

Climate drivers of airborne pollen variability: 31 years of monitoring in Barcelona (NE Iberian Peninsula)

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ABSTRACT

Climate change is increasingly modifying airborne pollen dynamics, with key implications for aeroallergen exposure in Mediterranean urban environments. This study analyses 31 years (1994–2024) of aerobiological and meteorological data from Barcelona (NE Iberian Peninsula) to assess long-term trends in pollen concentration, phenology, and their relationships with local climate variables and large-scale atmospheric circulation patterns. Meteorological records show significant warming, including higher autumn and summer maximum temperatures and summer minimum temperatures, together with reduced December precipitation and spring wind speed. Among the studied teleconnection indices, the Atlantic Multidecadal Oscillation (AMO) is the only index showing a significant positive trend at annual and winter scales, consistent with the predominance of a warm AMO phase during most of the 1994–2024 study period. Pollen trends indicate that arboreal taxa are more responsive to climatic variability than shrubs or herbaceous plants. Several tree taxa, notably *Alnus* and *Quercus*, exhibit increasing Annual Pollen Integrals and maximum daily concentrations, whereas shrubs show no significant trends. Pollen detection advances in most taxa, while duration shortens in deciduous *Quercus* and lengthens in Urticaceae. Total pollen shows significant increases in both annual integrals and daily peak concentrations. Air temperature, precipitation, and wind speed exert taxon-specific effects on pollen seasonality, with warmer conditions advancing the pollen season in 65% of taxa, and reduced spring wind speeds potentially limiting pollen dispersion. Teleconnection patterns, particularly the AMO, significantly modulate pollen timing and magnitude. Overall, these results highlight the strong sensitivity of airborne pollen dynamics to ongoing warming and atmospheric circulation variability, underscoring the importance of long-term aerobiological monitoring for public-health planning in Mediterranean cities.

1. Introduction

Respiratory allergies caused by airborne biological aerosols, particularly pollen, have shown a marked increase in recent decades, representing a growing public health concern in many regions of the world (Burbank, 2025). Numerous studies suggest that global warming is contributing to earlier onset of pollination periods and increased annual pollen loads for several allergenic taxa (Beggs et al., 2023; Damialis et al., 2019; Mousavi et al., 2024). These changes are primarily

attributed to shifts in air temperature patterns, precipitation regimes, and longer growing seasons associated with climate change (Galindo Ortiz et al., 2024; Montiel et al., 2025; Penedos et al., 2024; Rojo et al., 2021; Tomczyk et al., 2025).

The concentration of airborne pollen in a given region results from the interplay of local vegetation patterns, prevailing meteorological conditions, and long-distance pollen transport (Alarcón et al., 2022, 2023; Bayr et al., 2023; Bogawski et al., 2019; Izquierdo et al., 2011, 2017). Among environmental drivers, temperature and rainfall are

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particularly critical, as they influence plant growth rates, flowering phenology, and the total amount of pollen released (Majeed et al., 2018; Schramm et al., 2021). In Mediterranean regions such as Barcelona (Spain), precipitation can play a dual role: heavy rains may temporarily reduce airborne pollen through washout, while sufficient winter rainfall can enhance soil moisture, leading to higher pollen concentration in the following spring (Rodríguez-Solà et al., 2022). Temperature also acts as a key regulator of phenological development, affecting both the onset and duration of flowering, as well as pollen production (Adams-Groom et al., 2022; Ziska et al., 2019). Additionally, high air temperatures have been linked to increases in the allergenic content of pollen grains, potentially amplifying allergic responses (Ariano et al., 2010; Oh, 2022). Plant development generally progresses faster when cumulative daily temperatures (i.e., growing degree-days) surpass species-specific thresholds (Laaidi, 2001). As is the case with precipitation, wind exerts a twofold influence on airborne pollen concentrations (Hernández-Ceballos et al., 2026). On the one hand, wind facilitates pollen release by promoting the detachment of pollen grains from anthers in anemophilous species and enhances their transport through the atmosphere, increasing the availability of pollen in the air. On the other hand, strong or persistent winds may reduce pollen concentrations at a given location by dispersing pollen over larger areas or advecting it away from the sampling site, leading to lower values detected by volumetric traps. This dual effect of wind on airborne pollen dynamics has been previously documented and highlights the complex relationship between wind conditions and observed pollen levels (Damialis et al., 2005; Rojo et al., 2015; Silva Palacios et al., 2000).

Taken together, these dynamics indicate that climate change, particularly warming trends and shifting precipitation and wind patterns, can significantly modify both the timing and magnitude of pollen seasons, with noticeable consequences for allergy prevalence and public health management. Overall, climate-driven changes in these factors can alter pollen seasonality and concentration, highlighting the need to consider not only local meteorology but also large-scale atmospheric circulation patterns. Indices such as the North Atlantic Oscillation (NAO), Arctic Oscillation (AO), and Western Mediterranean Oscillation (WeMO) can strongly influence pre-seasonal conditions, including temperature, humidity, solar radiation, and wind speed, thereby modulating the timing and magnitude of pollen release in southern Europe.

The positive phases of the NAO and AO during winter are typically associated with increased solar radiation and reduced precipitation across the western Mediterranean region (Martín-Vide and López-Bustins, 2006). Similarly, positive WeMO index values during winter have been linked to enhanced sunshine and drier conditions in Northeastern Iberia (López-Bustins et al., 2008). In a more recent work, López-Bustins and Lemus-Cánovas. (2020) concluded that autumn and winter rainfall in the coastal region of Catalonia is significantly influenced by the negative phase of the WeMO, while in summer, the positive phase tends to dominate. Rainfall variability showed high values along the coast, particularly in southern Catalonia, moderate values in inland areas, and the lowest values in the Pyrenees. Winter exhibited the highest seasonal variability. Moreover, regions under stronger WeMO influence exhibit greater pluviometric irregularity, except in summer, when the pattern's influence is reversed. This seasonal-scale influence has been further refined by subsequent monthly analyses. In particular, based on a monthly rainfall assessment in Catalonia, Lana et al. (2024) found that precipitation amounts in October, November and December exhibit a significant linear relationship with the WeMO index.

Other studies identify distinct precipitation zones across Europe, Spain, and specifically Catalonia, and examine how various climate indices, including NAO, AO, and WeMO, influence precipitation patterns. Using Principal Component Analysis (PCA), Platikanov et al. (2025) shows that the NAO is a significant driver of both annual and seasonal rainfall variability in several subregions of Catalonia. Olmo et al. (2024), investigates the influence of large-scale atmospheric

circulation patterns, including the NAO, on rainfall and temperature across the Iberian Peninsula (IP), with a dedicated focus on Catalonia. Using multi-timescale statistical approaches, the authors find that NAO variability significantly affects both daily extreme events and long-term climate trends in the region. Another work focused on pollen dynamics, analysing the impacts of several Northern Hemisphere teleconnection patterns on biological and climatic variables in Catalonia for 1994–2011. It reported that positive phases of the AO are generally associated with lower seasonal pollen detection and an earlier onset of the pollen season, largely driven by altered precipitation and temperature patterns linked to the AO (Izquierdo et al., 2015).

The Atlantic Multidecadal Oscillation (AMO) is a mode of low-frequency North Atlantic sea-surface temperature variability, commonly described as alternating warm and cold phases on multi-decadal timescales (Enfield et al., 2001). During its positive (warm) phase, the North Atlantic experiences above-average temperatures, while during its negative (cold) phase, the waters are cooler than usual. The AMO has been linked to significant climate variability, influencing North Atlantic hurricane activity, rainfall patterns in the Sahel, and temperature and precipitation regimes across Europe and the Mediterranean region (Alexander et al., 2014; Knight et al., 2005; Zhang et al., 2019). In the Mediterranean region, the AMO has been shown to modulate climate variability. For instance, a study by Zampieri et al. (2017) found that the AMO influences weather regimes over Europe and the Mediterranean, particularly affecting spring and summer rainfall patterns. The research indicates that during positive AMO phases, there is an increased likelihood of dry conditions in the Mediterranean, while negative phases are associated with wetter conditions. This modulation occurs through changes in large-scale atmospheric circulation patterns, such as the NAO and the Scandinavian Pattern, which in turn affect the Mediterranean climate. Additionally, Qasmi et al. (2021) demonstrated that the intensity of the AMO influences the occurrence of heatwaves over the Euro-Mediterranean region. Their study revealed that during positive AMO phases, there is an increase in the frequency and intensity of heatwaves, particularly in southern Europe. This is attributed to the AMO's impact on atmospheric circulation, leading to the development of persistent anticyclonic conditions that promote hot and dry spells in the Mediterranean. Although the AMO is primarily expressed at multidecadal timescales, its relevance for airborne pollen studies lies in its capacity to modulate the background climatic conditions that control plant productivity and phenology. Therefore, while indices such as NAO or WeMO are useful for explaining seasonal atmospheric variability, the AMO may provide complementary information on lower-frequency climate forcing that shapes interannual tendencies in pollen abundance and season characteristics. Accordingly, AMO was included as a complementary large-scale climatic driver alongside the more regional atmospheric indices.

The main objective of this study is to assess long-term dynamics of airborne pollen in Barcelona (Catalonia) over a 31-year period (1994–2024), and to evaluate their relationships with both local meteorological conditions and large-scale climate variability. Specifically, we aim to (i) quantify temporal trends in key aerobiological parameters, including the Annual Pollen Integral, pollen season start and length, maximum daily pollen concentration or peak, and peak pollen release date; (ii) investigate how seasonal variability in air temperature, precipitation, and wind influences these parameters for the most abundant and allergenic taxa; and (iii) examine the role of major Euro-Mediterranean climate patterns, including the WeMO, NAO, AO, and AMO, in modulating airborne pollen dynamics at a regional scale. Given the complexity of climate–pollen interactions and the limited a priori knowledge available for many taxa, this study adopts an exploratory framework aimed at identifying robust and consistent climate–pollen relationships across multiple taxa and climatic drivers.

2. Data and methods

2.1. Study area

Barcelona is located in the northeastern part of the IP, within the region of Catalonia (Fig. 1). The city lies between the Besòs river to the north, the Llobregat river to the south, the Mediterranean Sea to the east, and the Pre-littoral Mountain Range (Collserola, 512 m a.s.l.) to the west. This geographical setting provides a unique combination of coastal and mountainous environments, which strongly influence the city's climate, urban development, and ecological dynamics (Casas-Castillo et al., 2025). The Pyrenees (200 km to the North) act as a barrier to northern airflows, while the Littoral and Pre-littoral ranges modulate both Atlantic and Mediterranean disturbances, resulting in mild temperatures and irregular but occasionally intense rainfall, mostly in autumn and spring. Over the 31-year study period, based on the meteorological dataset described in Section 2.3, the city recorded an average annual daily mean temperature of 16 °C, an annual precipitation of 577 mm, an average annual daily mean wind speed of 4 m s⁻¹ and a mean relative humidity of 69%. The surrounding vegetation is typically Mediterranean, dominated by evergreen oak (*Quercus ilex*, *Q. coccifera*, *Q. suber*) and mixed forests with deciduous oaks (mainly *Quercus humilis* and *Q. x cerrioides*), *Pinus halepensis* and *Pinus pinea*, along with some cultivated areas. Riparian vegetation (mainly *Populus alba*, *P. nigra*, *Alnus glutinosa*, *Fraxinus angustifolia* and *Ulmus minor*) grows along the Besòs and Llobregat rivers. Within the city, numerous plants used as ornamental (*Platanus x hispanica* the most abundant, several Cupressaceae taxa, such as *Cupressus* spp., *Juniperus* spp. and *Thuja* spp., and *Olea europaea* also frequently used) and ruderal plants (mainly species from the families Poaceae, Urticaceae, and Amaranthaceae) contribute to the airborne pollen spectrum.

2.2. Aerobiological data

Airborne pollen data were collected by the Aerobiological Network of Catalonia (Xarxa Aerobiològica de Catalunya, XAC) at the Barcelona station (41°24'N, 2°09'E, 93 m a.s.l.) (Fig. 1) for 1994–2024. Samples were obtained daily from Hirst samplers (Hirst, 1952) following the standardized method proposed by the European Aerobiological Association (Galán et al., 2014), and they were analysed following the standardized Spanish method (Galán et al., 2007) and the European standard (EN 16868 2019). Due to their abundance in the atmospheric pollen spectrum and their allergenic and/or landscape significance, 24 pollen taxa have been considered in this study; 14 trees: *Alnus* (ALNU), *Betula* (BETU), *Castanea* (CAST), Cupressaceae (CUPR), *Fagus* (FAGU), *Fraxinus* (FRAX), *Olea* (OLEA), *Pinus* (PINU), *Platanus* (PLAT), *Populus* (POPU), *Quercus* deciduous type (QUCA), *Quercus* evergreen type (QUPE), total *Quercus* (QTOT) and *Ulmus* (ULMU); 3 shrubs: *Corylus* (CORY), Ericaceae (ERIT) and *Pistacia* (PIST); and 7 herbs: Amaranthaceae (AMAR), *Artemisia* (ARTE), *Mercurialis* (MERC), *Plantago* (PLAN), Poaceae (POAC), Polygonaceae (POLI) and Urticaceae (URTI).

The total pollen (PTOT) has also been included.

We define the Main Pollen Season (MPS) of each pollen type and year as the period between the date (*Start*) in which the sum of the daily mean pollen concentrations reaches 2.5% of the annual sum, and the date (*End*) in which the sum reaches 97.5% (Andersen, 1991; Gehrig and Clot, 2021). The pollen parameters studied in this paper were: Annual Pollen Integral (API_n), sum of the mean daily pollen concentrations in a year (Pollen*day/m³); the date of the *Start* of the pollen season and the *Length* of the season (number of days between *Start* and *End*); the maximum concentration recorded in a year (Max, Pollen/m³) and its corresponding date (*Max date*). The end of the pollen season was not analysed as an independent parameter, as it is inherently reflected in the season length metric. Therefore, the combination of pollen season start and length was considered sufficient to characterise the main temporal dynamics of airborne pollen.

2.3. Meteorological data

Meteorological variables were provided by the Servei Meteorològic de Catalunya and included daily maximum air temperature (*Tmax*), minimum air temperature (*Tmin*), mean air temperature (*Tmean*), and monthly precipitation (*Prec*). These data were recorded at the Fabra Observatory of Barcelona (41°25'06" N, 2°07'27" E, 415 m a.s.l.), located approximately 5 km northwest of the pollen sampling site (Fig. 1). Cumulative daily values of *Tmax*, *Tmin*, *Tmean*, and *Prec* were computed as the progressive sum of monthly records (January; January–February; January–March, and so forth), considering their potential influence on pollen concentrations and the phenological timing of the MPS.

To characterize wind variability, we employed the Standardized Wind Speed Index (SWSI), a wind anomaly index designed to quantify deviations from the mean wind regime at the grid point or regional scale across multiple spatiotemporal resolutions (Andres-Martin et al., 2026). The index was provided by the Climate, Atmosphere and Ocean Lab (Climatoc-Lab) of the Spanish National Research Council (CIDE, CSIC-UV-GVA). In this study, we used the monthly wind speed series from the AEMET Fabra Observatory to calculate the 1-month SWSI.

The SWSI was computed via a parametric standardization approach: the wind series were first fitted to a Generalized Logistic (GLO) probability distribution using L-moments statistics to accurately model data extremes. Then, the theoretical cumulative probabilities were transformed into standardized z-scores following a standard normal distribution, N(0,1). This parametric step ensures a more robust and mathematically sound assessment than using simple, raw anomalies, providing a dimensionless representation of wind conditions across different time scales: negative values denote below-average wind activity (which can facilitate local pollen accumulation), whereas positive values indicate above-average, windier conditions (which typically enhance pollen dispersion and atmospheric dilution).

Since the SWSI follows a standard normal distribution, it can be directly related to statistical return periods. For example, an index value of ±2.58 corresponds to an event with a return period of 200 years,



Fig. 1. Location of the meteorological (blue) and aerobiological (green) stations in Barcelona. The satellite view was adapted from Google Earth imagery (© Google and data providers) in accordance with Google Earth terms of use.

thereby qualifying as an extreme anomaly, while a value of ± 1.28 corresponds to a return period of about 10 years. Values approaching zero represent more frequent, near-normal conditions. As an example, Fig. 2 illustrates the evolution of the SWSI index for April, May, and June in Barcelona, which correspond to the months with pollen presence in the air of most taxa considered in this study. The SWSI was calculated for the period 1994–2022.

2.4. Climate indices

The most influential Northern Hemisphere teleconnection patterns affecting the region were considered: NAO, AO, WEMO, and AMO. Monthly NAO (<https://www.ncei.noaa.gov/access/monitoring/nao/>), AO (<https://www.ncei.noaa.gov/access/monitoring/ao/>) and AMO (ERSST AMO (North Atlantic 0–60°N SSTA, <https://www1.ncdc.noaa.gov/pub/data/cmb/ersst/v5/index/ersst.v5.amo.dat>) index values were obtained from the NOAA/National Center for Environmental Prediction, Climate Prediction Center. Within the longer-term oscillatory behaviour of the AMO, the 1994–2024 study period was predominantly characterized by a positive (warm) phase, although interannual variability and a weakening tendency were observed in the most recent years. This phase has been associated with temperature and precipitation anomalies affecting the North Atlantic and adjacent European regions. The WeMO index was provided by the Climate, Atmosphere and Ocean Lab (Climatoc-Lab) of the Spanish National Research Council (CIDE, CSIC-UV-GVA). It was derived from daily mean sea level pressure data from the ERA5 reanalysis and adjusted to observations using a random forest (RF) approach, which provided the strongest correlation between the instrumental (López-Bustins et al., 2008) and reanalysis series ($R^2 = 0.991$). The RF model captured the systematic differences between reanalysis outputs and observations, applying this correction consistently across the full time series. This approach ensures continuity of the WeMO index beyond 2020, when the instrumental series ceased to be updated. Following established practice, the WeMO index was calculated relative to the 1961–1990 reference period, which is considered a climatologically neutral baseline and is recommended by both the World Meteorological Organization (WMO, 2026) and the Meteorological Service of Catalonia (SMC, 2026) for detecting climatic changes.

2.5. Statistical methods

Non-parametric Spearman's rank correlation coefficients were used to evaluate monotonic relationships, as this method is appropriate for

variables that may exhibit non-linear associations and non-normal distributions, such as aerobiological data. Correlations were calculated between pollen parameters and meteorological variables, as well as climate oscillations, over the 31-year study period (1994–2024), except for the wind index (SWSI), which was available for 1994–2022. Mean monthly meteorological variables (T_{max} , T_{min} , T_{mean} , $Prec$, and SWSI), together with their accumulated daily values (January; January–February; January–March; etc.), were correlated with annual pollen parameters (API_n , $Start$, $Length$, Max , and $Max\ date$). In addition, annual pollen parameters were correlated with annual and winter climate indices (NAO, WeMO, AO, and AMO), with winter defined here as December–March, as well as with climate indices from the preceding year. Furthermore, long-term trends in meteorology, climate indices, and pollen parameters were also analysed.

Statistically significant correlations were considered at the 95% confidence level ($p\text{-value} \leq 0.05$).

Correlation criteria by pollen parameter:

- API_n and $Length$: correlations within the MPS or during the preceding months were considered.
- $Start$: correlations in the first month of the MPS or the preceding months were included.
- Max and $Max\ date$: correlations were considered within the time interval of likely occurrence (LOP) or the preceding months. The LOP for each taxon was defined as the period between the earliest and latest dates of the annual maximum (Max) pollen concentration observed over the study period (1994–2024). Specifically, the date of the annual maximum was identified for each year, and the LOP was calculated as the interval bounded by the first and last occurrence of these dates across all years (highlighted in blue in Figs. 6 and 7).

Maximum possible correlations:

- The total number of MPS months for the 24 taxa (excluding total pollen) was 120 (yellow highlights in Figs. 3–7).
- For temperature variables, the maximum number of correlations was 360 (3 variables $\times$ 120 months), increasing to 480 when including the preceding months.
- For $Prec$ and SWSI, the maximum number of correlations was 120, increasing to 160 when including the preceding months.
- For Max and $Max\ date$, the total number of months within the LOP was 48, increasing to 88 when the preceding months were included. Consequently, the maximum possible correlations were 264 for temperature variables (3 $\times$ 88 months) and 88 for $Prec$ and SWSI.

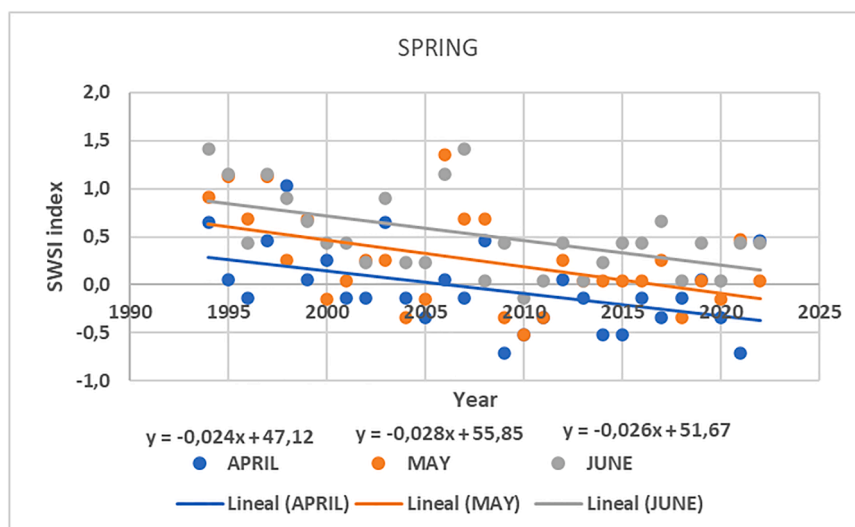


Fig. 2. The spring SWSI index (April, May, And June) in Barcelona for 1994–2022.

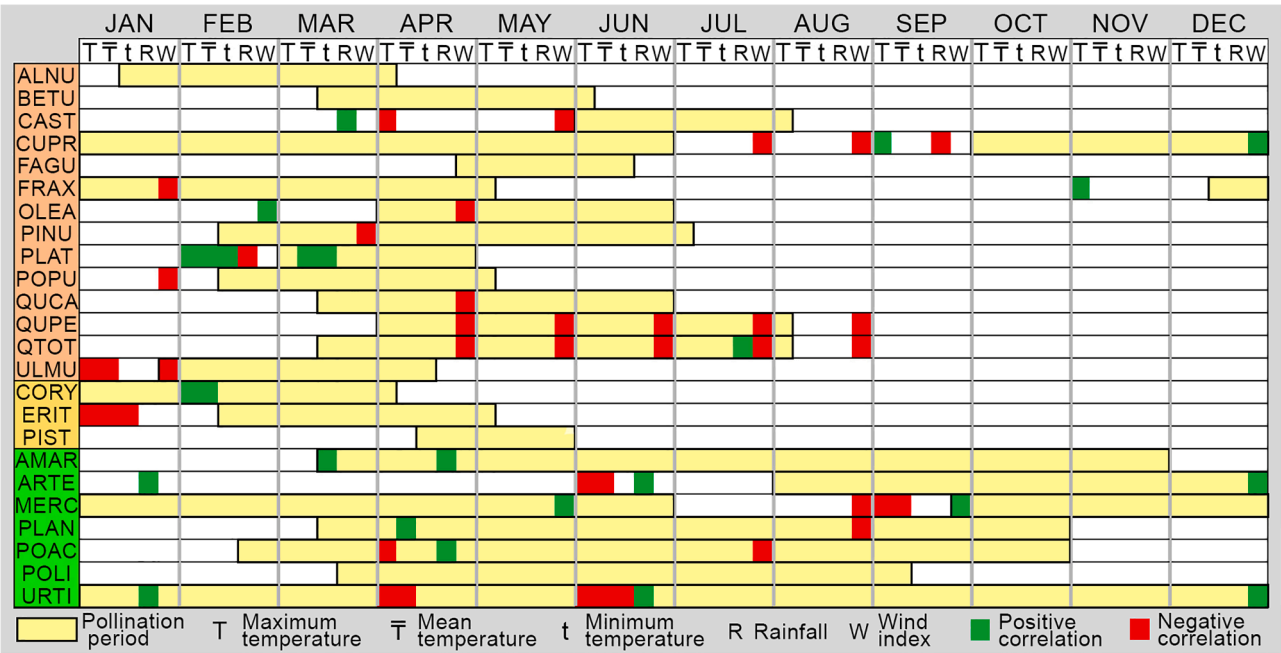


Fig. 3. Significant Spearman's correlations ($p \leq 0.05$) (positive in green and negative in red) between the Annual Pollen Integral (APIn) and the monthly meteorological variables: maximum temperature (T), mean temperature ($\bar{T}$), minimum temperature (t), precipitation (R), and the SWSI wind index (W). The yellow boxes indicate the main pollen season (MPS).

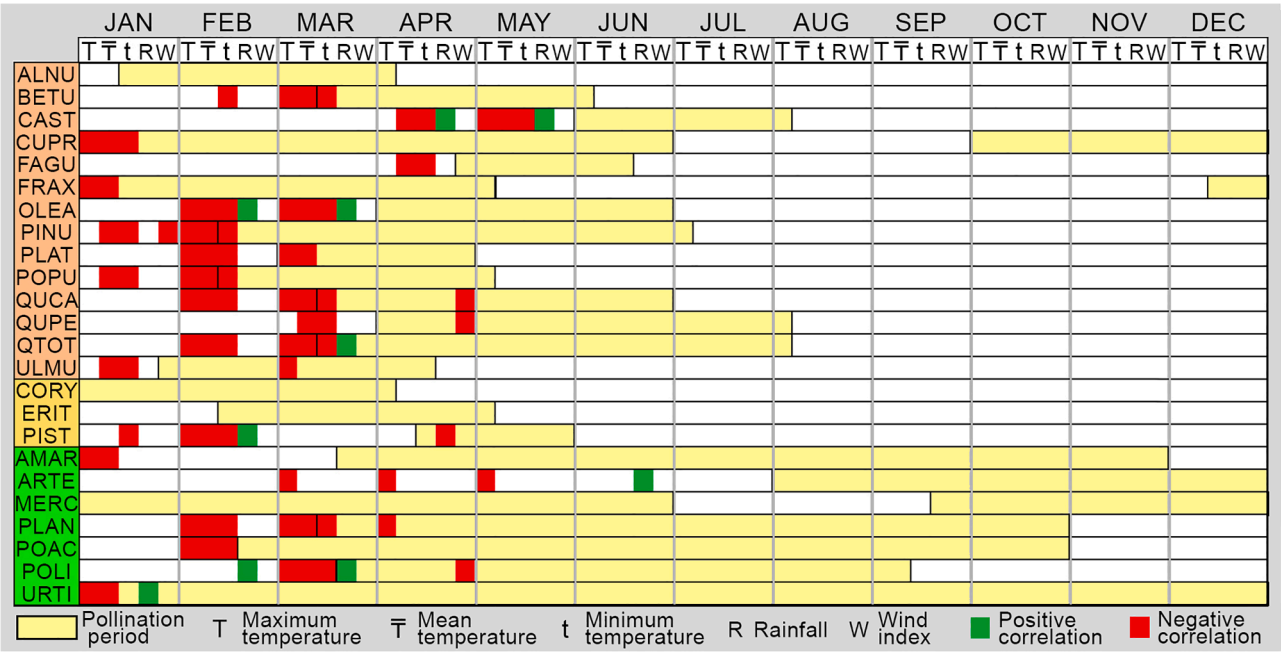


Fig. 4. Significant Spearman's correlations ($p \leq 0.05$) (positive in green and negative in red) between the onset of the pollination season (Start) and the monthly meteorological variables: maximum temperature (T), mean temperature ($\bar{T}$), minimum temperature (t), precipitation (R), and the SWSI wind index (W). The yellow boxes indicate the main pollen season (MPS).

Because a large number of statistical comparisons were performed, the proportion of significant correlations was also considered when evaluating the overall results. Although this criterion does not eliminate the possibility of Type I errors in individual tests, a frequency of significant associations substantially exceeding that expected by chance suggests that the observed associations are unlikely to be explained solely by random chance. Interpretation therefore focused primarily on recurring patterns observed across taxa and climatic drivers rather than

on isolated statistically significant correlations.

Overall, this analytical framework allows the evaluation of long-term trends and interannual variability in pollen seasonality, facilitating the assessment of climate-related changes in the timing, intensity, and duration of the pollen season.

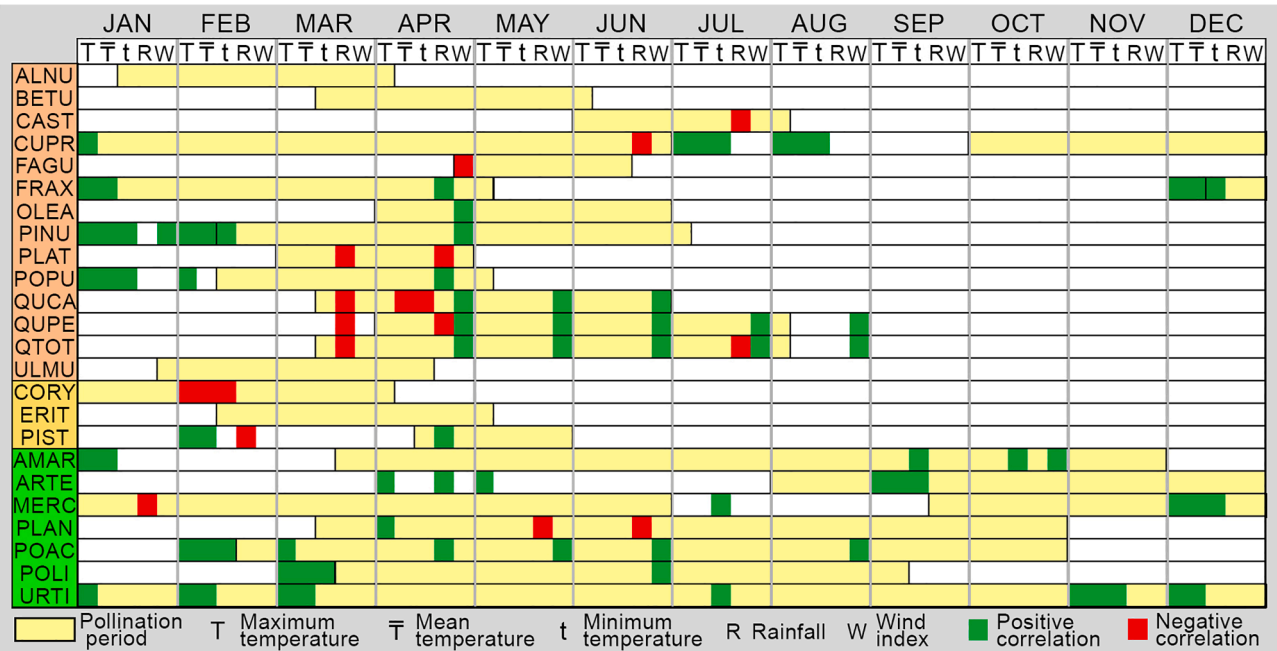


Fig. 5. Significant Spearman's correlations ($p \leq 0.05$) (positive in green and negative in red) between the duration of the pollination season (*Length*) and the monthly meteorological variables: maximum temperature (T), mean temperature ($\bar{T}$), minimum temperature (t), precipitation (R), and the SWSI wind index (W). The yellow boxes indicate the main pollen season (MPS).

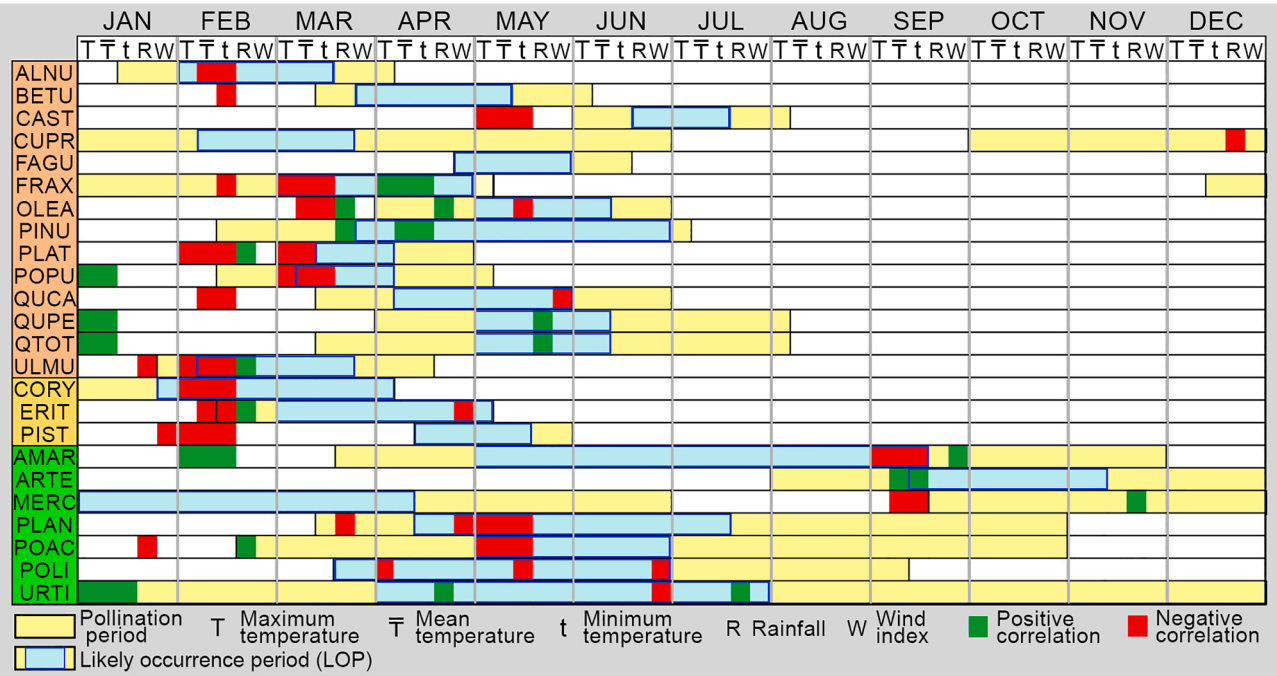


Fig. 6. Significant Spearman's correlations ($p \leq 0.05$) (positive in green and negative in red) between the date of the maximum concentration (*Max date*) and the monthly meteorological variables: maximum temperature (T), mean temperature ($\bar{T}$), minimum temperature (t), precipitation (R), and the SWSI wind index (W). The yellow boxes indicate the main pollen season (MPS). The blue area indicates the period of likely occurrence (LOP) for *Max*.

3. Results

3.1. Trends of the meteorological variables and teleconnection indices

Trends were assessed using Spearman's rho, which quantifies the magnitude and direction of monotonic changes over time. Positive rho values indicate consistent increases, while negative values indicate consistent decreases in the variable during the study period. This

approach provides a robust measure of trend directionality across years, although it does not capture more complex temporal patterns.

The three temperature variables showed positive significant trends ($p \leq 0.05$) in several months, more frequent for *Tmax* than for *Tmin* (Table 1). *Tmax* exhibited positive trend during summer, autumn, and early winter, whereas *Tmin* only showed significant increases during the summer months. Precipitation displayed a significant positive trend in July and a negative trend in December. The wind index (SWSI)

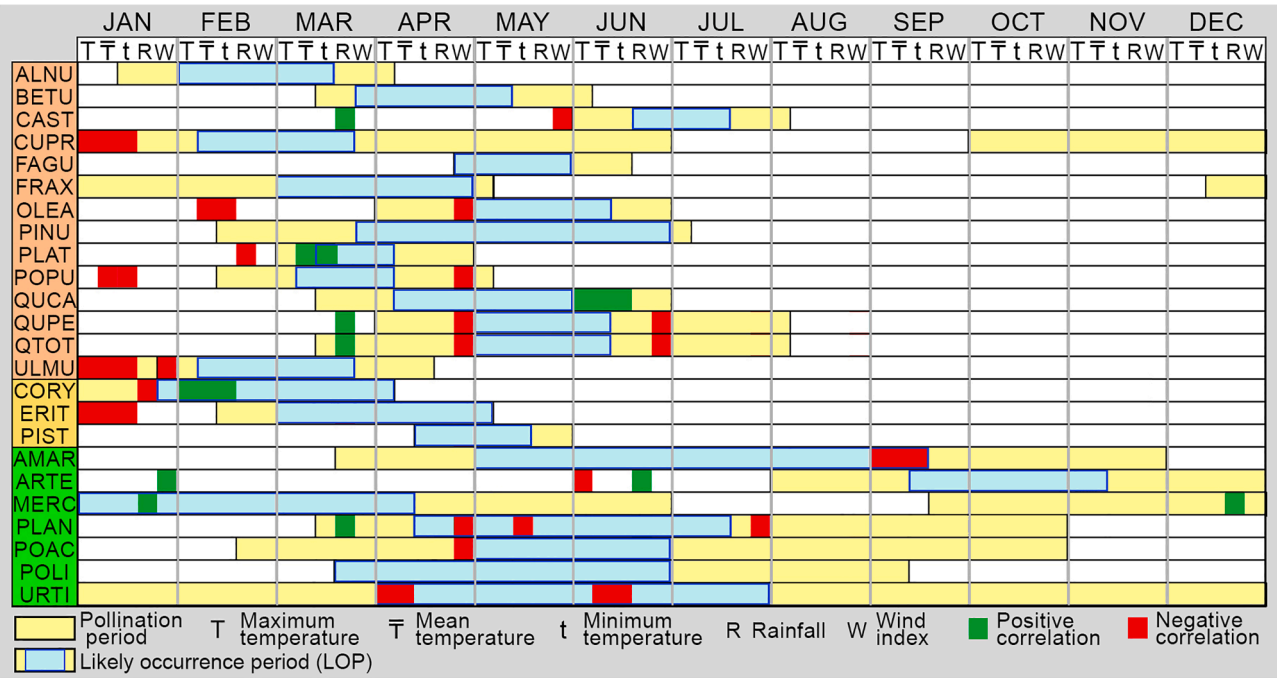


Fig. 7. Significant Spearman's correlations ($p \leq 0.05$) (positive in green and negative in red) between the maximum concentration (Max) and the monthly meteorological variables: maximum temperature (T), mean temperature ($\bar{T}$), minimum temperature (t), precipitation (R), and the SWSI wind index (W). The yellow boxes indicate the main pollen season (MPS). The blue area indicates the period of likely occurrence (LOP) for Max.

Table 1
Spearman's rho values for the significant trends in monthly meteorological variables at the 95% confidence level ($p \leq 0.05$). Values in bold indicate significance at the 99% confidence level ($p \leq 0.001$). Green and red denote positive and negative trends, respectively.

	<i>Tmax</i>	<i>Tmin</i>	<i>Tmean</i>	<i>Prec</i>	Wind SWSI
January	0.422				
February					
March					
April			0.376		-0.479
May					-0.448
June		0.364			-0.461
July	0.413	0.376	0.405	0.356	
August					
September	0.629	0.469	0.566		-0.453
October	0.425				
November	0.506		0.388		
December	0.582		0.444	-0.398	

significant trends were all negative, mainly during spring and also in September.

Regarding the teleconnection indices, only the AMO index exhibited a significant positive trend in both the annual and winter phases over the 1994–2024 study period (Supplementary Material, Table SM1). Given the multidecadal oscillatory nature of the AMO, this trend should be interpreted as the behaviour observed within the analysed time window, potentially reflecting part of a broader positive phase rather than a persistent long-term increase. Spearman correlations were also calculated between the different indices. The correlations between NAO, WeMO, and AO were all positive and high, with those between NAO and AO, in their annual phases, and between NAO and WeMO, as well as NAO and AO, in their winter phases, being significant at the 95% confidence level ($p \leq 0.05$). In contrast, the AMO index showed very low correlations with all other indices, and even a negative correlation with NAO in their annual phases (Supplementary Material, Table SM2).

3.2. Pollen trends

Table 2 shows the taxa whose pollen parameters presented significant trends ($p \leq 0.05$) during 1994–2024. *Alnus* and *Quercus* types (deciduous and evergreen) showed the highest number of significant changes (3 out of 5 parameters each). Among the analysed parameters, *APIn* exhibited the largest number of positive trends, particularly among tree taxa, followed by Max. Total pollen also showed positive trends in *APIn* and Max. A positive trend in *Start* indicates a delayed onset of the pollen season, whereas negative values correspond to an earlier onset. Two tree taxa (*Alnus* and *Quercus* evergreen type) and one herbaceous taxon (Polygonaceae) show a delayed onset, while only *Fagus* showed an earlier onset. Changes in pollen season duration were less frequent: Urticaceae showed a positive trend in *Length*, whereas *Quercus* deciduous type showed a negative trend.

Several taxa showed no significant trends in any of their parameters (i.e., *Betula*, *Castanea*, *Pinus*, *Ulmus*, Ericaceae, *Pistacia*, *Artemisia*, *Mercurialis*, and Poaceae).

Table 2

Spearman's rho correlation coefficients for the significant trends in pollen parameters at the 95% confidence level ($p \leq 0.05$). Values in bold indicate significance at the 99% confidence level ($p \leq 0.001$). Green and red denote positive and negative trends, respectively. Pollen taxa from trees are shown with an orange mask, bushes in yellow and herbs in green.

	<i>APin</i>	<i>Start</i>	<i>Length</i>	<i>Max</i>	<i>Max date</i>
ALNU	0.377	0.414		0.416	
CUPR					0.381
FAGU		-0.359			
FRAX	0.366				
OLEA	0.591				
PLAT				0.415	
POPU	0.419				
QUCA	0.512		-0.463	0.437	
QUPE	0.475	0.404		0.451	
QTOT	0.537			0.355	
CORY				0.431	
AMAR				-0.543	
PLAN					-0.418
POLI		0.401			
URTI			0.566		
PTOT	0.364			0.460	

3.3. Correlation between pollen parameters and meteorological variables

3.3.1. Annual pollen integral (*APIn*)

Table 3 summarizes the significant correlations ($p \leq 0.05$) of *APIn* and meteorological variables for each taxon for 1994–2024. Overall, air temperature showed the highest number of significant correlations,

followed by wind speed (SWSI), whereas precipitation exhibited the fewest associations. A total of 27 significant correlations were found with temperature variables (6% of all possible correlations), of which 11 were positive and 16 negative (T_{max} : 12, T_{min} : 5, and T_{mean} : 10). For monthly precipitation, 7 significant correlations were identified, 5 positive and 2 negative. Regarding SWSI, 28 significant correlations

Table 3

Significant correlations at the 95% confidence level (positive in green and negative in red) between pollen parameters and climate indices of the same year.

	NAO		WeMO		AO		AMO	
	annual	winter	annual	winter	annual	winter	annual	winter
ALNU							<i>Max_day</i>	<i>Max</i>
BETU				<i>Max_day</i>			<i>Length</i>	
CAST	<i>APIn</i>		<i>Start</i>	<i>Start</i>				
CUPR							<i>Length</i>	
							<i>Max_day</i>	
FAGU						<i>Length</i>		
OLEA							<i>APIn</i>	
PLAT		<i>Start</i>				<i>Max_day</i>		
						<i>Start</i>		
QUCA					<i>Max_day</i>		<i>Max</i>	
QUPE							<i>Start</i>	<i>Start</i>
ULMU							<i>Start</i>	
CORY	<i>Start</i>	<i>Max</i>				<i>Max</i>		<i>Max</i>
ERIT	<i>Max</i>					<i>Max_day</i>	<i>APIn</i>	<i>APIn</i>
	<i>Start</i>							<i>Max</i>
AMAR						<i>Start</i>	<i>Max</i>	<i>Length</i>
								<i>Max</i>
MERC		<i>Length</i>		<i>Length</i>				
PLAN	<i>Max_day</i>				<i>Start</i>			
POLI			<i>Start</i>			<i>Max_day</i>	<i>Start</i>	<i>Start</i>
URTI					<i>Length</i>	<i>Length</i>	<i>APIn</i>	<i>Start</i>
							<i>Length</i>	<i>Length</i>
PTOT						<i>Max_day</i>		

were found (18%), with 6 positive and 22 negative. The months with the most significant correlations were January, February, April and June for the temperature variables; in contrast, the temperatures in May, July, August, October, and December exhibited no significant correlations. April and June showed the highest number of significant correlations for *Prec*, while April, May, July and August were the most relevant months for SWSI.

Temperature accounted for most of the taxa, with *Tmax*, *Tmin*, and *Tmean* showing both positive and negative relationships across months with the *APIn* of the taxa. For instance, *Tmax* displayed positive correlations with *Platanus* and *Corylus* in February, Cupressaceae in September, and *Fraxinus* in November; but negative ones with *Ulmus* and Ericaceae (January), Poaceae and *Castanea* (April), Urticaceae (April/June), *Artemisia* (June), and *Mercurialis* (September). Similarly, *Tmin* and *Tmean* exhibited mixed patterns, including significant positive correlations with *Platanus*, *Corylus*, Amaranthaceae and *Plantago*, and negative correlations with Urticaceae, *Artemisia*, and *Mercurialis*. Ten taxa did not exhibit significant correlations with any temperature variable: Polygonaceae, *Pistacia*, *Quercus* (the three of them), *Olea*, *Betula*, *Alnus*, *Fagus*, *Pinus*, and *Populus*.

Precipitation produced fewer significant correlations overall. Positive associations were found with *Artemisia* (June), Urticaceae (January/June), *Castanea* (March), and total *Quercus* (July); whereas negative correlations were detected with *Platanus* (February) and Cupressaceae (September).

Wind speed (SWSI) was mainly associated with reductions in *APIn*, as reflected by the high proportion of negative correlations. Significant negative relationships were found for *Fraxinus*, *Populus* and *Ulmus* (January), *Pinus* (March), *Olea* (April), *Quercus* (April, May, June, July and August, 85% of the months of their MPS), and *Castanea* (May). In contrast, positive correlations were observed for Urticaceae, Cupressaceae and *Artemisia* (December), *Olea* (February), and *Mercurialis* (May and September). In almost half of the taxa, a negative correlation was observed between *APIn* and SWSI during the first month of the MPS or the preceding month. No significant correlations with SWSI were detected for: *Corylus*, Ericaceae and Amaranthaceae.

Five taxa did not show significant correlations with any of the meteorological variables considered: *Alnus*, *Betula*, *Fagus*, *Pistacia*, and Polygonaceae.

3.3.2. Onset of the pollination season (*Start*)

Significant correlations between increased air temperature and an advancement of the onset of the pollination season were observed in >65% of the taxa (15 out of 23) during the first month of the MPS or the preceding month (Fig. 4). When considering only tree taxa, this percentage increased to 71% (10 out of 14). Urticaceae was excluded from these calculations because its MPS extends throughout the entire year.

The highest number of significant correlations with temperature was detected in January, February, and March, summing up to 68 correlations (22 *Tmax* and *Tmin* each, 24 *Tmean*), which account for 31% of the 216 possible correlations for these three months. These correlations involved 11 tree taxa, 6 herb taxa, and 1 shrub. A total of 51 of these 68 correlations, corresponding to 53% of all possible cases, occurred during the first month of the MPS or during the preceding month, and all of them were negative, indicating an earlier presence of pollen in the air. Among these, 44 correlations, representing 46% of the total, were highly significant ($p \leq 0.001$). Percentages were calculated relative to the maximum number of possible correlations, which was 96, obtained from the combination of 17 taxa, three temperature variables, and two months, the first month of the MPS and the previous one. Four taxa (*Mercurialis*, *Corylus*, Ericaceae, and *Fagus*) did not show any significant correlation with temperature variables.

In contrast, monthly precipitation during the first month of the MPS or the preceding month exhibited fewer significant correlations, with a total of 7 cases (15% of the possible correlations). All but one correlation were positive, indicating delayed detection of airborne pollen. February

precipitation was positively correlated with the onset of the pollination of *Olea*, *Pistacia* and Polygonaceae; March precipitation with *Olea*, total *Quercus*, and Polygonaceae; April and May precipitation with *Castanea*; and June precipitation with *Artemisia*.

For monthly SWSI, all significant correlations were negative, accounting for 9% of all possible correlations. *Pinus* showed a significant correlation in January, whereas deciduous *Quercus*, evergreen *Quercus* and Polygonaceae exhibited significant correlations in April.

3.3.3. Duration of the pollination season (*Length*)

A total of 61 significant correlations (13% of the possible correlations) were observed between *Length* and the air temperature variables corresponding to the months of the MPS or the preceding months (Fig. 5). All correlations were positive except for *Corylus* and deciduous *Quercus*. Most of these correlations were in January and February, accounting for 18% of the possible correlations during these two months, and involved 4 tree taxa, 2 shrubs, and 3 herbs. Urticaceae exhibited the highest number of correlations, followed by Cupressaceae and *Pinus*. The taxa that did not show any correlation between the length of their MPS and temperature variables were Ericaceae, *Olea*, *Betula*, *Alnus*, *Fagus*, and *Ulmus*.

Regarding monthly precipitation, 18 significant correlations, representing 11% of all possible cases, were observed. Five of these correlations were positive and thirteen were negative. The three *Quercus* taxa and *Platanus* showed negative correlations with March and April precipitation, *Castanea* with July precipitation, *Plantago* with May and June precipitation, and *Pistacia* with February precipitation.

For SWSI, 22 correlations (14%) were identified, comprising 21 positive and 1 negative. Between April and June, the three *Quercus* taxa showed 9 positive correlations out of 9 possible cases, as well as a positive correlation in 76% of the months within its MPS (13 out of 17). Additional correlations were detected for other taxa in April, within their respective MPS, including *Fagus* (negative), *Olea* (positive), and *Pinus* (positive).

3.3.4. Date of the peak (*Max date*)

Similarly to the *Start* date, >67% of the taxa (16 out of 24) showed a correlation between an earlier *Max date* and higher air temperatures, either within the time interval of likely occurrence of the peak (LOP) or the preceding months (Fig. 6). A total of 66 correlations were identified, 71% of which were negative, involving 12 tree taxa, 3 shrubs, and 7 herbs. This represents 24% of all possible correlations. The highest number of correlations was observed in February (23 in total), corresponding to 32% of the possible correlations for that month and involving 6 trees, 3 shrubs, and 1 herb taxa.

Regarding precipitation, 16 correlations were identified out of 88 possible cases (18%), including 12 positive and 4 negative. Positive correlations within the LOP or in the preceding months were observed for *Platanus*, *Quercus* evergreen type, total *Quercus*, *Olea*, *Pinus*, and *Ulmus* among trees, Urticaceae among herbs, and Ericaceae among shrubs.

Finally, for SWSI, 7 correlations (8%) were recorded, 1 positive and 6 negatives.

All taxa showed at least one significant correlation between the *Max date* and meteorological variables, except *Fagus*.

3.3.5. Annual maximum daily concentration (*Max*)

A total of 29 significant correlations (12%) were identified between air temperature variables and the *Max*, within the LOP or the preceding month, including 8 positive and 21 negative correlations (Fig. 7). For Urticaceae, four negative correlations (33%) were observed during the five months corresponding to the LOP (March to July). Positive correlations were also detected within this interval for *Corylus* (33%) and *Platanus* (33%).

Regarding monthly precipitation, 8 correlations (10%) were found, being 6 positive and 2 negative. Four of the six positive correlations

occurred in March.

As for the *APIn*, although to a lesser extent, 33% of the taxa showed a negative correlation between Max and SWSI during the first month or the months preceding the LOP, involving 6 tree taxa and 2 herbs. A total of 13 correlations (15%) were identified, mostly negative. The highest number of correlations was observed in April (6; 25% of possible correlations for that month). *Quercus* taxa exhibited negative correlations in 44% of the months of LOP or the preceding months (4 out of 9).

Seven taxa did not show any significant correlation between Max and meteorological variables: *Alnus*, *Betula*, *Fagus*, *Fraxinus*, *Pinus*, *Pistacia* and *Polygonaceae*.

3.4. Correlation between pollen parameters and accumulated meteorological variables

Correlations between pollen parameters and accumulated daily air temperature and precipitation from January up to a given month were evaluated and compared with those obtained using monthly mean values. Figures illustrating this analysis are provided in Supplementary Material (Fig. SM1 to SM5). Overall, the use of daily accumulated variables did not substantially increase the number of significant correlations compared with monthly data, but it modified their temporal persistence and, in some cases, revealed additional relationships not detected with monthly values.

For *APIn*, fewer significant correlations were detected with daily accumulated temperature (23) than with monthly data (27), with 11 overlapping. *Corylus* and *Platanus* showed positive correlations with accumulated temperatures throughout the MPS, whereas correlations based on monthly data were restricted to the early MPS. A similar pattern was observed for *Ulmus* with negative correlations. Precipitation yielded a comparable number of correlations (10) with accumulated values than with monthly ones, although overlaps were limited to *Castanea* in March, *Urticaceae* in January, *Poaceae*, and *Plantago* in April. Notably, *Plantago* maintained a positive correlation with accumulated precipitation from the beginning of the MPS through most of the season. In addition, *Betula*, which showed no correlation with monthly precipitation, displayed a positive correlation with accumulated precipitation during the early MPS (April). No other taxa showed significant correlations with accumulated precipitation.

Regarding the other quantitative parameter, Max, 27 significant correlations were detected with accumulated temperature, a number comparable to the 29 identified using monthly data, with 14 overlapping cases. Correlating taxa included *Corylus*, *Ericaceae*, *Cupressaceae*, *Olea*, and *Ulmus*. Among the non-overlapping cases, *Corylus* was particularly notable: while it showed a positive correlation with monthly temperatures only in February, this relationship persisted throughout the MPS when accumulated temperatures were considered. With respect to precipitation, Max showed 9 significant correlations with accumulated values and 8 with monthly data, with only 2 overlaps. *Plantago* displayed positive correlations with accumulated precipitation across the entire MPS, whereas *Corylus* exhibited negative correlations with accumulated precipitation in February and March.

For time pollen parameters, correlations with accumulated temperatures were generally similar in number to those based on monthly temperatures, although correlation coefficients were often lower. For *Start*, most arboreal taxa showed weaker correlations with accumulated temperatures compared with monthly values, except for *Pinus* and *Populus*, which maintained similar coefficients, and *Plantago* and *Pistacia*, which exhibited higher values. The *Start* of several taxa that correlated with monthly temperatures only during the early MPS exhibited extended correlations when accumulated values were used. For example, *Platanus* extended its correlation from February (monthly) to February–April (accumulated), while *Pistacia* extended from January to February–May. *Olea* correlated with monthly temperatures in February–March, but with accumulated temperatures in February–June, and *Castanea* from April–May to April–August. All these correlations were

negative, indicating that higher accumulated temperatures early in the MPS were associated with an earlier presence of pollen in the air.

For the Max *date*, 12 taxa exhibited lower correlation coefficients when accumulated temperatures were considered, whereas four arboreal taxa (*Cupressaceae*, *Quercus*, *Olea*, and *Betula*) showed higher coefficients. Most correlations were negative, indicating an advancement of the peak date with increasing accumulated temperatures. Exceptions included all correlations involving *Urticaceae* and *Amaranthaceae*, as well as the January correlations for *Quercus* and *Populus*, which were positive.

3.5. Correlation between pollen parameters and teleconnection indices

Correlations were calculated between pollen parameters and teleconnection indices corresponding to the same year, as well as between pollen parameters and climate indices from the previous year. Table 3 presents the significant correlations (24% of all possible correlations) between pollen parameters and climate indices corresponding to the same year. Six taxa, three trees (*Fraxinus*, *Pinus*, and *Populus*), one shrub (*Pistacia*), and two herbs (*Artemisia* and *Poaceae*), showed no significant correlations and are therefore not included in the table. The taxa displaying the highest number of correlations were the shrub *Ericaceae* (6), and the herbs *Urticaceae* (6), *Amaranthaceae* (4), and *Polygonaceae* (4).

The index showing the highest number of correlations is the AMO, with 13 in the annual phase and 10 in the winter phase. It shows positive correlations with the pollination season start in evergreen *Quercus*, *Ulmus*, and *Polygonaceae*, as well as with the duration of the pollen season for *Betula*, *Cupressaceae*, *Amaranthaceae*, and *Urticaceae*. Additionally, positive correlations were observed with *Alnus* (Max), *Olea* (*APIn*), and deciduous *Quercus* (Max). In contrast, it displays negative correlations with pollen concentrations of *Ericaceae* (*APIn*, Max), *Amaranthaceae* (Max), and *Urticaceae* (*APIn*).

The WeMO index shows the lowest number of correlations, a total of five, all with timing parameters. Positive correlations were found with the *Start* of *Castanea* pollination, the Max *date* of *Betula*, and the *Length* of *Mercurialis*. It exhibits a negative correlation with the *Start* of the pollen season in *Polygonaceae*. The NAO index shows positive correlations with *APIn* of *Castanea* and Max of *Corylus*, while negative correlations were observed with the *Start* of *Platanus*, *Corylus*, and *Ericaceae*.

The AO index exhibits a total of 12 correlations. Four of these correlations are positive, including the pollen season *Start* of *Amaranthaceae*, the *Length* of *Urticaceae*, and the Max of *Corylus*. The remaining eight correlations are negative and involve primarily the time parameters of *Fagus*, *Platanus*, *Quercus* deciduous type, *Ericaceae*, *Plantago*, and *Polygonaceae*.

The number of correlations with the climatic indices of the previous year was higher than that of the same year (27%), as shown in Table 4. Herbs were also the group with the highest number of correlations: *Poaceae* (7), *Urticaceae* (6), and *Amaranthaceae* (6). However, some tree taxa also exhibited a relatively high number of correlations, such as *Betula* (5), *Castanea* (5), and *Ulmus* (4). The WeMO index, as in the case of the current year, showed the fewest number of correlations (7), whereas the AMO index had the highest number (20), followed by the NAO index (15).

4. Discussion

This 31-year assessment of airborne pollen dynamics and meteorological variables in Barcelona provides a long-term context for interpreting variability in pollen behaviour. The trends detected in the meteorological variables indicate changes in some of the climatic conditions that may affect pollen seasons, although their effects differ among taxa. The increasing trends detected in *Tmax* and *Tmin*, particularly in summer and autumn (Table 1), are consistent with long-term warming documented across the Iberian Peninsula and the western Mediterranean region (Adams-Groom et al., 2022; Ali et al., 2022;

Table 4

Significant correlations at the 95% confidence level (positive in green and negative in red) between pollen parameters and climate indices of the previous year.

	NAO		WeMO		AO		AMO	
	annual	winter	annual	winter	annual	winter	annual	winter
ALNU							Start	Start
BETU	APIn	APIn				Length		
		Length						
		Max						
CAST	Start	Start		Max_day		Start	Start	
CUPR						Length		
FAGU							Start	
OLEA							APIn	
PINU		Length						
PLAT					Start			
QUCA	Length							
ULMU		APIn		Max		Max		
		Max						
CORY							Max	
ERIT							APIn	
							Max	
PIST				Start				APIn
AMAR		Length			Length	Length	Length	Max
							Max	
ARTE				Max_day				
MERC	Length							
PLAN	APIn						Max_day	Max_day
POAC	Max_day	Max_day		Max	Max_day	Max_day		APIn
				Max_day				
POLI						Max_day		
URTI					Length		Length	APIn
							Start	Max
								Length
PTOT			Length			Length		

García-Mozo et al., 2017; Portero Serrano et al., 2020; Sousa et al., 2021). By contrast, precipitation showed fewer significant trends than temperature variables, with a single negative trend detected in December, indicating reduced rainfall during the early winter period. This result, together with the significant positive trend observed in July, is broadly consistent with the seasonal precipitation patterns described for the south-eastern Iberian Peninsula by Ruiz Sinoga et al. (2011). Wind speed (SWSI) displayed predominantly negative trends throughout the year, indicating a progressive weakening of the SWSI signal. Significant decreases were concentrated in spring (April, May, June), and September.

The significant positive trend detected in the AMO index (Table SM1) is consistent with the predominance of a warm AMO phase during most of the 1994–2024 study period and reflects broader North Atlantic variability, which has been linked to decadal climatic shifts and biological responses in Europe, including changes in forest productivity in the Iberian Peninsula (Mariani and Zavatti, 2017; Madrigal-González et al., 2017). However, given the 60/80-year oscillatory behaviour commonly described for the AMO, the positive trend detected over the 31-year period analysed here likely represents part of a broader multi-decadal phase rather than a persistent directional climatic trend. In contrast, the scarcity of significant trends in other teleconnection indices

(NAO, AO, WeMO) aligns with previous studies reporting limited or inconsistent influences of these indices on regional pollen dynamics (Galán et al., 2016; Menzel et al., 2005; Smith et al., 2009).

Pollen trends reveal a greater number of significant changes in arboreal taxa than in shrubs and herbs, both in terms of Annual Pollen Integral and the timing of the pollen season (Table 2). The dominance of positive *APIn* trends among trees, particularly *Olea* and *Quercus*, mirrors findings from other European aerobiological records, where warming has been associated with enhanced pollen production, especially in early-flowering taxa (Bogawski et al., 2019; Büntgen et al., 2022; Cariñanos et al., 2022; Emberlin et al., 2002, 2007; Ziello et al., 2012). The relative stability of pollen outputs in shrubs and herbs is also consistent with previous work suggesting that woody taxa respond more strongly to long-term climatic forcing due to their perennial growth dynamics and strong dependence on thermal cues (Galán et al., 2016; Rojo et al., 2021). The contrasting responses within taxa, such as the earlier pollination of *Fagus* versus the delayed onset observed in *Alnus*, evergreen *Quercus*, and Polygonaceae, reinforce that the specific thermal and precipitation thresholds of each taxon continue to modulate phenological trajectories despite overarching warming trends (Piotrowska-Weryszko et al., 2021).

Air temperature variables consistently emerged as the most

influential meteorological factor across most pollen parameters, showing the strongest and most coherent relationships, beyond what would be expected from random significance alone. Regarding *APIn*, the observed correlations with meteorological variables highlight a clear taxon-dependent and variable-specific response rather than a uniform climatic signal. Although air temperature accounted for the highest number of significant relationships, the direction of the correlations varied widely among taxa and months, indicating heterogeneous responses in airborne pollen production and/or release. Some taxa, such as *Corylus*, *Platanus*, and *Amaranthaceae*, showed more consistent positive relationships with temperature, whereas others, including *Urticaceae*, *Artemisia*, and *Mercurialis*, tended to show negative associations, suggesting contrasting ecological or phenological controls among taxa. Precipitation exhibited comparatively fewer and less consistent associations with *APIn*, with both positive and negative correlations depending on the taxon and season, indicating a limited and context-dependent influence. In contrast, wind speed (SWSI) was more frequently associated with reductions in *APIn*, although positive correlations in some taxa suggest that atmospheric transport processes may enhance pollen detection under specific conditions. Overall, these results indicate that *APIn* variability is shaped by multiple meteorological drivers acting in a non-uniform way across taxa, rather than reflecting a single dominant climatic control.

Negative correlations between temperature and *Start* or *Max date* (Figs. 4 and 6) indicate that higher temperatures are generally associated with earlier pollen season timing in several taxa. In particular, >65% of the taxa show negative correlations between temperature and the *Start* of the pollen season, and >67% show similar relationships for the *Max date*, indicating a generalized advancement under warmer conditions. This pattern has been reported in Mediterranean and temperate Europe (García-Mozo, 2022; Gehrig and Clot, 2021; Picornell et al., 2024; Rojo et al., 2021). Earlier pollination linked to winter and early-spring warming was particularly evident for tree taxa, although not all taxa responded consistently, suggesting heterogeneous phenological sensitivity among species. Conversely, precipitation generally acted to delay pollination, consistent with findings that reduced radiation and cooler conditions following rainy periods may inhibit early-season floral development (Rodríguez-Solà et al., 2022). Wind-related variable (SWSI) showed a limited but taxon-specific influence on pollen parameters. Negative correlations with *APIn* and *Max* may reflect enhanced pollen dispersion and atmospheric dilution under higher wind conditions. However, positive correlations observed for taxa such as *Cupressaceae* and several herbs (*Artemisia*, *Mercurialis*, and *Urticaceae*) suggest that wind may also facilitate pollen transport and detection in the atmosphere. Regarding *Start*, negative correlations with SWSI in a subset of taxa (*Pinus*, deciduous *Quercus*, evergreen *Quercus*, and *Polygonaceae*) may reflect earlier airborne pollen detection rather than direct phenological advancement. Overall, the observed correlations suggest a tendency towards earlier pollen seasons under warmer conditions, with some taxa also showing increases in pollen levels, although responses are not uniform across species. While temperature appears more frequently associated with pollen timing than precipitation or wind, the strength and direction of these relationships vary depending on taxa and pollen parameter considered. Therefore, the results support the existence of climatic sensitivity in pollen dynamics at the taxon level, but do not indicate a single, uniform response pattern across all taxa or parameters.

The analysis of accumulated meteorological variables provides insight into the cumulative climatic conditions over the months preceding pollination (Fig. SM1 to SM5). The finding that accumulated temperatures often produced weaker correlations with pollen parameters than monthly averages suggests that short-term thermal anomalies may be more relevant than long-term accumulation for triggering pollination, a pattern similarly observed in studies from central and southern Europe (Cristofolini et al., 2024; Tedeschini et al., 2014). However, for certain taxa such as *Corylus* and *Ulmus*, correlations along

the entire MPS with accumulated temperatures suggest a cumulative effect on pollen production capacity, also noted in long-term datasets from continental climates. In contrast, accumulated rainfall has less impact than monthly rainfall, except in the case of *Betula* and some herbs such as *Urticaceae*, *Poaceae* and *Plantago*, which favours their pollen production.

Large-scale climatic oscillations emerged as an additional modulator of pollen behaviour. In this context, the relevance of the AMO in our results should be understood primarily as a source of low-frequency climate variability capable of influencing regional meteorological conditions, rather than as a monotonic forcing. Numerous studies recognize the importance of AMO as a driver of Northern Hemisphere climatic variability (Kerr, 2000; Sun et al., 2015; Zhang et al., 2007) and highlight its complex interactions with the NAO (Peings and Magnúsdóttir, 2014). Warm-phase AMO conditions are typically associated with more frequent negative NAO states and increased cold-air incursions over Europe (Kavvada et al., 2013; Ting et al., 2014). Over the 31-year period analysed here, the correlations among NAO, WeMO, and AO are generally positive (Table SM2), as expected given their representation of related atmospheric variability. However, only the correlations between NAO and AO and between NAO and WeMO were statistically significant. In contrast, the AMO does not correlate with any of the other teleconnection indices, and its most robust correlation, although not statistically significant, is negative with NAO, in agreement with the cited studies. This weak coupling likely reflects differences in temporal scale, with the AMO representing low-frequency multidecadal oceanic variability, whereas NAO, AO, and WeMO primarily capture more dynamic atmospheric fluctuations at interannual to seasonal scales.

In this study, we explored the impact of these teleconnections on pollen metrics (Table 3), revealing that when significant correlations occurred simultaneously across indices, they generally shared the same sign. Only two exceptions were detected, both involving the start date: *Polygonaceae* correlated negatively with WeMO and positively with AMO (using indices from the year of pollination), while *Castanea* correlated positively with NAO and AO but negatively with AMO (using indices from the previous year, Table 4). This further highlights the non-parallel relationship between AMO and the other teleconnection patterns discussed above, as well as their potential opposing impacts on pollen. Teleconnection indices, particularly AMO, showed substantial associations with pollen metrics, exceeding those reported for NAO or AO in many previous Mediterranean studies (Galán et al., 2016; Izquierdo et al., 2015). The significant correlations found between AMO and pollen-season duration or peak concentration in taxa such as *Quercus* and *Olea* suggest that decadal-scale North Atlantic variability may exert a broader influence on pollen behaviour than previously recognized. These relationships should therefore be interpreted in the context of oscillatory AMO phases and their associated climatic anomalies during the study period. Winter and early-spring pollinating taxa (*Cupressaceae*, *Fraxinus*, *Betula*, *Platanus*, and *Quercus*) exhibited stronger correlations with the winter NAO of the previous year, whereas late-spring pollinating taxa showed stronger correlations with NAO of the year of pollination. These findings are consistent with those reported by Galán et al. (2016) in 12 Spanish cities, who observed negative correlations between airborne pollen concentrations and the winter NAO index. As noted in that study, among herbaceous pollen types, *Urticaceae*, which is present throughout the year, showed stronger correlations with the winter NAO index from the previous year. In contrast, taxa that flower in spring or summer-autumn, such as *Plantago*, *Poaceae*, *Amaranthaceae*, and *Artemisia*, exhibited stronger associations with the winter NAO of the year of flowering. Similarly, Stach et al. (2008) reported significant links between the onset and end dates of *Poaceae* and the winter NAO, although they did not find notable relationships with seasonal pollen totals. In our study, *Poaceae* showed no correlations with indices of the year of pollination but did show several with those of the previous year: positive correlations between *Max date* and NAO, WeMO, and AO, and between *Max* and WeMO; and a negative

correlation between *APIn* and AMO. The higher number of correlations with climate indices from the previous year (54 versus 48; Table 4) is also notable and supports the hypothesis that airborne pollen responds not only to immediate climatic conditions but also to conditions during bud formation in the prior season (Bogawski et al., 2019; Piotrowska and Kubik-Komar, 2012). A limitation of this study is that the end of the pollen season was not analysed as an independent phenological parameter. Although pollen season length was included as a descriptor of seasonal dynamics, the timing of season termination may be influenced by meteorological drivers that differ from those controlling season onset and overall season duration.

Considering the large number of statistical tests performed, some significant relationships may represent Type I errors. Consequently, individual correlations should be interpreted with caution, particularly when not supported by consistent patterns across taxa, climatic variables, or previous studies. Accordingly, the conclusions of this study are based primarily on recurrent and coherent responses observed across multiple taxa and climatic drivers rather than on isolated statistically significant associations. Overall, the analyses of trends, meteorological correlations, and teleconnection patterns suggest that airborne pollen in Mediterranean urban environments may be influenced by climate variability. While these results point toward potential climate-driven shifts, further research is needed to establish clear and consistent patterns. Earlier and occasionally extended pollen seasons, together with increases in annual pollen loads for several key allergenic taxa and the modulation of phenological phases by large-scale atmospheric patterns, indicate potential changes in aeroallergen exposure. These observations are consistent with projections of enhanced pollen exposure under global warming scenarios (Alarcón et al., 2024; López-Orozco et al., 2023; Picornell et al., 2024; Ziska et al., 2019) and support the value of integrating long-term aerobiological monitoring into public-health planning for climate-vulnerable regions such as the western Mediterranean.

5. Conclusions

The results of this 31-year aerobiological and meteorological analysis of airborne pollen in Barcelona suggest that regional climate, including both local meteorological variables and large-scale atmospheric circulation patterns, is closely associated with airborne pollen dynamics, intensity, and seasonality. Overall, the observed changes highlight the sensitivity of pollen cycles to a climatic context characterized by rising air temperatures, changes in wind regimes, and the modulating effects of teleconnection patterns. The main conclusions are as follows:

- Meteorological records show a consistent warming trend, with widespread increases in maximum temperatures and summer minimum temperatures, alongside a significant decline in December precipitation and weakening in spring wind indices. Among the large-scale climatic drivers, the Atlantic Multidecadal Oscillation (AMO) is the only teleconnection index displaying a significant positive trend, both in winter and annually, during the 1994–2024 period; however, this increase should be interpreted within the context of its multidecadal oscillatory behaviour.
- Pollen trends indicate that tree taxa, particularly *Alnus* and *Quercus*, are more responsive to climate change than shrubs and herbaceous taxa. Predominantly positive trends in *APIn* and increasing peak pollen concentrations were observed for several arboreal taxa, whereas most shrubs and herbaceous plants showed no significant changes in *APIn*. Changes in pollen season timing included an earlier onset in *Fagus* and a delayed onset in *Alnus*, evergreen *Quercus* and Polygonaceae. Pollen season duration decreased in deciduous *Quercus* but increased in Urticaceae. Total airborne pollen exhibited significant increases in both annual integral and maximum concentration.

- Warmer temperatures during the early MPS or the preceding months were associated with higher *APIn* in *Platanus*, *Corylus*, *Amaranthaceae*, and *Plantago*, while reducing it in *Ulmus*, *Ericaceae*, *Castanea*, *Poaceae*, and *Mercurialis*. Precipitation favoured higher pollen production in *Artemisia* and *Castanea* before the onset of the MPS but reduced it in *Platanus*. Wind appears to be an important factor in pollen dispersal and consequently reduces atmospheric pollen concentrations; however, because wind speed shows a marked decreasing trend in spring, its dispersal capacity for spring-pollinating taxa is likely to decline.
- Higher temperatures during the months preceding or coinciding with the first month of the MPS advance the detection of the pollen season in 65% of the taxa, whereas increased precipitation during these months has the opposite effect, delaying its detection. The only exceptions are *Alnus*, *Corylus*, *Ericaceae*, and *Mercurialis*. Wind speed is associated with an earlier season onset in *Pinus*, *Quercus*, and *Polygonaceae*, and with an extension of pollen season duration in *Pinus*, *Olea*, *Quercus*, *Poaceae*, and *Polygonaceae*.
- Teleconnection indices emerge as relevant modulators of pollen dynamics. The AMO, which exhibits a significant positive trend over the analysed period, shows the highest number of correlations, influencing the onset, duration, and magnitude of pollen seasons across several taxa. These effects likely reflect the influence of the AMO phase prevailing during the study window. NAO and AO also show significant effects, primarily on timing parameters, while WeMO exhibits a more limited influence. Climate indices from the previous year show a larger number of significant relationships, particularly affecting herbaceous taxa (*Poaceae*, *Amaranthaceae* and *Urticaceae*) and several tree taxa (*Betula*, *Castanea*, and *Ulmus*).

Given the exploratory nature of this study and the large number of statistical tests performed, some significant associations should be interpreted with caution. Nevertheless, the main conclusions are supported by recurrent and ecologically coherent patterns observed across multiple taxa and climatic drivers.

Together, these results are consistent with a marked sensitivity of airborne pollen dynamics in urban environments to ongoing climatic warming, with important implications for pollen exposure and public health in Mediterranean cities.

CRedit authorship contribution statement

Marta Alarcón: Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Raül Rodríguez-Solà:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Jordina Belmonte:** Writing – review & editing, Methodology, Funding acquisition, Data curation, Conceptualization. **Cesar Azorin-Molina:** Writing – review & editing, Methodology, Data curation. **Shaleny Bedoya-Valestt:** Writing – review & editing, Methodology, Data curation. **Miguel Andres-Martin:** Writing – review & editing, Methodology, Data curation. **María del Carmen Casas-Castillo:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.agrformet.2026.111471](https://doi.org/10.1016/j.agrformet.2026.111471).

Data availability

Data will be made available on request.

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