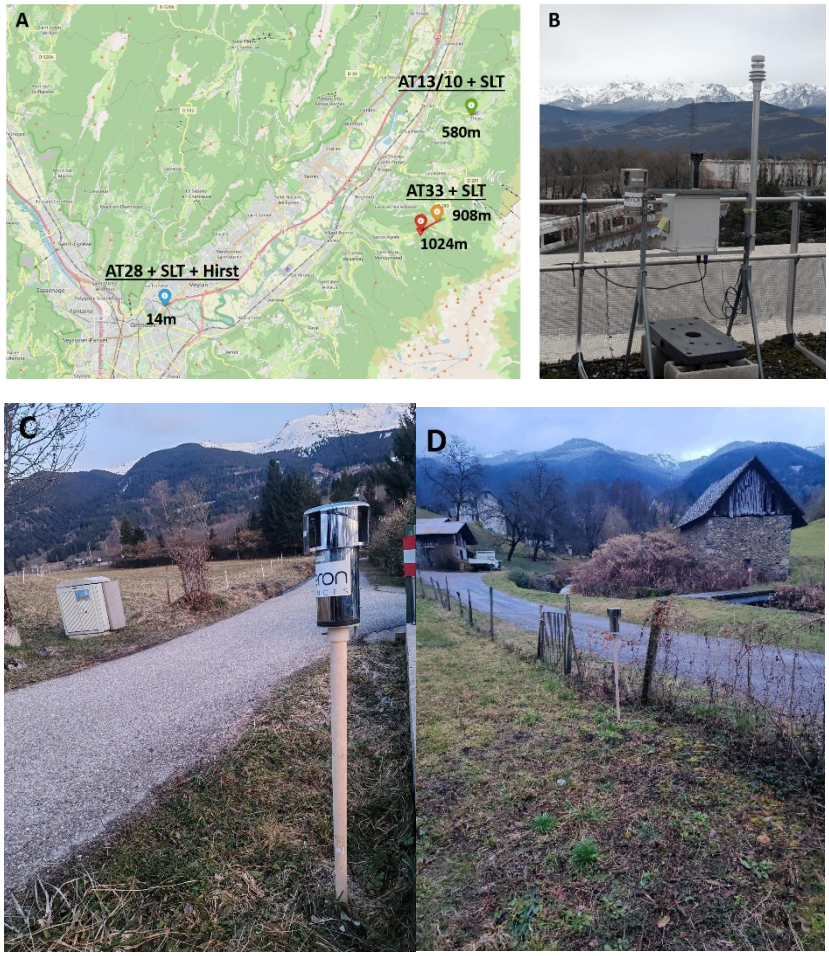


Figure 1: Monitoring sites and instrumentation used during the MontAdapt pollen monitoring campaign. (A) Map showing the locations and elevations of the monitoring stations in the Grenoble region. AT = Aerōtape automated pollen monitor; SLT = Sigma-2 passive pollen sampler; Hirst = Hirst volumetric pollen sampler. (B) Aerōtape device (AT28) installed on the rooftop monitoring station near La Tronche Hospital, Grenoble. (C) SLT at 580m. (D) SLT at 908m.

2.2 Monitoring Sites

To investigate the influence of altitude on airborne pollen concentrations, measurements were conducted at three locations within the Grenoble region (Figure 1).

Grenoble City Site (AT28)

The primary monitoring station was located near La Tronche Hospital in Grenoble. An Aerōtape device was installed on the roof of a 14-m-high building, representing pollen exposure conditions for both local residents and hospital patients. A Hirst sampler and a Sigma-2 sampler were installed alongside the Aerōtape for comparison and validation. All instruments were operational from the end of January 2026.

Mid-Elevation Site (~580 m)

The second monitoring site was located in the Belledonne Massif at approximately 580 m above sea level. A Sigma-2 sampler was installed on 24 February 2026, followed by an Aerōtape device in early May 2026.

High-Elevation Site (~1,000 m)

The third site was established at approximately 908 m above sea level with a Sigma-2 sampler operating from late February 2026 onward. An Aerōtape device was installed in early May and subsequently relocated on 28 May to a nearby location at 1,024 m altitude.

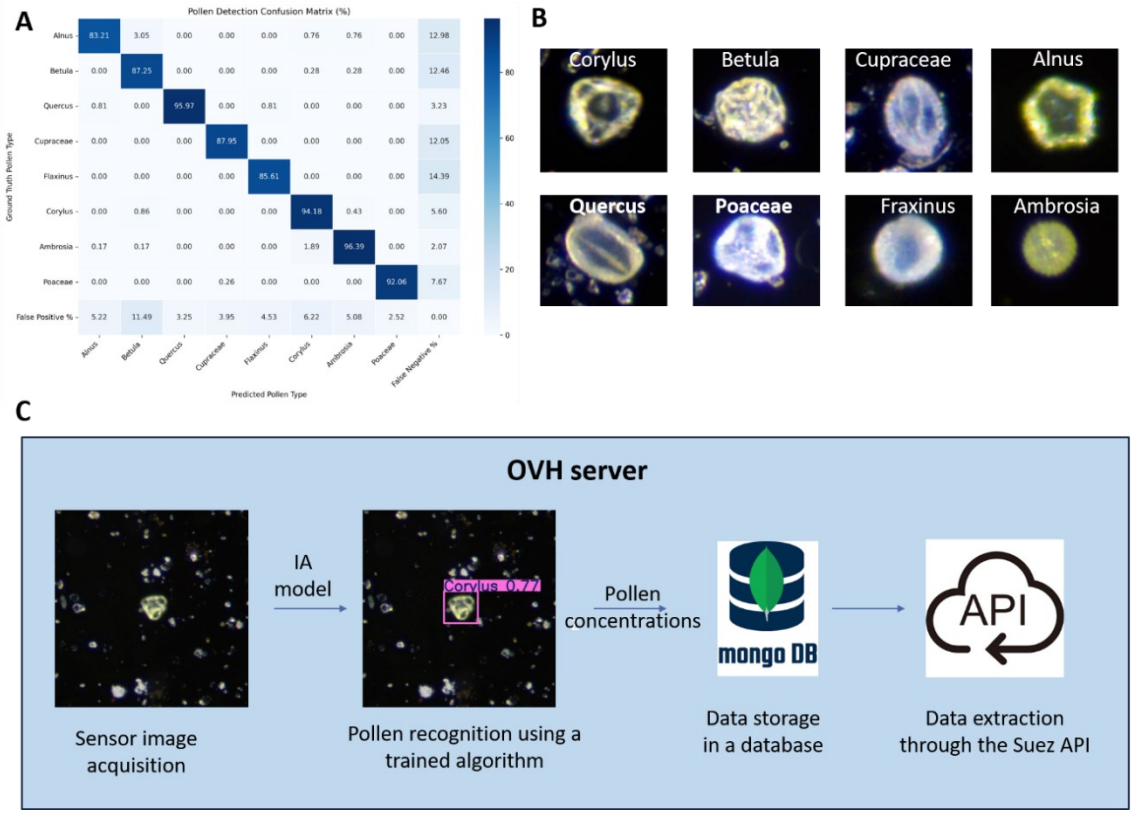


Figure 2: Artificial intelligence-based pollen recognition and automated data-processing pipeline developed for the Aerōtape monitoring system. (A) Confusion matrix showing pollen classification performance of the AI model, including correct classifications, false positives, and false negatives for each pollen taxon. (B) Representative Aerōtape images of the eight allergenic pollen taxa detected by the model. (C) Schematic representation of the automated data-processing workflow: images acquired by Aerōtape sensors are transmitted to the server, processed by the AI-based pollen recognition algorithm, converted into pollen concentration data, stored in a database, and subsequently made available to the Suez client through a dedicated API.

2.3 Data Analysis and Pollen Recognition

Sigma-2 samples were analysed manually after staining with Basic Fuchsin dye to improve pollen visibility under optical microscopy. Pollen grains were identified and counted by trained personnel.

Aerōtape data consisted of microscopic images containing airborne particles, together with meteorological measurements recorded by an integrated weather station. The meteorological parameters included air temperature, relative humidity, precipitation, wind speed, and wind direction.

The morphology of pollen grains differs substantially among taxa and can be recognised from Aerōtape images (Figure 2B). To automate pollen detection, an object detection model based on the YOLO11 deep-learning architecture was trained and fine-tuned using annotated pollen images. The resulting model achieved classification accuracies ranging from 83% for *Alnus* pollen to 95% for *Ambrosia* pollen (Figure 2A).

An automated data-processing pipeline was developed to enable real-time pollen monitoring (Figure 2C). The workflow included:

- Acquisition of sensor images;
- Pollen recognition using a trained AI algorithm;
- Calculation of pollen concentrations;
- Storage of processed data in a database;
- Data extraction through a custom Suez API.

This pipeline enabled near real-time delivery of pollen information through the Suez Air Advanced Sentinel platform, providing access to environmental health information for authorities, healthcare professionals, and allergy sufferers.

The AI model was trained to identify eight major allergenic pollen taxa:

Corylus (hazel), *Alnus* (alder), *Betula* (birch), Cupressaceae (cypress/juniper), *Fraxinus* (ash), *Quercus* (oak), Poaceae (grasses), *Ambrosia* (ragweed)

Daily pollen concentrations were converted into allergy risk levels using thresholds adopted from the French National Aerobiological Monitoring Network (RNSA) (Table 1).

Risk Level	Description	Alnus	Betula	Quercus	Cupressaceae	Fraxinus	Corylus	Ambrosia	Poaceae
0	Null	<6	<5	<6	<7	<6	<6	<1	<1
1	Very Low	6–13	5–19	6–13	7–13	6–13	6–13	1	1–3
2	Low	14–70	20–49	14–70	14–56	14–70	14–70	2–4	4–9
3	Moderate	71–227	50–99	71–227	57–141	71–227	71–227	5–9	10–34
4	High	228–456	100–170	228–456	142–227	228–456	228–456	10–29	35–99
5	Very High	≥457	≥171	≥457	≥228	≥457	≥457	≥30	≥100

Table 1. Pollen concentration thresholds (pollen m^{-3}) used to assign allergy risk levels for the eight monitored allergenic pollen taxa. Risk categories were adapted from the methodology of the French National Aerobiological Monitoring Network (RNSA).

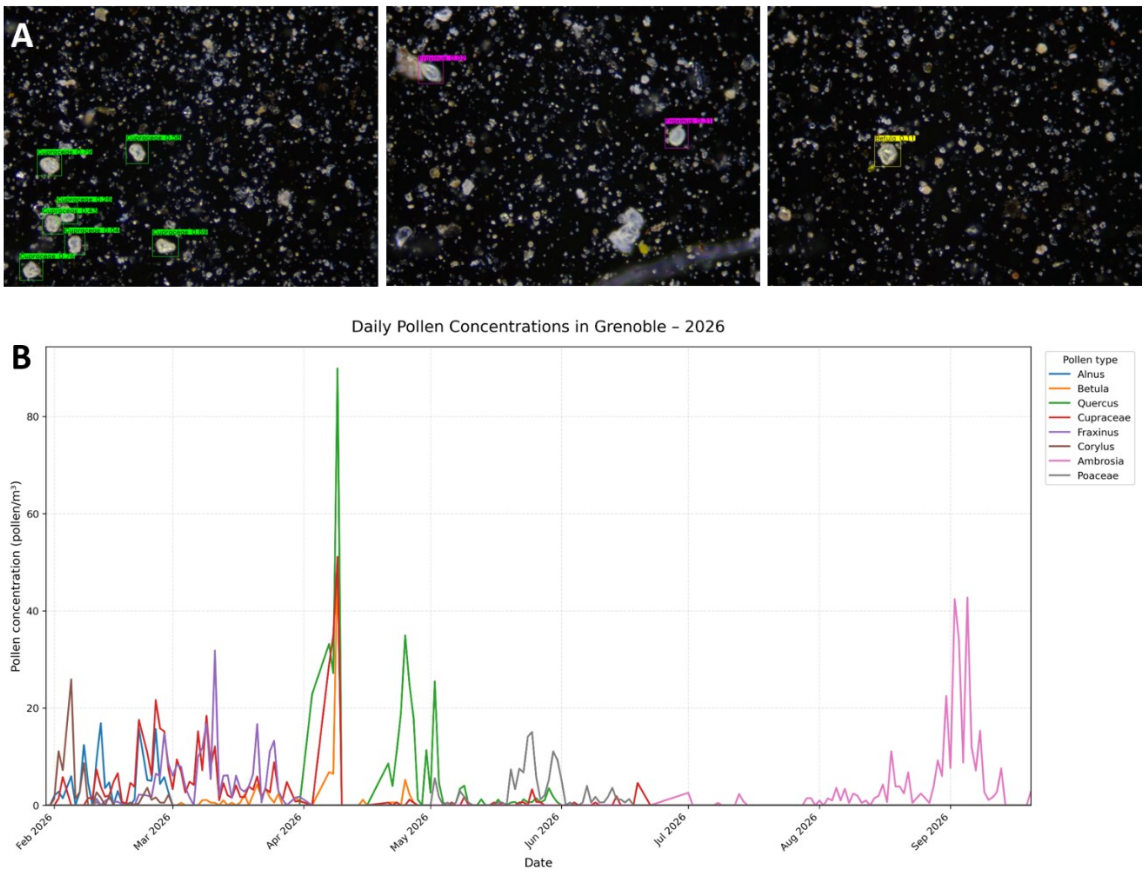


Figure 3: Seasonal pollen monitoring in Grenoble using the Aerōtape automated pollen sensor during the 2026 pollen season. (A) Representative Aerōtape images showing different pollen taxa and their identification by the AI-based recognition algorithm. (B) Daily pollen concentrations for the eight monitored allergenic taxa measured throughout the 2026 observation period.

3. Pollen Detection Results

3.1 Pollen Monitoring in Grenoble

Pollen monitoring in Grenoble was conducted on the rooftop of a 14-m-high building located near the La Tronche hospital complex. The Aerōtape automated pollen monitor successfully detected the major seasonal peaks of allergenic pollen throughout the observation period (Figure 3).

Strong concentrations of *Corylus* (hazel) and *Alnus* (alder) pollen were observed during February, with the season ending in early March. *Betula* (birch) pollen was detected from March until the beginning of May. Pollen from the Cupressaceae family appeared from late February and persisted at lower concentrations throughout the spring. *Fraxinus* (ash) exhibited a pronounced peak during March, while *Quercus* (oak) pollen was predominantly observed during April. The *Poaceae* (grass) pollen season began in mid-May and continued up to the end of June. Finally, *Ambrosia* (ragweed) was detected throughout August and September.

Two periods with very low allergenic pollen risks occurred, one during the first half of May, coinciding with a period of persistent rainfall and another throughout July between the *Poaceae* and *Ambrosia* seasons. This suggests that precipitation significantly reduced airborne pollen concentrations through washout effects in May.

Comparison between Aerōtape measurements and the co-located Sigma-2 (SLT) sampler demonstrated good agreement between the two methods (Figure 4). Both monitoring systems successfully captured the major pollen peaks and seasonal dynamics of the dominant allergenic taxa, confirming the reliability of the automated monitoring approach.

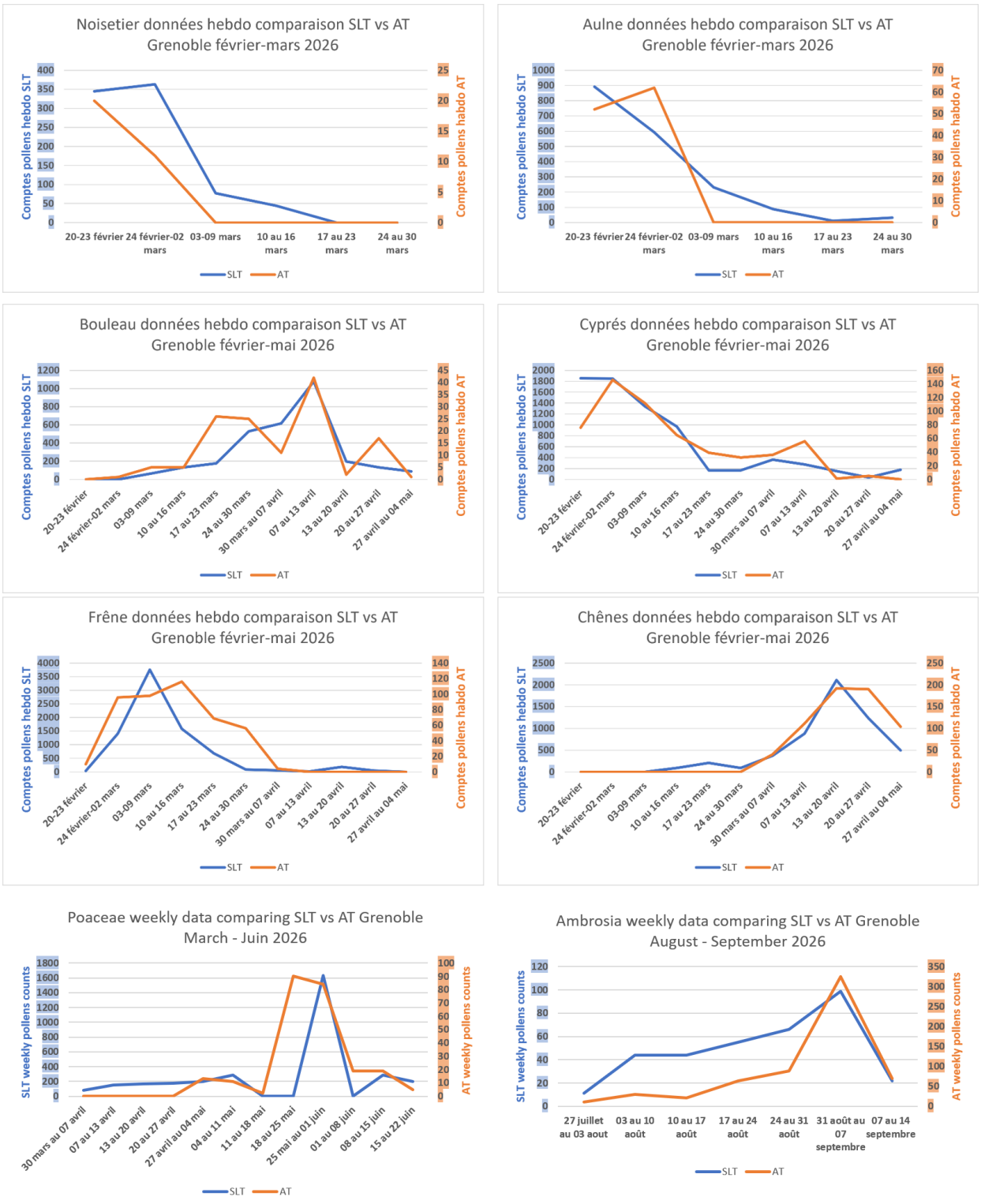


Figure 4: Comparison of pollen measurements obtained from the Aerōtape automated monitoring system and the Sigma-2 (SLT) sampler at the Grenoble reference site. Seasonal dynamics are shown for six major allergenic pollen taxa: *Corylus* (hazel), *Alnus* (alder), *Betula* (birch), Cupressaceae, *Fraxinus* (ash), and *Quercus* (oak).

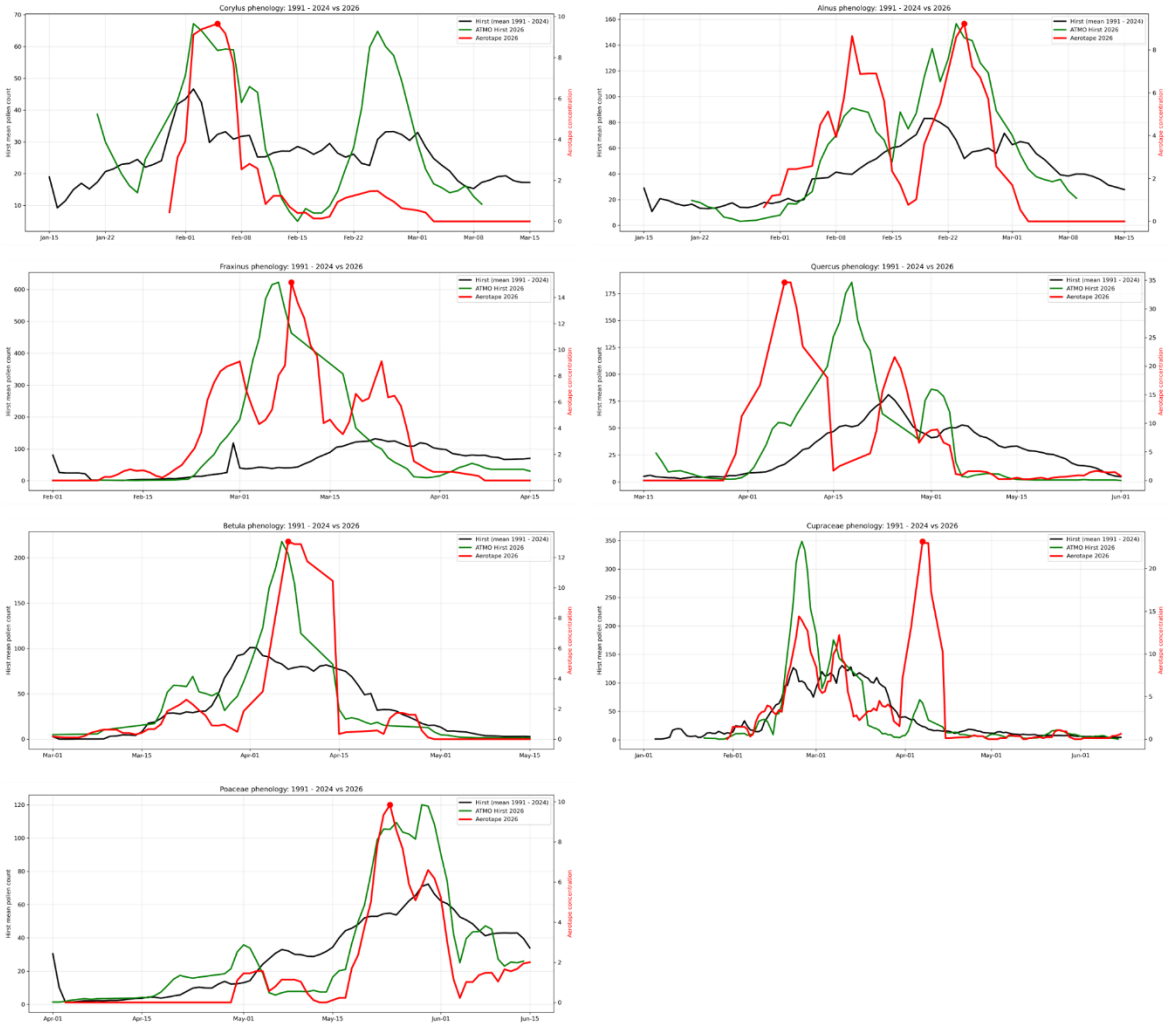


Figure 5: Comparison of seasonal pollen dynamics measured by the Aerōtape monitoring system in 2026 with historical Hirst pollen observations from 1991–2024 obtained from the RNSA open database and with open source ATMO Hirst data 2026. Daily pollen concentrations are shown for seven major allergenic taxa. Data were smoothed using a 5-point centered moving average.

Historical comparisons revealed that the onset and peak timing of several pollen seasons occurred earlier in 2026 than the long-term average recorded since 1991 (Figure 5). The most pronounced shifts were observed for *Fraxinus*, *Quercus*, *Alnus* and *Poaceae*.

In contrast, the *Betula* pollen season was comparable to historical observations, showing little deviation from the long-term average. Cupressaceae pollen was detected over an extended period compared with previous years, suggesting a lengthening of the pollen season for this taxon.

These observations are consistent with the effects of warmer winter and spring temperatures, which may accelerate flowering and pollen release in several tree species.

Aerōtape pollen measurements were also compared with open-access Hirst pollen data from 2026 (Figure 5). For *Alnus, Betula*, and *Poaceae,* both Aerōtape and the ATMO Hirst sampler detected peak pollen concentrations at approximately the same time, indicating strong agreement between the two monitoring systems.

For *Corylus*, the first major peak was detected by both systems; however, the second large peak observed by the Hirst sampler at the end of February was only weakly detected by Aerōtape. For *Quercus*, pollen peaks appeared to be shifted by approximately one week between the two monitoring systems, affecting both major peak events. *Cupressaceae* pollen was detected similarly by both systems during the first and second peaks, whereas the third peak was substantially more pronounced in the Aerōtape data.

These differences may reflect the different locations of the monitoring stations within the Grenoble area and could therefore represent local variations in pollen production, dispersal, and atmospheric transport rather than differences in sensor performance.

3.2 Pollen Monitoring in Mountain Environments

To investigate the influence of altitude on pollen occurrence, monitoring stations were installed at approximately 580 m and 908 m above sea level in the Belledonne mountain range northeast of Grenoble. Sigma-2 samplers were deployed from February onwards, while Aerōtape monitors were installed at both locations in early May. The Aerōtape instrument initially located at 908 m was subsequently relocated to a nearby site at 1,024 m altitude (Figure 1).

Comparison of Aerōtape measurements from the three sites between May and June (Figure 6) showed that *Poaceae* pollen dominated at all elevations during this period. The major grass pollen peaks occurred simultaneously at all sites, indicating that the onset of the grass pollen season was not substantially delayed by altitude within the studied elevation range.

However, important differences in pollen concentrations were observed. The highest *Poaceae* concentrations were measured at approximately 908 m altitude, where peak values were roughly twice those recorded in Grenoble and at the 580 m site. This pattern is likely related to the increasing presence of alpine and subalpine meadows at higher elevations, where grasses become the dominant vegetation type.

Quercus pollen was detected at all sites but showed markedly higher concentrations in Grenoble. A pronounced peak reaching approximately 25 pollen m^{-3} was observed in early May in the city, whereas only weak

concentrations were detected at the mountain stations. Cupressaceae pollen was detected only sporadically and at low concentrations at all sites during this period, indicating a relatively low allergy risk.

Ragweed (*Ambrosia*), a highly allergenic pollen, was detected almost exclusively in Grenoble, reaching concentrations of up to 42 pollen/m³ (Figure 7). These levels corresponded to the highest allergy risk during the last week of August and the first two weeks of September. In contrast, substantially lower ragweed pollen concentrations were detected at higher altitudes, rarely exceeding 5 pollen/m³ and corresponding to a low allergy risk. These results highlight the striking difference in ragweed-related allergy risk between lowland and mountain environments. They may also point to the potential influence of climate change on allergy risks in mountain regions, as the detection of ragweed pollen at higher altitudes could provide an early indication of its expansion into these environments.

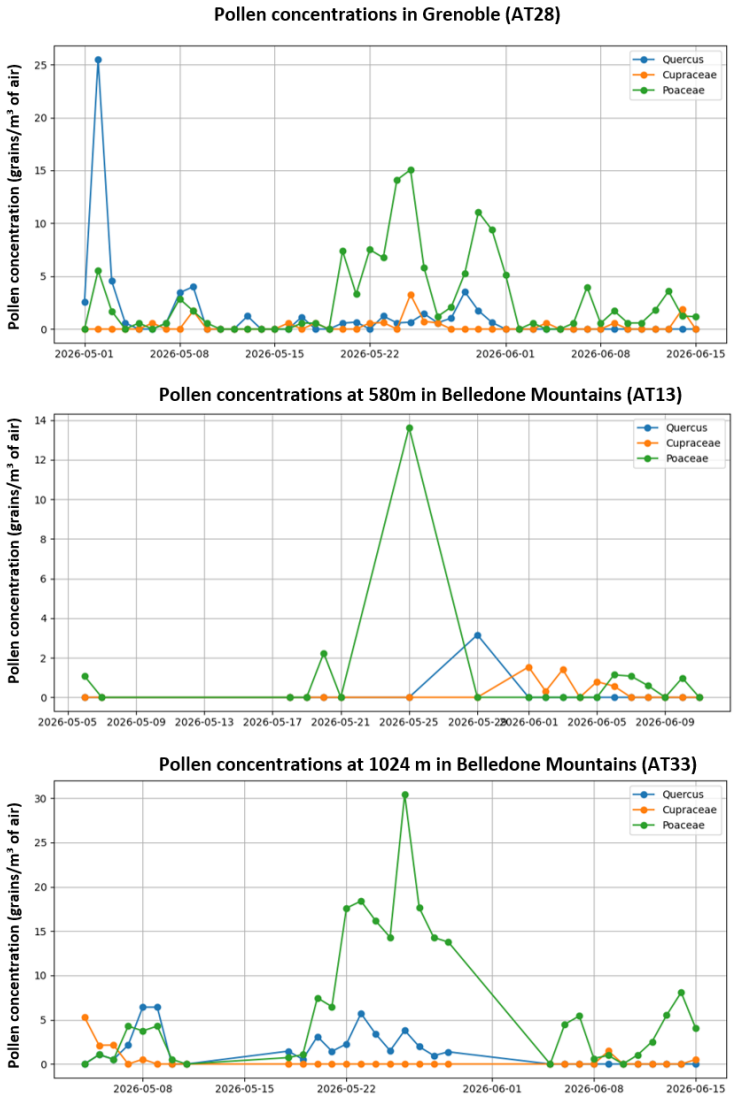


Figure 6: Comparison of pollen concentrations measured by Aerōtape monitoring stations located in Grenoble, at 580 m altitude, and at 1024 m altitude during May and June 2026.

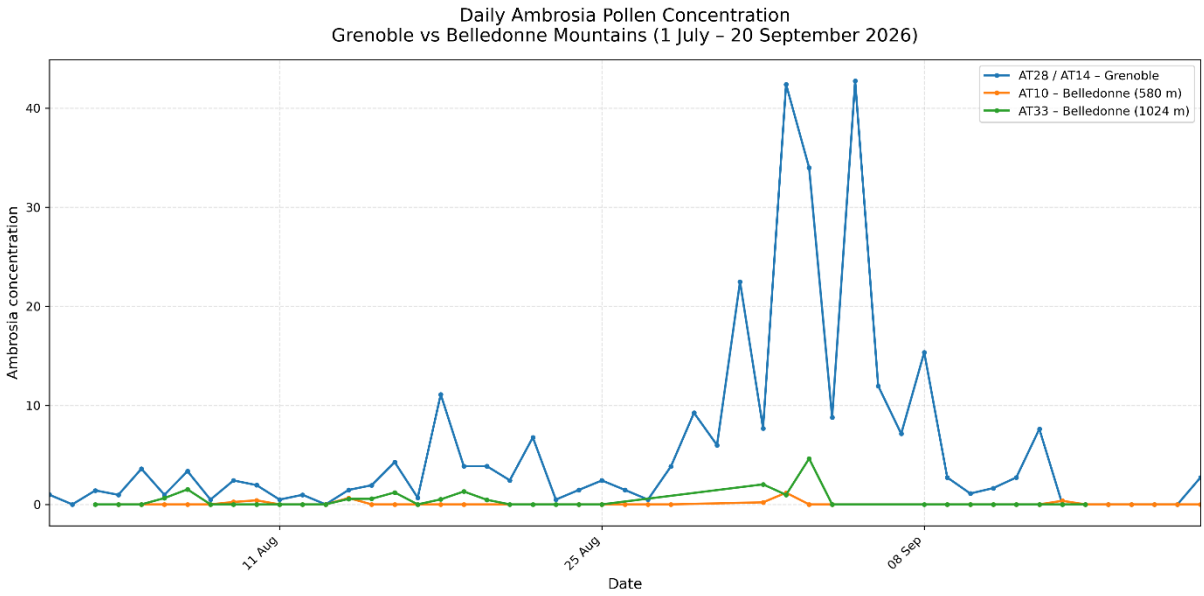
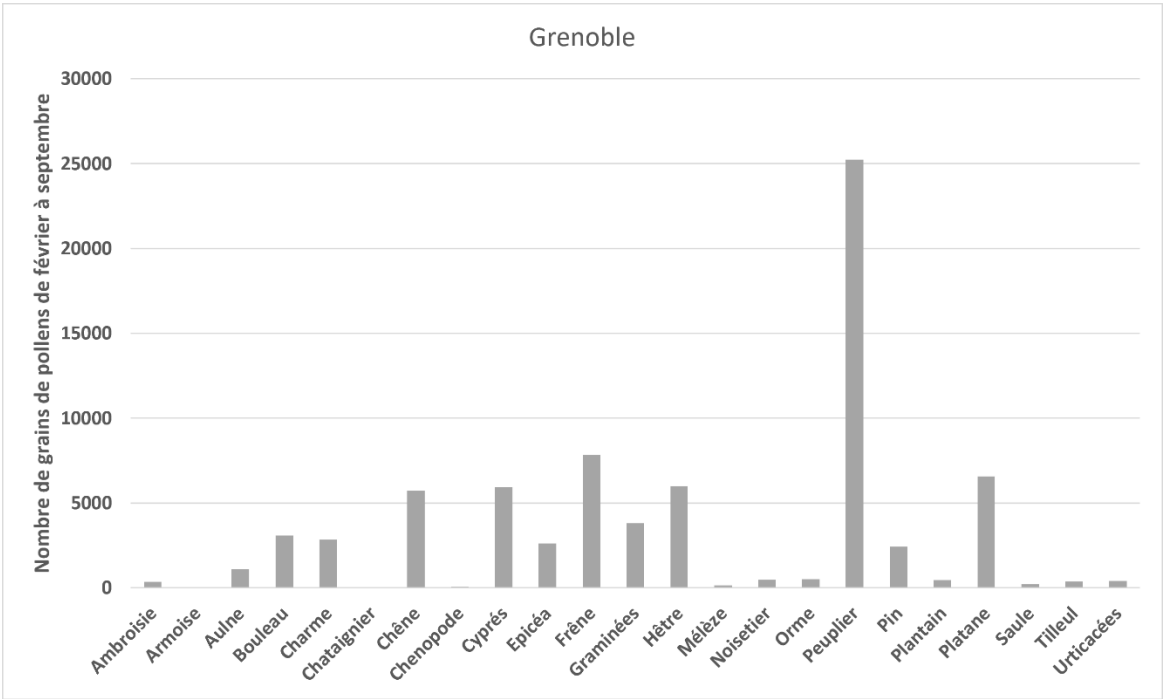


Figure 7: Comparison of ragweed pollen concentrations measured by Aerōtape monitoring stations located in Grenoble, at 580 m altitude, and at 1024 m altitude during August and September 2026.

The Sigma-2 samplers provided a longer observation period and enabled comparison of pollen assemblages throughout spring and early summer (Figure 8 - 10). Distinct differences in pollen composition were observed between the urban and mountain environments (Figure 8).



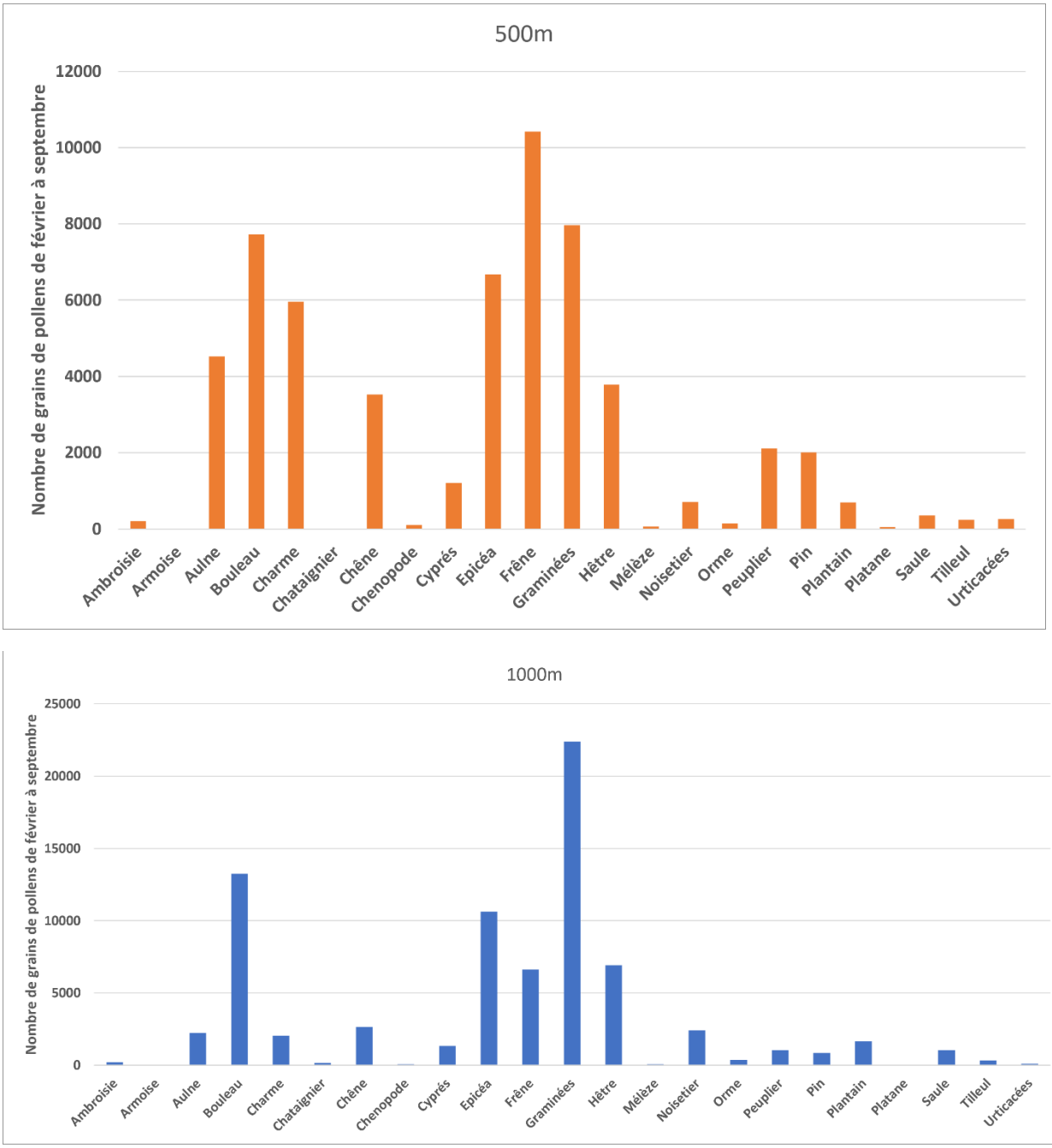


Figure 8: Distribution of airborne pollen taxa measured using Sigma-2 (SLT) samplers at three monitoring sites in the Grenoble region: Grenoble valley, 580 m altitude, and 908 m altitude.

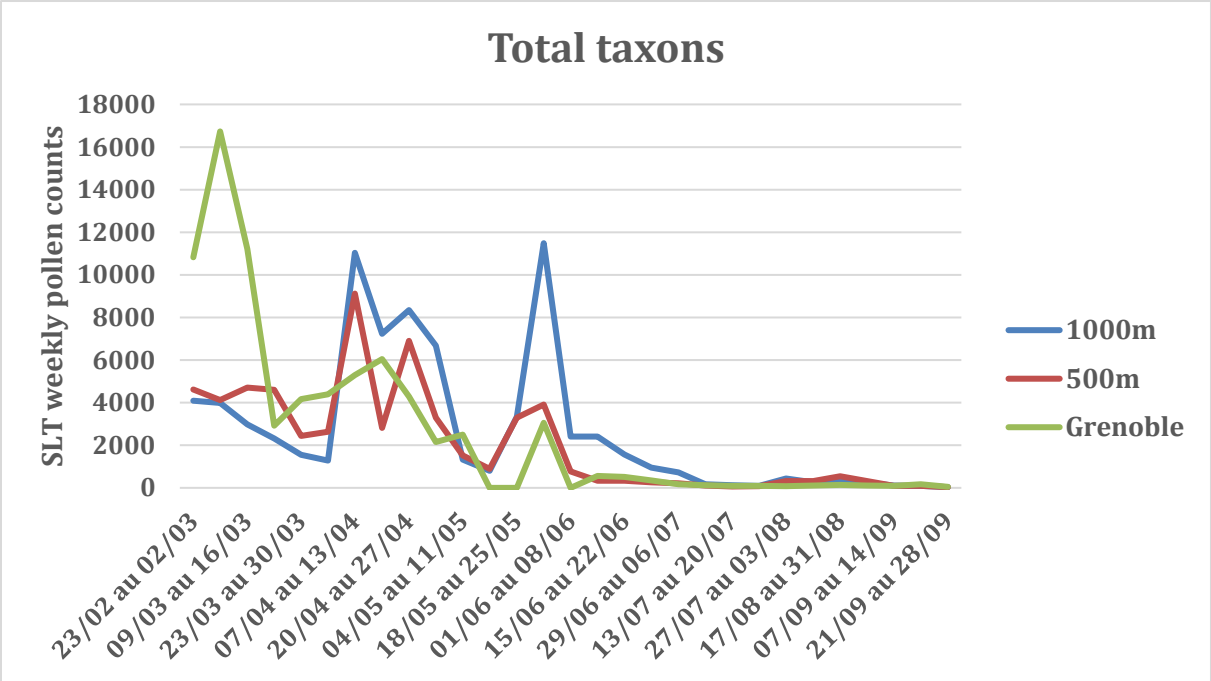


Figure 9: Total pollen counts measured by Sigma-2 (SLT) samplers across three monitoring sites: Grenoble valley, 580 m altitude, and 908 m altitude.

The total pollen counts across all allergenic taxa were considerably higher in Grenoble in March but declined from April onwards. In contrast, pollen concentrations at 1,000 m increased later in the season, from April onwards, reaching their peak in early June (Figure 9).

Comparison of pollen season timing and pollen abundance across the three locations revealed relatively similar flowering dynamics for *Corylus*, *Alnus*, and *Betula* (Figure 10). Pollen release began at approximately the same time across the altitudinal gradient, suggesting a limited delay in flowering for these taxa within the studied elevation range. *Betula* pollen was detected predominantly at the mountain sites, with lower concentrations in Grenoble.

Hornbeam (*Carpinus*) pollen was detected over a longer period at 580 m, although the onset of the pollen season was similar across all three sites. Oak (*Quercus*) also showed a similar onset of pollen release across the study locations, but concentrations were higher in Grenoble.

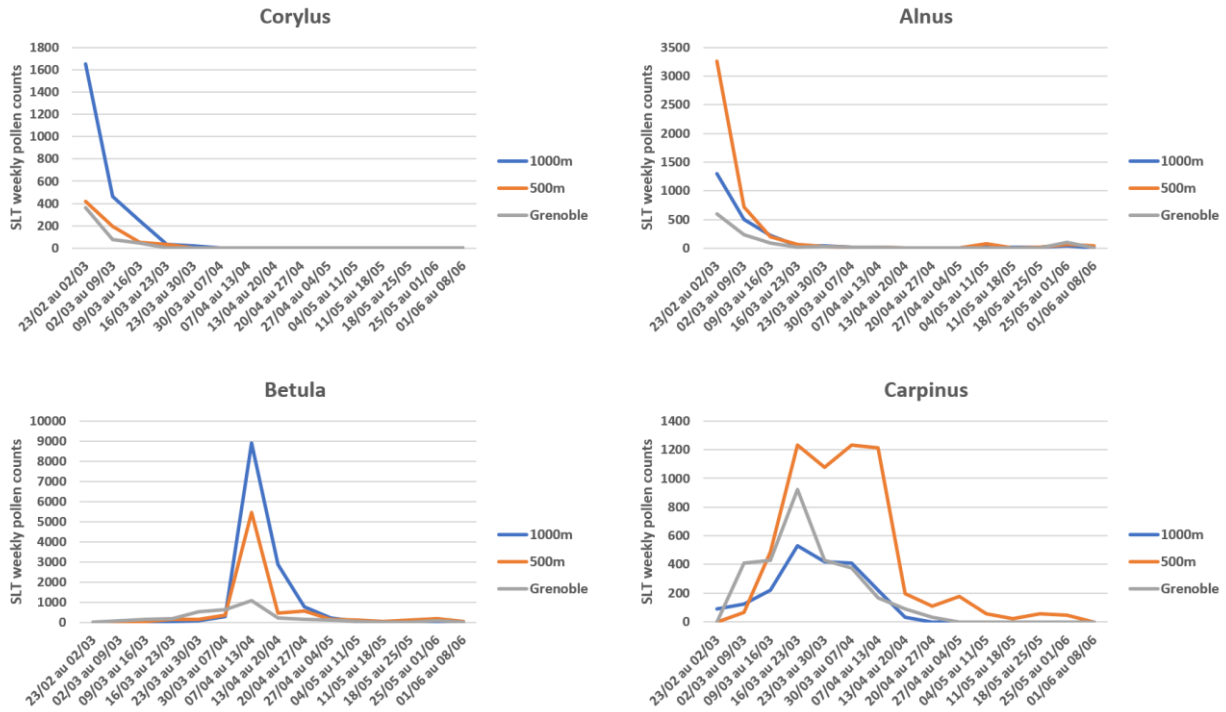
Cupressaceae pollen was largely absent from the mountain monitoring stations but was consistently detected in Grenoble. This pattern likely reflects the widespread use of ornamental cypress trees in urban environments, whereas these species are less common in mountain ecosystems.

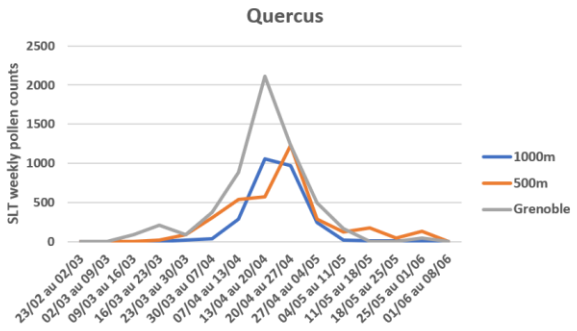
Spruce (*Picea*), willow (*Salix*), and grasses (*Poaceae*) showed a greater presence at the mountain sites, with grass pollen particularly prominent at 1,000 m. In contrast, poplar (*Populus*) and plane tree (*Platanus*) pollen were detected primarily in Grenoble and were nearly absent at higher elevations.

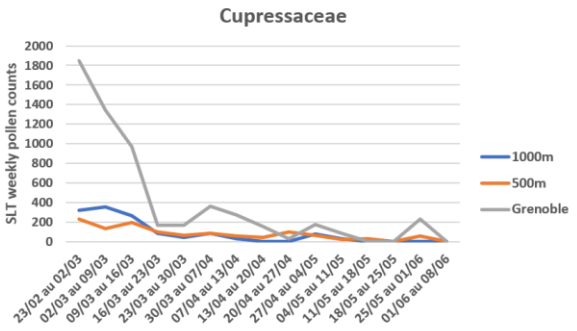
Ash (*Fraxinus*) pollen was observed at all three sites, although its onset appeared to be delayed by approximately one week at the mountain sites, and overall concentrations decreased with increasing altitude.

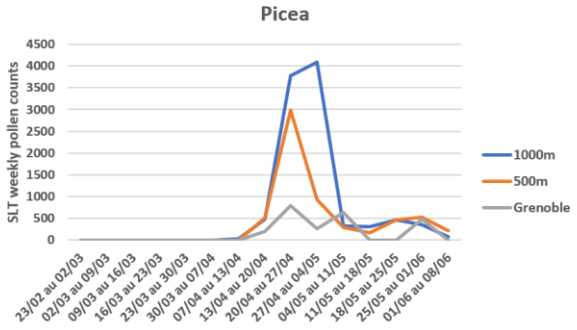
Plane tree (*Platanus*) pollen was detected almost exclusively in the urban environment of Grenoble, highlighting the influence of ornamental tree planting on allergenic pollen exposure among urban residents.

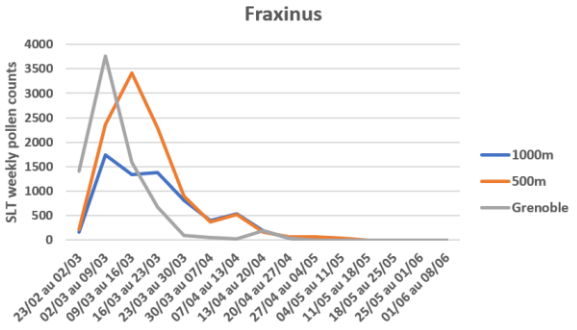
Finally, ragweed (*Ambrosia*) pollen was abundant in Grenoble but was also detected at the mountain sites, indicating that ragweed pollen exposure was not restricted to the lowlands.

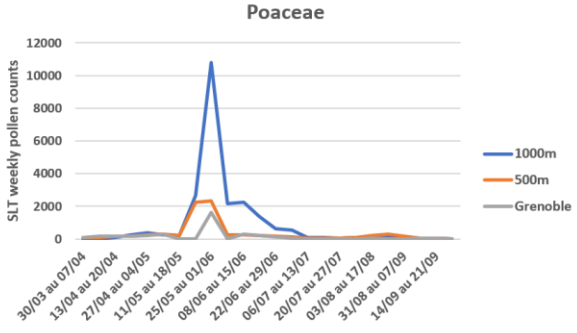


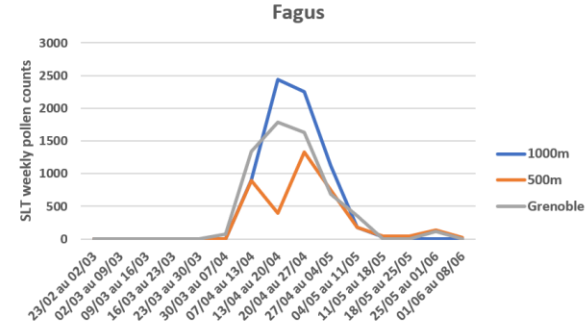

Quercus
SLT weekly pollen counts
2500
2000
1500
1000
500
0
1000m
500m
Grenoble
23/02 au 02/03
02/03 au 09/03
09/03 au 16/03
16/03 au 23/03
23/03 au 30/03
30/03 au 07/04
07/04 au 13/04
13/04 au 20/04
20/04 au 27/04
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04/05 au 11/05
11/05 au 18/05
18/05 au 25/05
25/05 au 01/06
01/06 au 08/06

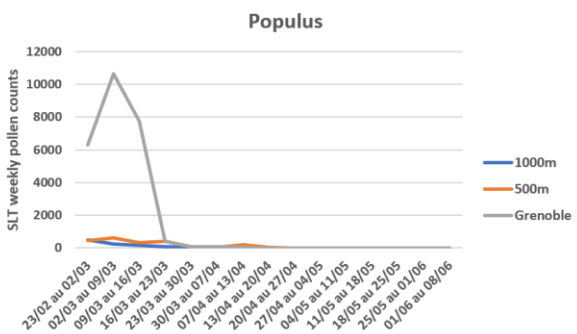

Cupressaceae
SLT weekly pollen counts
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1000m
500m
Grenoble
23/02 au 02/03
02/03 au 09/03
09/03 au 16/03
16/03 au 23/03
23/03 au 30/03
30/03 au 07/04
07/04 au 13/04
13/04 au 20/04
20/04 au 27/04
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18/05 au 25/05
25/05 au 01/06
01/06 au 08/06

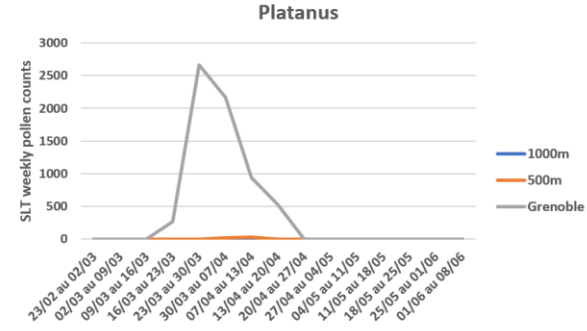

Picea
SLT weekly pollen counts
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1000m
500m
Grenoble
23/02 au 02/03
02/03 au 09/03
09/03 au 16/03
16/03 au 23/03
23/03 au 30/03
30/03 au 07/04
07/04 au 13/04
13/04 au 20/04
20/04 au 27/04
27/04 au 04/05
04/05 au 11/05
11/05 au 18/05
18/05 au 25/05
25/05 au 01/06
01/06 au 08/06


Fraxinus
SLT weekly pollen counts
4000
3500
3000
2500
2000
1500
1000
500
0
1000m
500m
Grenoble
23/02 au 02/03
02/03 au 09/03
09/03 au 16/03
16/03 au 23/03
23/03 au 30/03
30/03 au 07/04
07/04 au 13/04
13/04 au 20/04
20/04 au 27/04
27/04 au 04/05
04/05 au 11/05
11/05 au 18/05
18/05 au 25/05
25/05 au 01/06
01/06 au 08/06


Poaceae
SLT weekly pollen counts
12000
10000
8000
6000
4000
2000
0
1000m
500m
Grenoble
30/03 au 07/04
13/04 au 20/04
27/04 au 04/05
11/05 au 18/05
25/05 au 01/06
08/06 au 15/06
22/06 au 29/06
06/07 au 13/07
20/07 au 27/07
03/08 au 17/08
31/08 au 07/09
14/09 au 21/09


Fagus
SLT weekly pollen counts
3000
2500
2000
1500
1000
500
0
1000m
500m
Grenoble
23/02 au 02/03
02/03 au 09/03
09/03 au 16/03
16/03 au 23/03
23/03 au 30/03
30/03 au 07/04
07/04 au 13/04
13/04 au 20/04
20/04 au 27/04
27/04 au 04/05
04/05 au 11/05
11/05 au 18/05
18/05 au 25/05
25/05 au 01/06
01/06 au 08/06


Populus
SLT weekly pollen counts
12000
10000
8000
6000
4000
2000
0
1000m
500m
Grenoble
23/02 au 02/03
02/03 au 09/03
09/03 au 16/03
16/03 au 23/03
23/03 au 30/03
30/03 au 07/04
07/04 au 13/04
13/04 au 20/04
20/04 au 27/04
27/04 au 04/05
04/05 au 11/05
11/05 au 18/05
18/05 au 25/05
25/05 au 01/06
01/06 au 08/06


Platanus
SLT weekly pollen counts
3000
2500
2000
1500
1000
500
0
1000m
500m
Grenoble
23/02 au 02/03
02/03 au 09/03
09/03 au 16/03
16/03 au 23/03
23/03 au 30/03
30/03 au 07/04
07/04 au 13/04
13/04 au 20/04
20/04 au 27/04
27/04 au 04/05
04/05 au 11/05
11/05 au 18/05
18/05 au 25/05
25/05 au 01/06
01/06 au 08/06

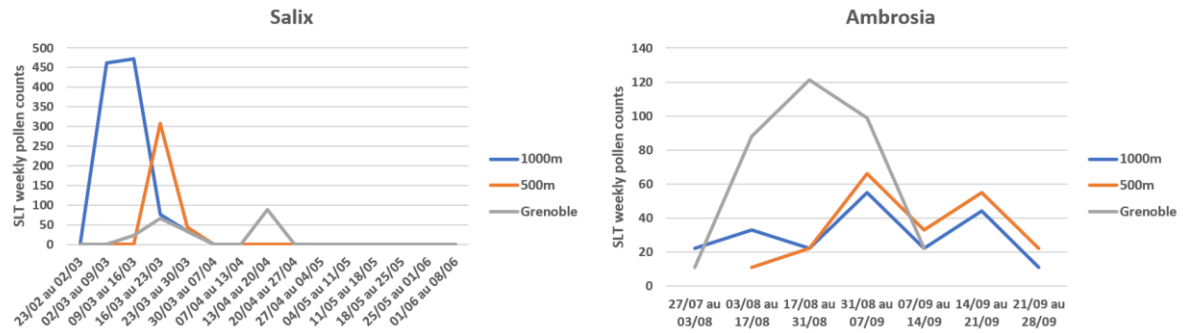


Figure 10: Detailed comparison of individual pollen taxa counts measured by Sigma-2 (SLT) samplers across three monitoring sites: Grenoble valley, 580 m altitude, and 908 m altitude.

4. Conclusions

The MontAdapt pollen monitoring campaign demonstrated the value of combining AI-based Aerōtape monitoring with traditional sampling methods to characterize airborne pollen dynamics across an altitudinal gradient in the Grenoble region. Automated monitoring captured the major seasonal pollen peaks and broadly agreed with manual observations, while providing high-frequency measurements and near real-time information on pollen concentrations and associated allergy risks. These results support the potential of AI-based real-time monitoring as a valuable tool for environmental surveillance and public health applications.

The observations revealed a clear seasonal succession of allergenic pollen taxa, from early-flowering trees such as *Corylus* and *Alnus* to spring taxa including *Betula*, *Fraxinus*, and *Quercus*, followed by *Poaceae* during late spring and summer and *Ambrosia* in late summer and early autumn. Comparison with historical Hirst observations from 1991–2024 suggested that the pollen peaks of several taxa, particularly *Corylus*, *Alnus*, *Fraxinus*, and *Quercus*, occurred earlier in 2026 than their historical averages. Although this pattern is consistent with the potential influence of warmer conditions on flowering phenology, longer-term observations combined with meteorological data are required to establish whether these changes represent a persistent climate-driven trend.

Altitude influenced pollen abundance and taxonomic composition more clearly than the timing of seasonal onset for several of the monitored taxa. The Grenoble urban site exhibited greater contributions from *Cupressaceae*, *Platanus*, *Populus*, and *Ambrosia*, reflecting the influence of urban vegetation and the local distribution of pollen sources. In contrast, the

mountain sites showed greater representation of *Betula*, *Picea*, *Salix*, and *Poaceae*. These differences highlight the importance of local vegetation, land cover, and atmospheric transport in shaping pollen exposure across the altitudinal gradient.

Grass pollen was a major component of the late-spring and early-summer pollen season at all three elevations, with the highest concentrations recorded around 900–1,000 m. This finding demonstrates that mountain environments cannot necessarily be considered low-exposure areas for allergenic pollen. Although the timing of several pollen seasons was broadly similar across the studied elevations, the abundance of individual taxa differed substantially between sites, resulting in distinct seasonal exposure profiles.

Ragweed (*Ambrosia*) provided a particularly clear example of these differences. Concentrations in Grenoble reached approximately 42 pollen/m³ during late August and early September, corresponding to very high allergy risk under the thresholds used in this study. At the mountain sites, concentrations were substantially lower, rarely exceeding 5 pollen/m³. Nevertheless, the detection of ragweed pollen at higher elevations indicates that exposure is not restricted to urban lowlands. However, airborne detection alone does not demonstrate the establishment or expansion of ragweed plants in mountain environments, and further monitoring is needed to determine the origin and persistence of this pollen.

Overall, the findings demonstrate that allergenic pollen exposure in the Grenoble region is shaped by the combined effects of seasonal phenology, altitude, and local environmental conditions. The integration of reliable, high-frequency pollen observations into environmental monitoring and public information systems could ultimately support more localized allergy-risk assessments and strengthen climate adaptation strategies for both urban and mountain communities.