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Influence of synoptic meteorology on airborne allergenic pollen and spores in an urban environment in Northeastern Iberian Peninsula

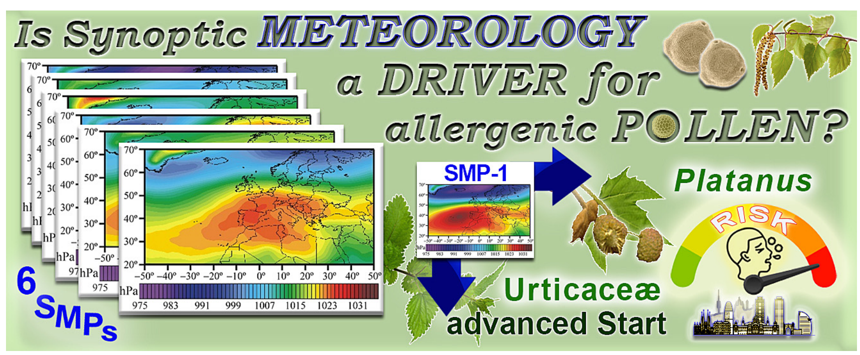
Marta Alarcón [a,*], Raül Rodríguez-Solà [b], M. Carmen Casas-Castillo [c], Francisco Molero [d], Pedro Salvador [d], Cristina Periago [a], Jordina Belmonte [e,f]

[a] Departament de Física, EEBE, Universitat Politècnica de Catalunya·BarcelonaTech, Eduard Maristany 16, 08019 Barcelona, Spain
[b] Departament de Física, ETSEIB, Universitat Politècnica de Catalunya·BarcelonaTech, Diagonal 647, 08028 Barcelona, Spain
[c] Departament de Física, ESEIAAT, Universitat Politècnica de Catalunya·BarcelonaTech, Colom 1, 08222 Terrassa, Spain
[d] Departamento de Medio Ambiente, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Avenida Complutense 22, 28040 Madrid, Spain
[e] Departament de Biologia Animal, Biologia Vegetal i Ecologia, Facultat de Biociències, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain
[f] Institut de Ciència i Tecnologia Ambientals (ICTA-UAB), Universitat Autònoma de Bellaterra, 08193 Bellaterra, Spain

HIGHLIGHTS

- Six synoptic situations explain most weather variability in Iberian Peninsula.
- Airborne pollen/spore dynamics in Barcelona is influenced by synoptic meteorology.
- There is one synoptic pattern where *Platanus* shows always high allergy risk values.
- The start of pollination of Urticaceae was advanced under certain weather patterns.
- *Alternaria* has a greater presence under the most frequent summer scenario.

GRAPHICAL ABSTRACT



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ABSTRACT

The influence of the most frequent patterns of synoptic circulation on the dynamics of airborne pollen/spores recorded at the Barcelona Aerobiological Station (BCN) was analysed. Six pollen types (*Platanus*, Cupressaceae, *Olea*, Poaceae, Urticaceae and Amaranthaceae), and one fungal spore (*Alternaria*) were selected for their high allergenic effect in sensitive people. Six synoptic meteorological patterns were identified through cluster analysis of sea level pressure fields as the main responsible of the weather conditions in the Iberian Peninsula. The local meteorological conditions in Barcelona associated with each one of the synoptic types were also stablished. Different statistical methods were applied to analyse possible relationships between concentrations and timing of the recorded aerobiological particles and specific synoptic types. The study, focused in the 19-year period 2001–2019, shows that one of the scenarios, frequent in winter and linked to high stability and air-mass blockage, registered the highest mean and median values for *Platanus* and Cupressaceae, but it was not very relevant for the other taxa. It was also this scenario that turned out to be the most influent on the pollination timing showing a significant influence on the start occurrence of Urticaceae flowering and on the peak date of *Platanus*. On the other hand, the most frequent synoptic type in the period, relevant in spring and summer, was linked to sporadic episodes of levels considered to be of high risk of allergy to *Platanus*, Poaceae, and Urticaceae pollen, and *Alternaria* fungal spore. This synoptic pattern, characterized by the presence of the Azores anticyclone and the Atlantic low located in the north of the United Kingdom, was associated with high temperatures,

* Corresponding author.
E-mail addresses: marta.alarcon@upc.edu (M. Alarcón), raul.rodriguez@upc.edu (R. Rodríguez-Solà), m.carmen.casas@upc.edu (M.C. Casas-Castillo), f.molero@ciemat.es (F. Molero), pedro.salvador@ciemat.es (P. Salvador), cristina.periago@upc.edu (C. Periago), jordina.belmonte@uab.cat (J. Belmonte).

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low relative humidity and moderate winds from the NW in Barcelona. The identification of an interaction between synoptic meteorology and pollen/spore dynamics will allow better abatement measures, reducing adverse health effects on sensitive population.

1. Introduction

Biological aerosols have been the subject of increasing interest because of their impact on air quality and population health (Sauliene et al., 2015; Aerts et al., 2021). This impact is especially relevant in urban environments, since a relationship has been observed between air pollution, airborne pollen, and allergenic effects. For instance, epidemiological studies in Canada showed that the allergenic effect of ambient aeroallergens was significantly higher after exposure to air pollutants, increasing the effect of pollen on symptoms (Cakmak et al., 2012). A relationship was found between asthma hospitalizations and exposure to tree pollen and fine particulate matter (PM2.5, median aerodynamic diameter less than or equal to 2.5 μm), and exposure to grass pollen and PM10 particulate matter (median aerodynamic diameter less than or equal to 10 μm). Furthermore, it was found in France and USA that exposure to ozone increases the frequency of respiratory allergies (Riediker et al., 2001). On the other hand, different studies analysed the impact on health of exposure to pollen based on different health indicators. For example, in the city of Paris, they found that up to the threshold of 30 Pollen m^{-3} of grasses, the number of hospitalizations for asthma in the total population increases significantly, then the effects remain stable regardless of pollen concentration levels above this threshold (Caillaud et al., 2014). The same study found effects on allergic rhinitis and asthma that appeared for low values of grasses (< 10 Pollen m^{-3}) due to a very gradual release of these pollen grains before the pollination season; concluding that the entire pollen season of grasses could be considered risky (Caillaud et al., 2014).

A study at the European continental-scale showed evidence of a trend towards an increase in atmospheric pollen in Europe, including highly allergenic taxa such as *Alnus*, *Ambrosia*, *Artemisia*, *Betula*, *Corylus*, Cupressaceae, *Olea*, Poaceae (Ziello et al., 2012). These trends could not be attributed to rising temperatures, but experimental studies suggested that they might be influenced by anthropogenic increases in the greenhouse gas CO_2 (Rogers et al., 2006). However, another continental-scale study in North America found that the impact of CO_2 concentrations was important, but temperature had a much stronger effect on pollen variability (Anderegg et al., 2021). Both factors, temperature and CO_2 concentration, are synergistically connected and further global increase in both is projected, leading to further increases in pollen concentrations and greater exposure of the population to pollen allergens. More research is needed in this area given the negative consequences for public health.

The emission of pollen depends on characteristics of the environment (soil composition, moisture content, vegetation cover), and on local atmospheric conditions such as temperature, humidity and wind speed (Rojo et al., 2015). Many studies have concluded that temperature is the main meteorological variable that influences timing and pollen levels (Veriankaitė et al., 2012; Majeed et al., 2018). Recent studies found little but significant influence of moderately extreme rainfall on later pollination (Kirchner et al., 2022; Rodríguez-Solà et al., 2022). These studies showed that an increase in precipitation in the previous winter appeared to be positively correlated with increased pollen counts for herbaceous taxa in subsequent seasons, whereas for the arboreal taxa the proportion of positive correlations was lower.

After pollen is released into the atmosphere, its fate is determined by mesoscale and synoptic scale mechanisms that govern the regional and long-range atmospheric transport (Adams-Groom et al., 2017). An important fraction of the released pollen settles near the emission sources, but another part can be transported by air masses and cause allergies to sensitive people in more or less distant regions (Alarcón et al., 2022; Belmonte et al., 2008; Izquierdo et al., 2011, 2017; Sofiev et al., 2013). Atmospheric transport in the Western Mediterranean is highly influenced by the complex meteorology that characterize the region. Different factors such as the orography close to the entire coastline, the westerly wind regime, the subtropical high-pressure regime, mesoscale phenomena and Mediterranean advections contribute to this complexity (Lana et al., 2021). Several studies have shown the occurrence of transport patterns that favour the arrival of pollen in Catalonia, region located on the northeast of the Iberian Peninsula (IP), from specific source areas in Central Europe (Belmonte et al., 2000; Belmonte et al., 2008; Fernández-Llamazares et al., 2012), Pyrenees (Izquierdo et al., 2017) and northwest of the IP (Alarcón et al., 2022). The knowledge of the synoptic atmospheric circulations leading these transport patterns can help to interpret pollen dynamics.

Other studies carried out in the Mediterranean region have shown that synoptic meteorological patterns (SMP) play a significant role in the formation and regional transport of several pollutants like O_3, NO_x and particulate matter (Russo et al., 2014) and in the development of high air pollution episodes and new particle formation processes (Salvador et al., 2021). Furthermore, the relationship between synoptic atmospheric circulations and the transport of African dust towards south European countries has been demonstrated (Russo et al., 2020; Salvador et al., 2014). Transport routes have often been linked to cyclonic activity over the Mediterranean and to the presence of high-pressure systems over North Africa (Àvila et al., 2007; Avila and Alarcón, 1999; Escudero et al., 2005). Recent studies have characterized the transport of pollen/spores towards the European continent during African dust outbreaks (Grewling et al., 2019; López-Orozco et al., 2020).

Multivariate techniques such as cluster analysis and principal component analysis have been widely used in studies related to air pollution. For instance, cluster analysis supported the classification of rains for provenance to identify the source areas of pollutants in precipitation in a Catalan rural site (NE Spain) (Avila and Alarcón, 1999). Another study obtained a classification of the synoptic patterns associated with the episodes of extreme rain recorded at the Ebro Observatory in the period 1905–2003 (Pérez-Zanón et al., 2018). Principal Component Analysis of the pressure and geopotential fields revealed the synoptic configurations that caused the entry of extremely cold and hot air masses into the IP (Mohammed et al., 2018). In the recent years, similar techniques based on clusters of circulation types have been applied to interpret pollen levels in a mountain valley in Central Italy (Pace et al., 2022). Ojrzynska et al. (2020) have studied the influence of synoptic and local meteorology on the *Betula* and *Alnus* pollen concentrations in Wroclaw, Poland. Paschalidou et al. (2020) have applied a method of synoptic circulation-to-environment classification to explain the relationship between different weather patterns and pollen concentrations in Thessaloniki (Greece).

In this work we focused on six pollen types and one fungal spore abundant in the study area and with impact on the well-being and health of sensitized people due to their allergenic capacity (Ojeda et al., 2018). Consequently, its emission and subsequent presence in the air is highly conditioned by the local weather. However, transport on a regional scale and also over long distances is not negligible. Our starting hypothesis is that the levels we measure in Barcelona (BCN) are influenced by both synoptic and local meteorology. The question we want to answer is whether there is a direct link between certain atmospheric circulation patterns and the levels and timing of airborne pollen/spore in the Mediterranean city of Barcelona. The study comprises 19 years of daily airborne pollen/spore data at the BCN aerobiological station. A robust classification of the main synoptic weather patterns that occurred during that period (2001–2019) over the IP has also been used. The classification process of sea level pressure daily data fields used to generate these patterns, as well as the validation of this process, has been previously published (Salvador et al., 2021). The specific objectives here were: (1) Establish the local meteorological characteristics linked to each synoptic meteorological pattern (SMP) and the type of weather they give in Barcelona. (2) Determine the influence of SMPs on the concentration and timing (start, end and duration of the pollination and peak date) of the taxa under study.

2. Methodology

2.1. Area of study

Barcelona is a Mediterranean city, located in the region of Catalonia, northeast of IP (Fig. 1). The vegetation in the area is typically Mediterranean, with evergreen oaks (*Quercus ilex*) forests, mixed with deciduous oaks (*Q. pubescens, Q. cerrioides*) in the wetter areas and abundantly mixed with *Pinus halepensis* and *Pinus pinea*. Maquis are also present and some cultivations persist. Two important rivers at the north and the south of the city add the typical plants of genus *Salix* and *Populus*. In the city, a long list of ornamental and ruderal species adds their pollen to the airborne spectra and between them we find the ones selected for this study: Cupressaceae, *Olea* and *Platanus* as ornamental trees, Poaceae making part of the grasses in the city and the surroundings, and Amaranthaceae and Urticaceae as ruderal plants. See detailed information in: https://land.copernicus.eu/pan-european/corine-land-cover

The weather in Catalonia is characterized by processes related to circulation patterns in mid-latitudes, but also by subtropical phenomena. Its climatic diversity is greatly influenced by its proximity to the Mediterranean Sea and the complex orography of the region (Clavero et al., 1996; Lana et al., 2020; Llabrés-Brustenga et al., 2020). The Pyrenees, along the north border between France and Catalonia, act as a barrier in many parts of the country against the northern and north-western flows (Izquierdo et al., 2017). In the same way, the effects of the Mediterranean disturbances are limited to the coastal regions and have a lesser effect inland because the Littoral and Pre-littoral chains, parallel to the coastline from north to south, reduce their effects. Likewise, the passage of the westerly winds that come from the Atlantic to the Mediterranean coast through the IP weakens the effect of the Atlantic disturbances, reducing the intensity of the rains, being only North-western Catalonia significantly affected. Consequently, the coastal and pre-coastal zones, where Barcelona is located, are governed mainly by Mediterranean advection, with the effect of breezes also being very important. Barcelona has a typically Mediterranean climate, characterized by mild temperatures and infrequent but sometimes torrential rains, concentrated mainly in autumn and spring. In the 19-year period studied here, the average annual rainfall in BCN was 620 mm, with an average annual temperature of 16 °C, and relative humidity of 68 %.

2.2. Pollen record

Airborne pollen data were produced by the Aerobiological Network of Catalonia (Xarxa Aerobiològica de Catalunya, XAC) at Barcelona (BCN, 41° 23′ 37.42" N, 2° 09′ 53.72″ E, 93 m a.s.l.) (Fig. 1) over the 19-year

Fig. 1. Geographical location of the Barcelona aerobiological station.

period 2001–2019, following the European aerobiological standards (Galán et al., 2014).

Airborne daily samples were obtained from Hirst sampler (Hirst, 1952) and analysed using the standardized Spanish method (Galán Soldevilla et al., 2007). Six pollen taxa and one fungal spore of high interest due to their abundance in the atmospheric pollen and spore spectrum and allergenic significance were considered in this study. Some selected pollen types were from trees: *Platanus* (PLAT), Cupressaceae (CUPR), *Olea* (OLEA); other from herbaceous plants: Poaceae (POAC), Urticaceae (URTI), Amaranthaceae (AMAR); and the fungal spore was *Alternaria* (ALTE).

The results obtained in the analysis at the light microscope of the samples from the Hirst trap (pollen/spore counts) are converted into daily concentrations thanks to the conversion factor resulting from the suction power of the trap, the proportion of sample analysed, and the optical values of the microscope used. Thus, for each studied pollen/spore type one concentration value per day of the period 2001–2019 is considered. These daily concentrations are the basis for establishing, by summing up all the values of the year, the Annual Pollen Integral (APIn) per taxon and year. In this paper the Main Pollen/Spore Season (MPS) of each pollen/spore type and year has been defined (Andersen, 1991; Gehrig and Clot, 2021) as the period between the date when the sum of daily mean pollen concentrations reaches 2.5 % of the APIn (Start), and the date when the sum reaches 97.5 % of the APIn (End). Then, the pollen/spore parameters included in this study were: the dates of Start and End of the MPS; the date of the Peak, or date of the daily maximum concentration in a year; and the Seasonal Pollen Integral (SPIn) or Seasonal Spore Integral (SSIn), or sum of the daily pollen or spore concentrations between the Start and End dates (Galán et al., 2017).

Based on the intensity of the recorded pollen and spore concentrations and their impact on the allergic population, each day was classified, for each pollen/spore type, into 5 levels of risk of allergy, being 0 the lowest concentration and risk, and 4 the highest concentration and maximum risk. The concentration of particles assigned to the allergenicity risk levels differ from one taxon to another (Docampo et al., 2007; Galán et al., 2010). We have grouped levels 0, 1, 2 into a single group LC (low pollen/spore concentration) and levels 3 and 4 into the single group HC (high pollen/spore concentration). LC for *Platanus*, Cupressaceae and *Olea* include daily concentrations from 0 to 50 pollen m^{-3}, for Poaceae, Urticaceae and Amaranthaceae from 0 to 8 pollen m^{-3} and for *Alternaria* from 0 to 30 spores m^{-3}. HC are the concentrations over the LC upper threshold.

2.3. Synoptic classification

Non-hierarchical k-means cluster analysis was the technique employed by Salvador et al. (2021) for classifying into similar groups, reanalysis data fields of sea level pressure (SLP) at 12 UTC in the period 2001–2019. First, SLP global fields at 12 UTC derived from the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) Reanalysis dataset (Kalnay et al., 1996) provided by NOAA/OAR/ESRL PSD, USA were obtained for all the days of the period of study. Data were distributed in each field in a 2.5° latitude x 2.5° longitude global grid. Those data contained in the region located between 50°W-50°E and 20°N-70°N were downloaded, resulting in 861 SLP grid points for each daily field. Belis et al. (2019) recommend performing classifications of synoptic meteorological patterns (SMPs) using SLP data fields, for discriminating periods of high atmospheric stability. Under such stagnant meteorological conditions, concentration of pollen and spores from local plants and trees can reach very high levels.

The k-means cluster is one of the statistical methods most widely used for classification of atmospheric circulation patterns. It comprises 5 stages (Belis et al., 2019; Salvador et al., 2021):

Stage 1: define an initial partitioning of the SLP fields: k daily fields representing different representative synoptic meteorological situations in the study area were selected as initial cluster centers. In this study, the most frequent atmospheric circulation patterns over the Iberian Peninsula were selected. They were identified from previous studies and used as initial conditions in the clustering procedure.

Stage 2: calculate the change in the clustering criterion that result from changes in membership and reassign SLP fields. Hence, the euclidean distance from each SLP field to each cluster-center k was calculated for every grid-point value of their 861 SLP observations and summed. Finally, the SLP field was assigned to the cluster with the smallest total distance from its cluster center.

Stage 3: recalculate the cluster centers after all the SLP fields have been examined and assigned. The cluster centers were recalculated as the arithmetic mean of all members of any cluster.

Stage 4: repeat the steps 2 and 3 iteratively until no SLP field changes its cluster assignment. Then, composite synoptic maps could be obtained by averaging all the SLP fields allocated in each group, grid-point by grid-point.

Stage 5: The optimum number of clusters to be retained was selected according to the percentage change in within-cluster variance as a function of the number of clusters. This statistic increases abruptly as clusters which are significantly different are joined. Moreover, a validation procedure on the resulting clusters was performed with the aim to assure their physical meaning. It was based on the analysis of heterogeneous data sets of meteorological variables and atmospheric stability parameters, obtained from measurements performed in an instrumented tower, numerical models and radiosondes carried out in the central region of the Iberian Peninsula.

This circulation classification methodology produced six different clusters each one representing a prevailing SMP over the IP. Detailed information on the characteristics of the reanalysis SLP data fields, the circulation classification process and the validation procedure of the results, can be found in Salvador et al. (2021). The composite synoptic weather maps representing each SMP, which were obtained by averaging the SLP corresponding to the days of the different clusters and the main features that characterize the SMPs are provided as Supplementary material (Fig. A.1).

2.4. Meteorological data

The influence of the 6 SMPs on the surface meteorological parameters registered in the Madrid metropolitan area, located in the center of the IP, was analysed as part of the validation procedure in Salvador et al. (2021). In the present study, meteorological data were also used in order to characterize each synoptic type with the local meteorology of the aerobiological sampling site, in this case, the city of Barcelona, and thus represent the average meteorological conditions during each SMP. The data, provided by the Servei Meteorològic de Catalunya (SMC), were recorded in the Fabra Observatory (41°25′N, 2°07′E, 415 m a.s.l.), at approximately 5 km north of the pollen sampling site. Daily values of maximum temperature (Tmax), minimum temperature (Tmin), mean temperature (Tmean), precipitation (PREC), relative humidity (RH), solar irradiance (SI), mean sea level pressure (SLP), and wind speed and direction at 10 m above ground level were used. The available periods for the different variables and used in this study were: Tmax, Tmin, Tmean, 2001–2019 (with the exception of 10 days in May 2002 and 8 days in December 2003); PREC, 2001–2019; RH, 2001–2019 (with the exception of November 2003); SI, 2002–2010; SLP, 2002–2019 (with the exception of 2007); wind, 2013–2019.

2.5. Statistical methods

Boxplots of the daily mean values of the meteorological variables showing the median and the interquartile range (range between the 25th and 75th percentile) were obtained in order to characterize the local meteorology associated with each SMP. The median and average concentrations as well as the Pollen/Spore Integral values corresponding to the dates of each synoptic meteorological pattern (SMP) in Barcelona were also computed. Besides, Pearson and Spearman correlations between the number of days with a given SMP during the Main Pollen/Spore Season (MPS) and the Seasonal Pollen/Spore Integral (SPIn/SSIn) were obtained.

In addition, two different statistical approaches, described in the following sections, were applied.

2.5.1. Frequency comparison

First, the time periods of likely occurrence (LOPs) of the Start, End and Peak parameters for each taxon were defined as the period between the earliest observed date of occurrence and the latest one in the period 2001–2019. Then, we have considered two types of date samples, each date with its corresponding SMP: one sample corresponds to the dates in which the occurrence of the parameters was observed (observational sample with 19 values for each parameter and taxon) while the other corresponds to all the dates of the LOPs. Next, the percentage frequency of the different SMPs in each sample is compared to assess the influence of each SMP on the occurrence of the pollen/spore time parameters. If the percentage of a specific SMP is the same or similar in both types of samples, it could be interpreted as that the SMP of the day did not influence the parameter to occur. Instead, if the percentages are significantly different the SMP could have influenced it.

Let us denominate as P the occurrence percentage corresponding to a specific SMP in the observational sample for a time parameter and taxon (sample size of 19), and P_{LOP} the percentage corresponding to the same SMP in the LOP sample for the same time parameter and taxon. For each taxon and parameter, the P and P_{LOP} percentages corresponding to each SMP can be calculated as follows:

$$P = \frac{\text{Number of occurrences in the SMP}}{19} \text{x}100 \tag{1}$$

$$P_{LOP} = \frac{\text{Number of occurrences in the SMP}}{\text{Number of LOP dates x 19}} \text{x}100 \tag{2}$$

To compare these two percentages and assess the difference between them, a statistical test has been applied. Comparing proportions between the two samples, the test determines if the percentage differences are statistically significant or only a consequence of the variability derived from samples of finite sizes. To this end it has been constructed the statistic Z as a variable whose values follow a standardized normal probability distribution with a mean of 0 and a standard deviation of 1:

$$Z = \frac{P - P_{LOP}}{\sqrt{P_{LOP}\,(100 - P_{LOP})/N}} \tag{3}$$

N is the number of years of the observational sample (19 years). For a significance level of 95 % ($p \leq 0.05$), the value of Z must exceed ± 1.96 to ensure that the percentages are significantly different.

2.5.2. Performance index

In order to evaluate the association of each Pollen/Spore Integral to each SMP a Performance Index (PI), defined as (Paschalidou et al., 2020):

$$PI = 100x\left[\frac{(\text{Pollen(Spore) Integral in SMP})/(\text{Pollen(Spore) Integral in the Season})}{\text{Number of days in SMP/Number of days in the Season}} - 1\right] \tag{4}$$

where Pollen/Spore Integral in the Season is the sum of SPIn/SSIn of the 19-year period, and Pollen/Spore Integral in SMP is the sum of daily concentrations corresponding to each SMP along the 19-year period.

When the values of PI approach 0, it can be interpreted as the daily mean pollen/spore concentration is uniformly distributed in different synoptic patterns. Instead, PI values >0 mean that higher daily pollen concentrations are more frequent under the specific SMP, and negative PI values

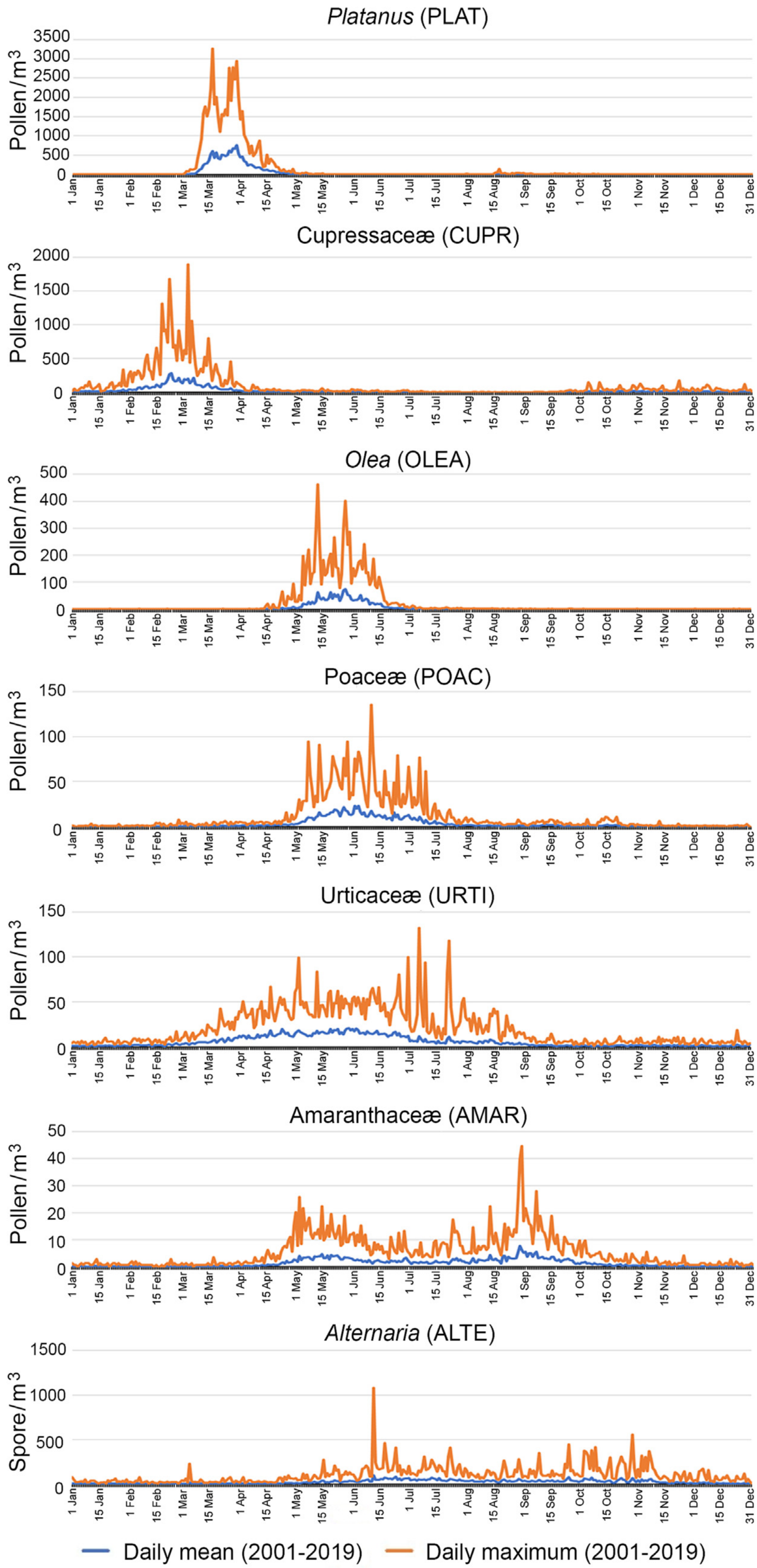

Fig. 2. Summary of the daily dynamics of the mean (blue line) and maximum (orange line) pollen/spore concentration (Pollen m^{-3}, Spore m^{-3}) of the studied taxa along the year during the period 2001–2019 in Barcelona.

Table 1
Number of days and the corresponding percentage with low (LC) and high (HC) pollen/spore concentration during the period (shown in Table 1) for each taxon. The minimum and maximum concentrations considered here for allergenicity risk of each taxon are also shown.

	LC		HC	
	Min-Max (Pollen·m^{-3})	Number of days (%)	Min-Max (Pollen·m^{-3})	Number of days (%)
PLAT	0–50	895 (59)	50–3263	610 (41)
CUPR	0–50	4847 (90)	50–1895	568 (10)
OLEA	0–50	880 (82)	50–463	194 (18)
POAC	0–8	3092 (81)	8–136	702 (19)
URTI	0–8	3701 (71)	8–132	1509 (29)
AMAR	0–8	3718 (95)	8–45	183 (5)
ALTE	0–30	3820 (68)	30–1081	1805 (32)

mean that daily pollen concentrations are lower. Positive values of *PI* might be reflecting severe conditions of allergenic risk, while negative ones would correspond to situations for which a lower pollen/spore concentration than the mean has been collected, and therefore, a less risk of allergenic conditions.

3. Results

3.1. Pollen parameters overview

Daily mean and daily maximum concentrations in BCN for the period 2001–2019 are shown in the Fig. 2.

As shown in Table 1, the number of days with LC in the period considered is always higher than the number of days with HC, although this could change in some cases if we do not consider the 0 concentration values or if we consider the exact pollination period of a particular year. The particles being able to cause allergenic troubles during a longer period were *Alternaria*, followed (decreasing order) by Urticaceae, Poaceae, *Platanus*, Cupressaceae, *Olea* and Amaranthaceae.

The time periods of likely occurrence (LOPs) of the pollen/spore parameters Start, End and Peak for the studied taxa at the BCN station in the period 2001–2019 are listed in Table 2.

As shown in Fig. 2 and Table 2, the taxa studied have a rather different airborne dynamics not only when considering the moment of the year in which the pollination/sporulation period occurs but also in the concentration values per day, which vary notably along the year and from year to year, these shown by the maximum daily concentrations (orange line in Fig. 2). Some pollen types are present in the air throughout the year (Cupressaceae, Urticaceae and Amaranthaceae), other are more limited on time (Poaceae, *Platanus* and *Olea*,). *Alternaria* shows a yearly spread sporulation. As also shown in Fig. 2 and Table 1, pollen from trees is more abundant (*Platanus* peak mean values ranging 500 Pollen m^{-3} in a day but with an absolute maximum ranging 3.300 Pollen m^{-3}; Cupressaceae 500 and 2.000 Pollen m^{-3}; and *Olea* 80 and 500 Pollen m^{-3}) than pollen from herbs (Poaceae 25 and 130 Pollen m^{-3}; Urticaceae 25 and 100 Pollen m^{-3}; and Amaranthaceae 10 and 45 Pollen m^{-3}). *Alternaria* ranges between 100 and 1.000 Spore m^{-3} per peak day.

3.2. Synoptic meteorological patterns and local associated meteorology

The dynamics of each SMP can be seen in Fig. 3, where the absolute frequency throughout the year is shown. Boxplots of the time series of daily mean values of the meteorological variables maximum temperature (Tmax), minimum temperature (Tmin), mean temperature (Tmean), relative humidity (RH), solar irradiance (SI), mean sea level pressure (SLP), wind speed (W10m), total precipitation and average daily precipitation for the different synoptic meteorological patterns (SMP) in the meteorological station of BCN are shown in Fig. 4. The wind rose plot for each synoptic meteorological pattern obtained from the wind data at 10 m a.g.l. is shown in Fig. 5.

SMP-1 was the type of circulation that presented the lowest values of Tmax, Tmin, Tmean, RH and SI, and the highest values of pressure and wind speed. Under the influence of this typically winter regime, NW and W flows were dominant in BCN mainly in dry sunny days, in an atmosphere of strong stability. It was absolutely absent from April to September (Figs. 3, 4, 5 and A.1).

In contrast, SMP-2 presented the highest values of temperatures and SI, and the lowest values of RH, as well as light winds from the SW and W, sometimes accompanied by precipitations of convective origin. This typical spring-summer pattern presents the best meteorological conditions to favour pollination.

SMP-3 presented lower temperatures and solar radiation, but higher RH than SMP-2 and the lowest pressure of all SMPs. Frequent in spring and autumn, it produced episodes of low pressure above NW IP accompanied by storms and moderate/high westerlies (Figs. 3, 4, 5 and A.1).

SMP-4 was more frequent in autumn/winter than in spring/summer, and the associated temperatures in BCN were quite similar to those of SMP-3. It was characterized by the presence of an extensive anticyclone over Eastern Europe and a northward displacement of the Atlantic low, with SI, pressure and HR values higher than those of SMP-3. Winds were more moderate and did not show a predominant direction.

SMP-5 was more frequent in spring/summer than in autumn/winter. It was characterized by high or moderate temperatures and SI, and relatively low RH values, prevailing smooth fluxes from the SW. This was the pattern with the highest accumulated precipitation and the highest mean value of daily precipitation, after SMP-4. SMP-2 represents the typical summer pattern in BCN, while SMP-5 together with SMP-3 would represent the prevalent SMPs occurring in spring.

SMP-6 was a winter/autumn pattern, totally absent in summer, and gave rise to moderately low temperature and SI values, high pressures at the surface level, and almost no precipitation in BCN. This pattern, which like the SMP-1 resulted in high atmospheric stability associated with anticyclonic weather.

The mean value of the meteorological variables in each SMP during the pollination period of each taxon has been computed and represented in Fig. 6 for *Platanus* and Cupressaceae. On the left, wind speed versus pressure is represented, and, as a third variable, the difference between the average daily precipitation in each SMP and the average daily precipitation in the 19-year period (balls size), in blue positive values and, in grey, negative values. On the right, solar irradiance as a function of mean temperature is represented, and the difference between the average relative humidity

Table 2
Earliest and latest observed days (day of the year and date) in which the Start, End and Peak pollen/spore parameters occurred, in the period 2001–2019 at the BCN station. The last column indicates the average length (number of days) of the main pollen/spore season (MPS/MSS).

	Start		End		Peak		Length
	Earliest	Latest	Earliest	Latest	Earliest	Latest	Days
PLAT	67 (3/7/16)	90 (3/31/05)	103 (4/13/14)	257 (9/14/05)	75 (3/16/07)	96 (4/5/05)	84
CUPR	8 (1/8/13)	37 (2/16/10)	146 (4/27/11)	354 (12/21/13)	39 (2/8/04)	86 (3/27/05)	296
OLEA	106 (4/16/01)	133 (5/12/16)	159 (6/8/17)	212 (7/31/18)	125 (5/5/03)	165 (6/14/07)	58
POAC	58 (2/27/06)	112 (4/11/12)	254 (9/11/07)	295 (10/22/05)	128 (5/8/15)	188 (7/7/19)	195
URTI	20 (1/20/07)	76 (3/17/10)	285 (10/11/04)	349 (12/15/19)	89 (3/30/06)	212 (7/31/01)	279
AMAR	37 (2/6/07)	116 (4/26/02)	287 (10/14/03)	320 (11/16/09)	123 (5/3/15)	258 (9/15/01)	204
ALTE	18 (1/18/11)	87 (3/28/15)	317 (11/13/01)	354 (12/19/04)	64 (3/4/08)	312 (11/8/01)	298

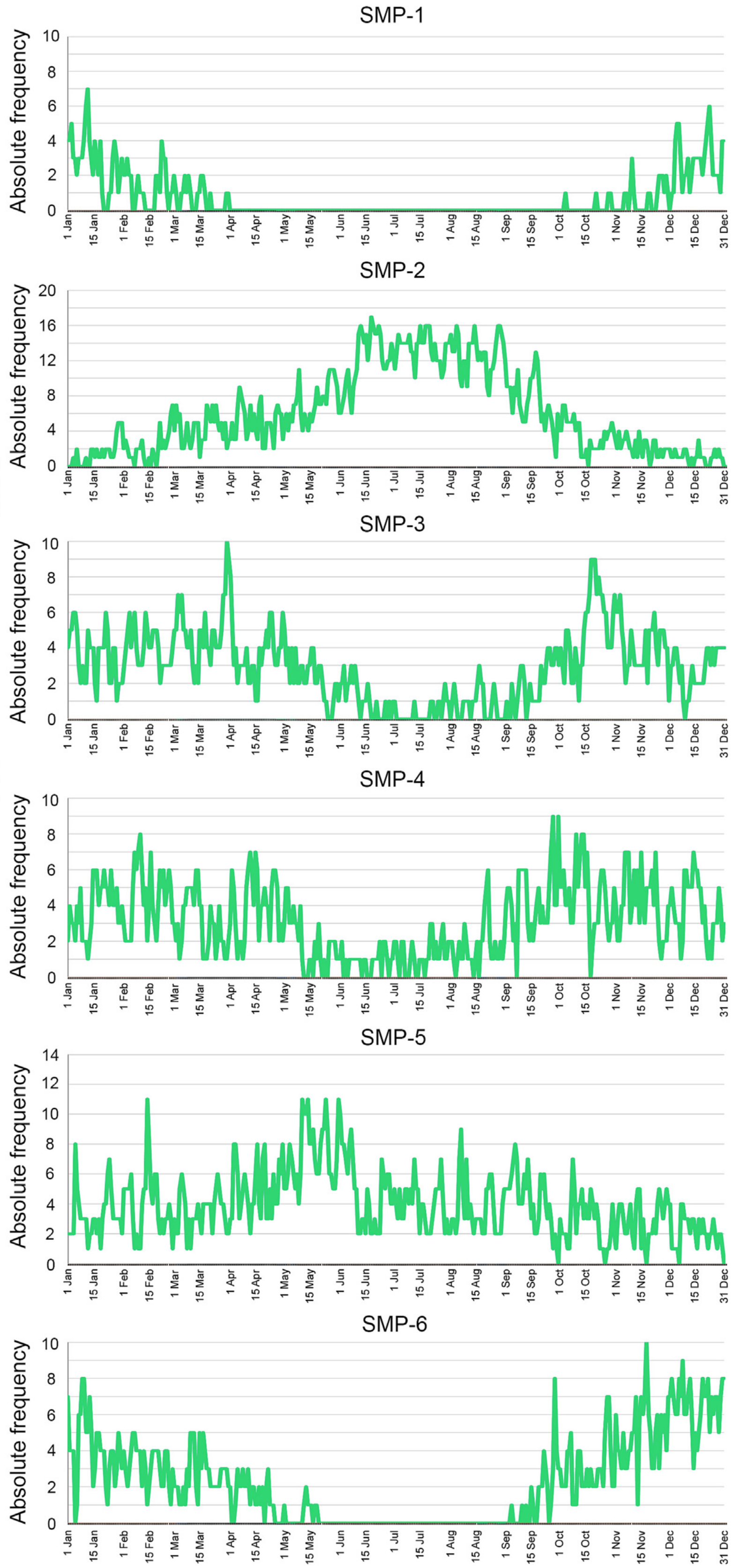

Fig. 3. Absolute frequency of each SMP along the year in the period 2001–2019.

and its value in each SMP as third variable. Both taxa presented similarities, e.g., SMP-1 was the coldest and driest synoptic type. SMP-2 also presented similar characteristics in both pollination periods with high temperatures and solar irradiance. However, SMP-3 showed differences in precipitation and relative humidity, with higher values in the Cupressaceae period, and higher solar irradiance in the *Platanus* period.

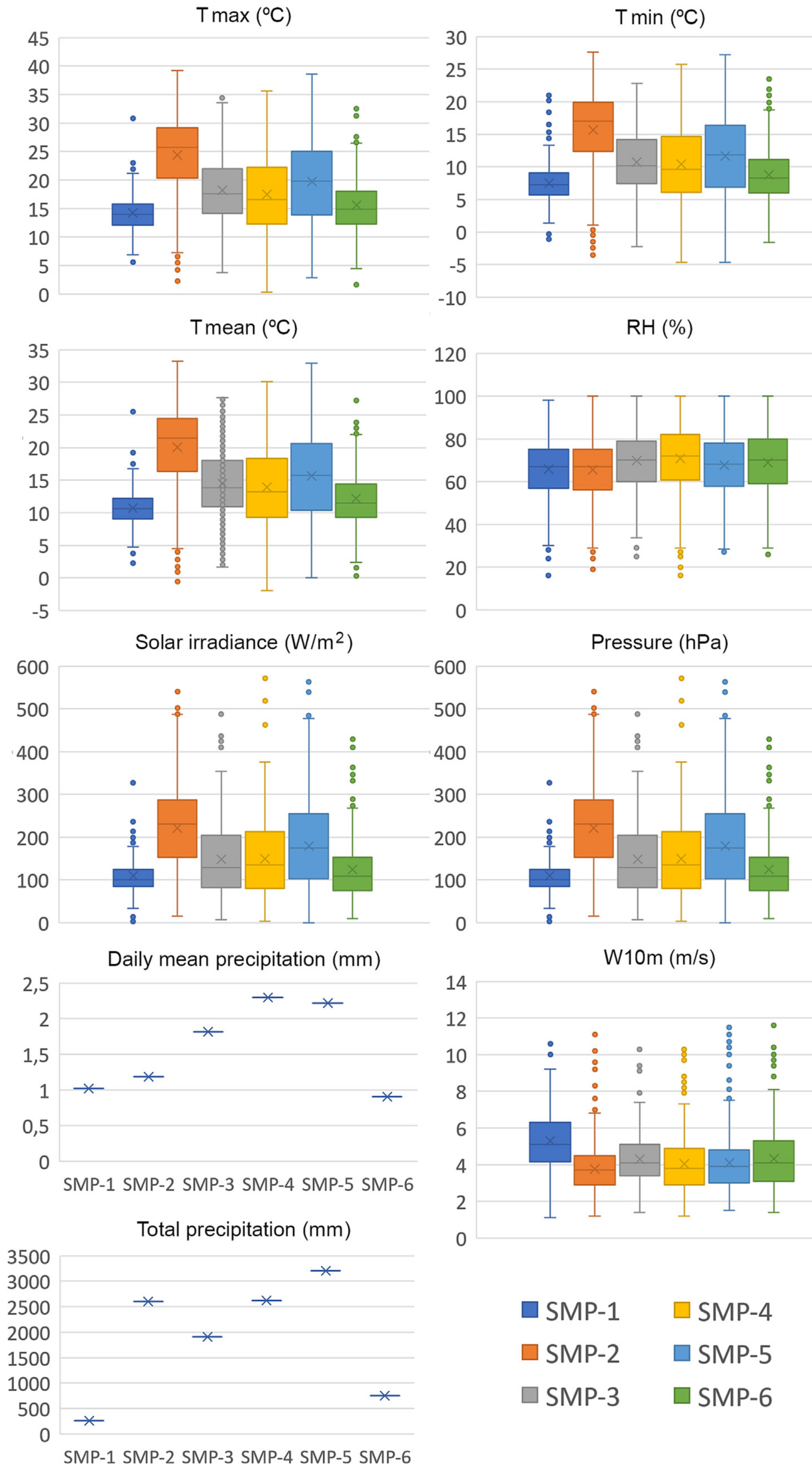

Fig. 4. Boxplots of daily mean values of the meteorological variables showing the median and the interquartile range (range between the 25th and 75th percentile) corresponding to the dates of each synoptic meteorological pattern (SMP) in Barcelona.

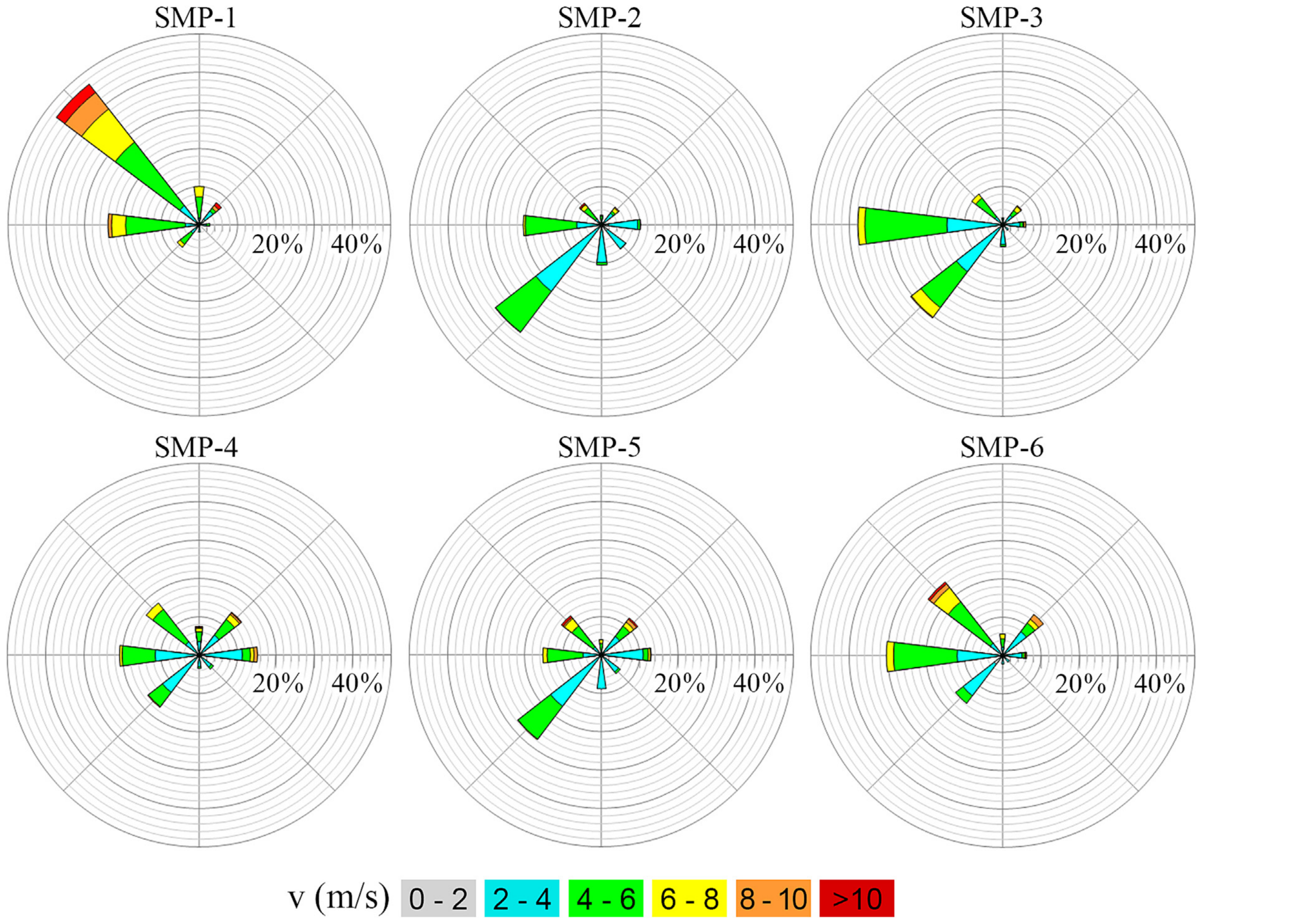

Fig. 5. Wind rose plot for each synoptic meteorological pattern (SMP) obtained from the wind data at 10 m a.g.l. registered in the meteorological station of Barcelona.

The mean value of the meteorological variables in each SMP during the pollination period of the other taxa is shown in Supplementary material (*Olea*/Poaceae in Fig. A.2, Urticaceae/Amarantaceae in Fig. A.3 and *Alternaria* in Fig. A.4). It is remarkable the similarities between Urticaceae, Poaceae and Amarantaceae. There are differences only in SMP-1 and SMP-3 for precipitation, more abundant in the Urticaceae period for which the wind is also slightly higher. The greatest differences between the taxa in the local meteorology linked to the SMPs correspond to the pollination period of *Olea*, in which the coldest synoptic type, with the least insolation and the highest precipitation, is SMP-5, being SMP-6 the windiest pattern with the lowest relative humidity (Supplementary material, Fig. A.2).

3.3. Pollen/spore concentration and synoptic types. Correlations

Boxplots with the median pollen/spore concentrations (Pollen m^{-3}) and the interquartile range (range between the 25th and 75th percentile) of the daily pollen/spore time series registered during each synoptic pattern, for the Main Pollen/Spore Season (MPS) of each taxon, are shown in Fig. 7. The number of cases N (days with measured concentration during the MPS of each taxon), the percentage of HC days with respect to the total days, the Pollen/Spore Integral, and the mean daily concentration in each synoptic pattern are shown in Table 3. The most abundant synoptic type (Supplementary material, Fig. A.1), SMP-2, presented the highest total number of cases for all taxa. The highest median and mean values for Urticaceae corresponded to SMP-5 followed by SMP-2, and the lowest values corresponded to SMP-4. In the case of Poaceae, also the highest mean values were in SMP-5 and SMP-2, but the median value in SMP-2 slightly exceeded that of SMP-5, while SMP-1 was the synoptic type with the lowest median and frequency for this taxon. On the other hand, SMP-2 was also the circulation type that presented the highest concentrations for Amaranthaceae.

Cupressaceae, with the longest pollination period, has an interannual pollen season from October to April. Unlike Urticaceae and Poaceae, also with long pollination periods, it was during the most frequent synoptic types in autumn/winter (SMP-1, SMP-6 and SMP-3) that the highest daily mean values of Cupressaceae pollen were recorded. The lowest daily mean values of Cupressaceae occurred in SMP-2, which, however, was the most frequent synoptic type for this taxon (Table 3). The spring/summer pollen *Olea* presented an Integral value of zero during SMP-1 and the highest median values corresponded to SMP-3. For this taxon, the highest daily mean concentration corresponded to SMP-6 (Table 3), which was the synoptic pattern with the lowest relative humidity and higher wind The also spring pollen *Platanus* presented only 12 cases (out of a total of 1505) in SMP-1, but all of them with very high values (mean 1094 Pollen m^{-3}), in the range of high allergenicity risk (Table 1); it was followed by SMP-6, SMP-3,and SMP-4 with also high daily concentrations (mean values of 390, 312, and 175 Pollen m^{-3}, respectively), included in the HC. The fungal spore *Alternaria* showed the highest values of median and mean during SMP-2 episodes.

Significant correlations have been found between the number of days with a given SMP in the Main Pollen/Spore Season and the Pollen/Spore Integral in the period, SPIn/SSIn. Table 4 shows the Pearson and Spearman correlation coefficients obtained for the level of significance $p \leq 0.1$. It is remarkable the fact that all the significant correlations were negative. SMP-2, the most frequent SMP, correlated with 5 out of the 7 taxa, some with long pollination periods, i.e. Cupressaceae, Urticaceae and Poaceae; and other with the shortest ones, i.e. *Platanus* and *Olea*. The fungal spore *Alternaria*, with the longest period of presence in the air, showed no

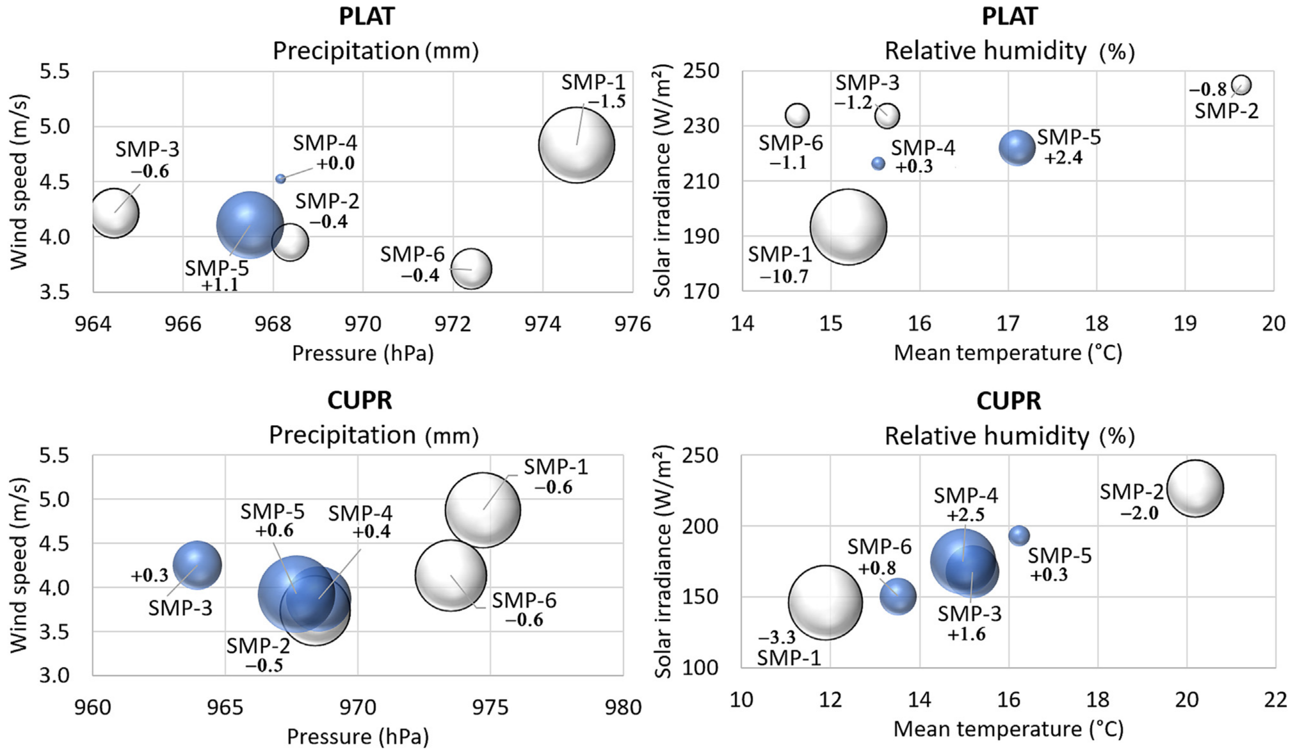

Fig. 6. Mean value of the meteorological variables in Barcelona in each synoptic meteorological pattern during the Main Pollen Season of *Platanus* and Cupressaceae for the period 2001–2019. Left: wind speed vs. pressure; balls size represents the difference between average daily precipitation in the SMP and average daily precipitation in the 19-year period (blue and grey, positive and negative values, respectively). Right: same than left for the variables: mean temperature, solar irradiance and relative humidity.

correlation with any of the synoptic types. *Platanus* is the pollen that showed more correlations: with SMP-2, SMP-4 and SMP-5. Cupressaceae correlated with SMP-2 and SMP-4, while Poaceae correlated with SMP-2 and SMP-3. Urticaceae and *Olea* only had significant correlations with SMP-2. It should also be noted that if we go up to the significance level of $p \leq 0.05$, only Cupressaceae and *Platanus* showed significant correlations. These correlations were with the circulation types SMP-2 and SMP-5 (Fig. 8).

The number of days with LC (low pollen/spore concentration) and HC (high pollen/spore concentration) in each synoptic meteorological pattern is shown in Table 3. *Platanus* pollen had the highest proportion of HC days in most of the patterns. For this taxon, during SMP-1, HC occurred on 100 % of the days, near 90 % during SMP-6, over 60 % during SMP-3 and SMP-4, and around 30 % during the other patterns. The HC percentages were also high for Urticaceae, with over 33 % of HC days under SMP-2 and SMP-5. Poaceae also presented high concentrations for these same synoptic types. The fungal spore *Alternaria*, which is present every day of the year, registered the highest number of days under SMP-2, being the HC percentage of 45 % under this synoptic pattern.

SMP-2 is the circulation pattern concentrating the highest proportion of HC days (*Alternaria*, Urticaceae, Poaceae and Amaranthaceae), followed by SMP-1, SMP-3 and SMP-5. None of the taxa showed a higher proportion of HC days under SMP-4 and SMP-6.

3.4. Relationship between SMPs and pollen/spore parameters. Frequency comparison

To evaluate the influence of each SMP on the occurrence of pollen/spore time parameters, a comparison has been done between the P percentage and P_{LOP} percentage for each SMP. While the samples of observed dates of occurrence have a size of 19 days, one per year, the size of the samples corresponding to each LOP is much longer, ranging from 418 days for the Peak of *Platanus* (22 days between the first (75) and last (96) dates, multiplied by 19 years) to 4731 days for the Peak of *Alternaria* (249 days between the dates 64 and 312, multiplied by 19 years) (Table 2). Fig. 9 shows the percentage differences $P - P_{LOP}$ for each taxon, parameter and SMP. The statistic Z of Eq. (3) has been applied to determine if the difference of these percentages is statistically significant or not. For a significance level of 95 % ($p \leq 0.05$) the sample percentages are significantly different if the value of Z exceeds ± 1.96. As an example, Table 5 shows the Z values obtained for the parameter Start of Urticaceae.

It only exceeds the threshold value of ± 1.96 for SMP-1 (2.52). Therefore, it can be stated that the number of times for which the parameter Start occurred in a SMP-1 day is higher than the expected number, in relation to the percentage of SMP-1 days in the corresponding LOP. Instead, negative values of Z would indicate that the time parameter occurred less than expected under the considered SMP, i. e., the SMP would disfavour the occurrence of the time parameter.

Asterisks in Fig. 9 show all the cases with significant percentage differences after applying the test Z for each taxon and time parameter. In all these cases Z resulted positive, i. e., the specific parameter occurred more frequently than expected for the indicated SMPs. One of these cases is the aforementioned Start of Urticaceae for the SMP-1, with a percentage of $P_{LOP} = 7\%$ among the dates of the corresponding LOP while the percentage among the observed dates is $P = 21\%$, which is the maximum percentage among the Start dates of Urticaceae. According to this, the type of synoptic pattern had an influence on the Start occurrence of Urticaceae, and SMP-1 was the most influential.

The End parameters of Cupressaceae, *Platanus*, Amaranthaceae and *Alternaria* show percentage differences for diverse SMPs. In dates with these SMP the main pollen/spore season of the mentioned taxa has more frequently ended than expected considering the observed occurrence probability P. The greatest percentage differences corresponded to dates with SMP-2 for Amaranthaceae ($P = 32\%$ vs. $P_{LOP} = 13\%$) and dates with SMP-5 for *Alternaria* ($P = 32\%$ vs. $P_{LOP} = 14\%$). The case of dates with SMP-4 for Cupressaceae is debatable because this significant difference is due to two anomalous years for which the End occurred much earlier than commonly: day 146 in 2011 (May 26) and day 149 in 2019 (May

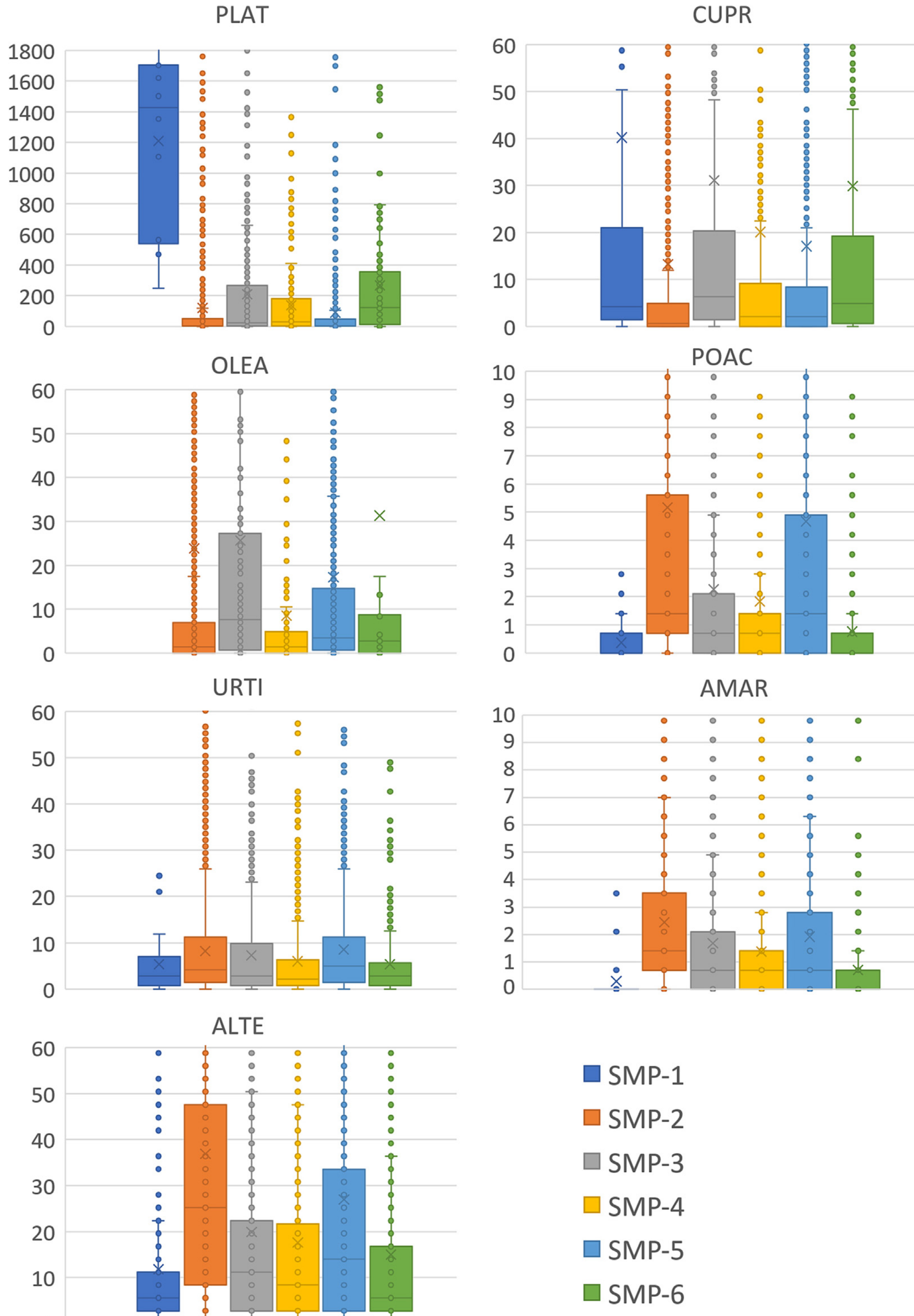

Fig. 7. Boxplots of the time series of daily pollen/spore concentrations (Pollen m^{-3} and Spore m^{-3}) during the Main Pollen/Spore Season showing the median values (line inside the box) and the interquartile range (range between the 25th and 75th percentile, limit of the boxes) registered in each synoptic meteorological pattern (SMP) in Barcelona for the time period 2001–2019.

29). In the rest of the years the End always occurred after summer, the earliest in day 283 (October 10). Because of these two anomalous Ends, the LOP of Cupressaceae has been enlarged in 137 days, with consequences in the percentages of each SMP in this period. If these two years are not considered, none of the SMPs show significant percentage differences. Another possible consideration to make is to take an interannual season pollen for this taxon, since it adjusts better from October of the previous year to April of the current year than the natural year. In this case, the series of End dates don't show outliers, but significant percentage differences appear for SMP-2 and SMP-6. Considering the observed occurrence probability P_{LOP}, in dates with SMP-6 the main pollen season of Cupressaceae has more frequently ended than expected, being less frequently ended under SMP-2 dates.

For *Platanus*, a higher percentage of End occurred under SMP-6 dates, and a higher percentage of Peak occurred during SMP-1 dates. Even though

Table 3
Number of days with measured concentration during the pollination/sporulation period of each taxon (N), percentage of HC days with respect to the total days in the SMP (HC/N), Pollen/Spore Integral (units: Pollen/Spore*day m^{-3}), and mean daily concentration (units: Pollen/Spore m^{-3}), in each SMP.

		SMP-1	SMP-2	SMP-3	SMP-4	SMP-5	SMP-6
	N	12	649	210	188	373	73
	HC / N (%)	100	26	62	57	34	88
	Pollen Integral	13,132	81,880	65,545	32,972	47,816	28,450
PLAT	Daily mean	1094	126	312	175	128	390
	N	97	1927	802	869	1225	495
	HC / N (%)	37	5	18	9	8	22
	Pollen Integral	9542	28,095	30,944	21,967	23,399	22,954
CUPR	Daily mean	98	15	39	25	19	46
	N	0	543	101	67	354	9
	HC / N (%)	0	17	32	12	18	11
	Pollen Integral	0	14,821	4318	1455	10,231	526
OLEA	Daily mean	0	27	43	22	29	58
	N	6	1779	387	490	1022	110
	HC / N (%)	0	21	16	9	21	6
	Pollen Integral	5	10,601	1607	1471	5796	216
POAC	Daily mean	1	6	4	3	6	2
	N	71	2054	749	793	1145	398
	HC / N (%)	14	33	28	20	33	17
	Pollen Integral	298	16,766	5231	4514	9586	1907
URTI	Daily mean	4	8	7	6	8	5
	N	7	1824	484	511	918	157
	HC / N (%)	0	5	5	4	4	2
	Pollen Integral	4	4644	951	911	1973	194
AMAR	Daily mean	1	3	2	2	2	1
	N	106	2090	836	878	1218	497
	HC / N (%)	16	45	22	22	32	18
	Spore Integral	2050	80,041	18,763	18,654	37,156	10,125
ALTE	Daily mean	19	38	22	21	31	20

the expected probability was very low in both cases ($P_{LOP} = 1\%$), the observed probability was much higher ($P = 11\%$) since two times of the total of 19 years the End of *Platanus* occurred in SMP-6, and also two times of the 19 years the Peak day was SMP-1.

3.5. Performance index

The association of Pollen/Spore Integral to each SMP has been assessed using the Performance Index (*PI*) of Eq. (4). This *PI* index has been calculated for each SMP and taxon (see Fig. 10). *PI* index is useful to show, for each taxon, which SMPs comprise the days with the highest concentrations, suggesting that some meteorological conditions might result more severe in terms of risk of allergy. Anyway, this index must be interpreted carefully, bearing in mind the daily concentrations and the number of LC and HC pollination days in each SMP (see Table 3) besides the proportions that appear in Eq. (4). For instance, the positive values of *PI* found for Urticaceae, Poaceae and Amaranthaceae during SMP-2 have diverse significance in terms of allergenic risk. Although Table 3 shows mean concentration of 8, 6 and 3 Pollen m^{-3} respectively, which can seem low, the respective number of HC days under this SMP-2 are 33 %, 21 % and 5 % On the other hand, for the interpretation of the high positive values of *PI* found for Cupressaceae and *Platanus* in SMP-1 (295 and 512 respectively) and for *Olea* in SMP-6 (107) (Fig. 10), it has to be kept in mind that even though mean daily pollen concentrations are important in SMP-1 for Cupressaceae (98 Pollen m^{-3}) and *Platanus* (1094 Pollen m^{-3}), and in SMP-6 for *Olea* (58 Pollen m^{-3}) (Table 3), the pollen concentrations in these synoptics situations last few days: around 5 days per year in the case of Cupressaceae and <1 day per year for *Platanus* and *Olea*. But, when they occur, the concentrations are HC in 100 % of the cases for *Platanus*, 37 % for Cupressaceae and 11 % for *Olea*.

However, the value of the index *PI* is very significant for Cupressaceae and *Platanus* in SMP-3 and SMP-6 (53 and 85 for Cupressaceae and 75 and 114 for *Platanus*), since the pollen concentrations registered in these synoptic situations are much more frequent, especially for Cupressaceae with >42 days per year in SMP-3 (18 % HC days) and >26 days per year in SMP-6 (22 % HC days) (Table 3). For *Platanus*, 88 % of the days under SMP-6 showed HC and 57 % under SMP-3. Moreover, the negative values of *PI* for these two taxa in the SMP-2 and SMP-5 situations are also very remarkable because these are the most frequent synoptic situations during their main pollen season (26 % and 34 % of HC days for *Platanus* and 5 % and 8 % for Cupressaceae, respectively). This result is in accordance with the finding of a negative correlation between the Pollen Integral collected during the Cupressaceae and *Platanus* main pollen seasons and their occurrences (see Table 4 and Fig. 8).

The large negative values of *PI* in the SMP-1 synoptic situation for Poaceae (−84) and Amaranthaceae (−73) indicate the almost absence of pollen in these situations, and the complete absence for *Olea* (−100).

For *Alternaria* the values of *PI* in all the considered SMPs range between −34 (SMP-1, with the lowest N and only 16 % of HC days) and + 29 (SMP-2, with the highest N and 45 % of HC days). The spore concentrations are more uniformly distributed among the different synoptic meteorological situations.

4. Discussion

The possible connection between the most frequent synoptic situations affecting the Iberian Peninsula and the daily concentrations and timing of some selected airborne allergenic pollen and spore taxa in the city of Barcelona has been analysed. To this end, we have used several complementary

Table 4
Significant correlations at p ≤ 0.1 and correlation coefficients, Pearson's r and Spearman's ρ, between the number of days with a given SMP during the Main Pollen Season and the corresponding Pollen/Spore Integral (SPIn/SSIn). All correlations are negative.

		SMP-2	SMP-3	SMP-4	SMP-5
PLAT	Pearson	$p = 0.008$		$p = 0.085$	$p = 0.031$
		$r = -0.591$		$r = -0.406$	$r = -0.497$
	Spearman	$p = 0.021$		$p = 0.084$	$p = 0.04$
		$\rho = -0.526$		$\rho = -0.407$	$\rho = -0.474$
CUPR	Pearson	$p = 0.007$			$p = 0.014$
		$r = -0.596$			$r = -0.556$
OLEA	Pearson	$p = 0.075$			
		$r = -0.418$			
POAC	Pearson	$p = 0.096$	$p = 0.055$		
		$r = -0.393$	$r = -0.447$		
	Spearman	$p = 0.09$	$p = 0.039$		
		$\rho = -0.399$	$\rho = -0.476$		
URTI	Pearson	$p = 0.068$			
		$r = -0.427$			
	Spearman	$p = 0.024$			
		$\rho = -0.515$			
AMAR	Spearman			$p = 0.084$	
				$\rho = -0.407$	

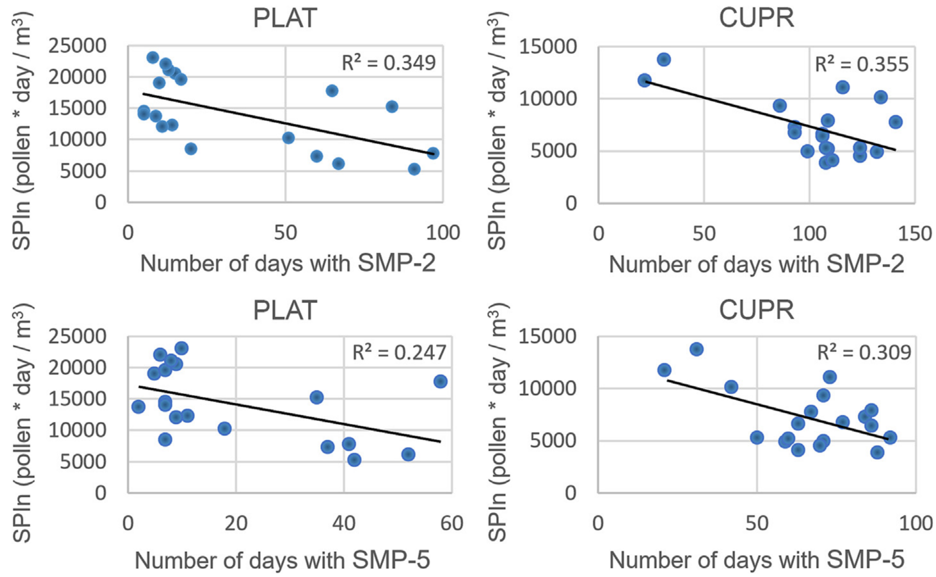

Fig. 8. Seasonal Pollen Integral SPIn vs. number of days in the synoptic meteorological pattern (SMP) for the taxa with significant correlations at the level $p \leq 0.05$.

statistical methodologies that have provided different results, coherent among them. The synoptic types, obtained by cluster analysis of the surface pressure fields, showed a clear seasonality. The scenario described as SMP-1 is dominant in winter, along with SMP-6 which is also frequent in fall. In summer and spring SMP-2 predominates. The SMP-5 pattern occurs in all seasons, and similarly SMP-3 and SMP-4, but to a much lesser extent in summer the last two. This seasonality, added to the phenology of the taxa studied here, makes it difficult to interpret possible relationships. The taxon with the shortest pollination period is *Olea* followed by *Platanus*, which flower in summer and spring, respectively. On the other hand, Urticaceae, Poaceae and Amaranthaceae pollen types are present in spring, summer and autumn, while Cupressaceae pollen and *Alternaria* spore are present throughout the year. The interannual pollen seasons, as is the case of the Cupressaceae, represent an added difficulty. Another special case is the bimodal patterns of the pollen and spore curves, such as the case of Amaranthaceae, *Alternaria* or even Urticaceae pollen (Picornell et al., 2022). All these particularities in pollen dynamics add complexity to the analysis of the influence of synoptic meteorological conditions. The preliminary results obtained from the descriptive statistics attributed to SMP-2 an important influence on the pollen/spore concentration levels measured in Barcelona. This is not surprising since this scenario is linked to high temperatures, low precipitation, and moderate north-westerly winds (Figs. 4 and 5), a favourable meteorology for pollination. Moreover, it is the SMP presenting the highest absolute frequencies along spring and summer. However, in subsequent analyses with the other methods, it has been seen that this pattern is not as influential. Nevertheless, SMP-2 is the most frequent pattern in absolute terms (one third of the total days in a year), and it is also the most frequently occurring during the pollination period of all taxa. The performed analyses show that SMP-2 is especially relevant for those taxa with long pollination periods such as Amaranthaceae, Urticaceae, Poaceae and *Alternaria*. Instead, for the only pollen that pollinates throughout the year, Cupressaceae, the median and mean values are low during the SMP-2 scenario. These contrasts could be explained from the characteristics of the local meteorology associated with each pollination period and SMP. In the case of Urticaceae and Poaceae, both with long pollination periods spanning from February to November, the coincidence in the high mean daily values observed during SMP-2 and SMP-5 (Table 3) is consistent with the similarity in local meteorology associated to their Main Pollen Season (Supplementary material, Fig. A.2 and A.3). In the case of *Olea*, the taxon that differs the most from the others in the local meteorology associated with its MPS, the low relative humidity and high wind values during SMP-6 (Supplementary material, Fig. A.2) could explain why the highest daily mean concentration is found in this pattern.

The winter SMP-1 scenario, which is not very relevant for the rest of the taxa, is, however, the one that registers the highest mean and median values for Cupressaceae and *Platanus* (Table 3, Fig. 7), consistent with the very high values also obtained of the Performance Index (*PI*, Fig. 10). This is remarkable considering that SMP-1 is the least frequent type. The reason for the high concentration of these taxa could be, added to the explosive pollination they show, that the configuration linked to SMP-1 causes blocking of air-mass and high stability over the IP and the Mediterranean Sea due to the position of the Azores anticyclone, displaced in front of the IP, and the deep low at the latitude of Iceland, extending to the east (Supplementary material, Fig. A.1). During atmospheric blocking situations, high pressure zones remain stationary for several days, giving rise to stagnation of air mass, accumulation of pollutants, including pollen and spores, and, eventually, causing serious air pollution situations (Otero et al., 2022). *Platanus* and Cupressaceae also showed both the highest daily mean concentration in SMP-1 and SMP-6 (Table 3). This coincidence could be due to the similarity of the meteorological conditions in their respective pollination periods (Fig. 6). The conditions in SMP-1, SMP-2, SMP-5, SMP-4 were similar, although with higher precipitation and relative humidity during SMP-4 in Cupressaceae. This presence of precipitation could explain the favouring of the End of Cupressaceae obtained for this synoptic pattern (Fig. 9). The main differences are observed during SMP-6, with higher relative humidity in Cupressaceae and higher temperature and solar irradiance in *Platanus*, and during SMP-3, with higher precipitation and relative humidity in the Cupressaceae period and higher insolation in the *Platanus* period (Fig. 6).

The analysis of the SPIn and SSin reflected in Table 4 and Fig. 8 reduces the possible masking effect that seasonality of the variables can introduce. It is noteworthy that no significant positive correlations at $p \leq 0.1$ level were found between the number of days that a given synoptic pattern appears during the pollination period of the different taxa and the SPIn and SSin. The few significant correlations obtained were all negative (Table 4). In the case of *Platanus* and Cupressaceae we found negative correlations with SMP-2 and SMP-5 with a higher significant level ($p \leq 0.05$) (Fig. 8). These results agree with those obtained applying the Performance Index (*PI*) in which negative values were obtained for these taxa during SMP-2 and SMP-5, indicating lower concentrations than expected of *Platanus* and Cupressaceae pollen during these scenarios. There is also a commonality between the different methods in describing SMP-1 scenario

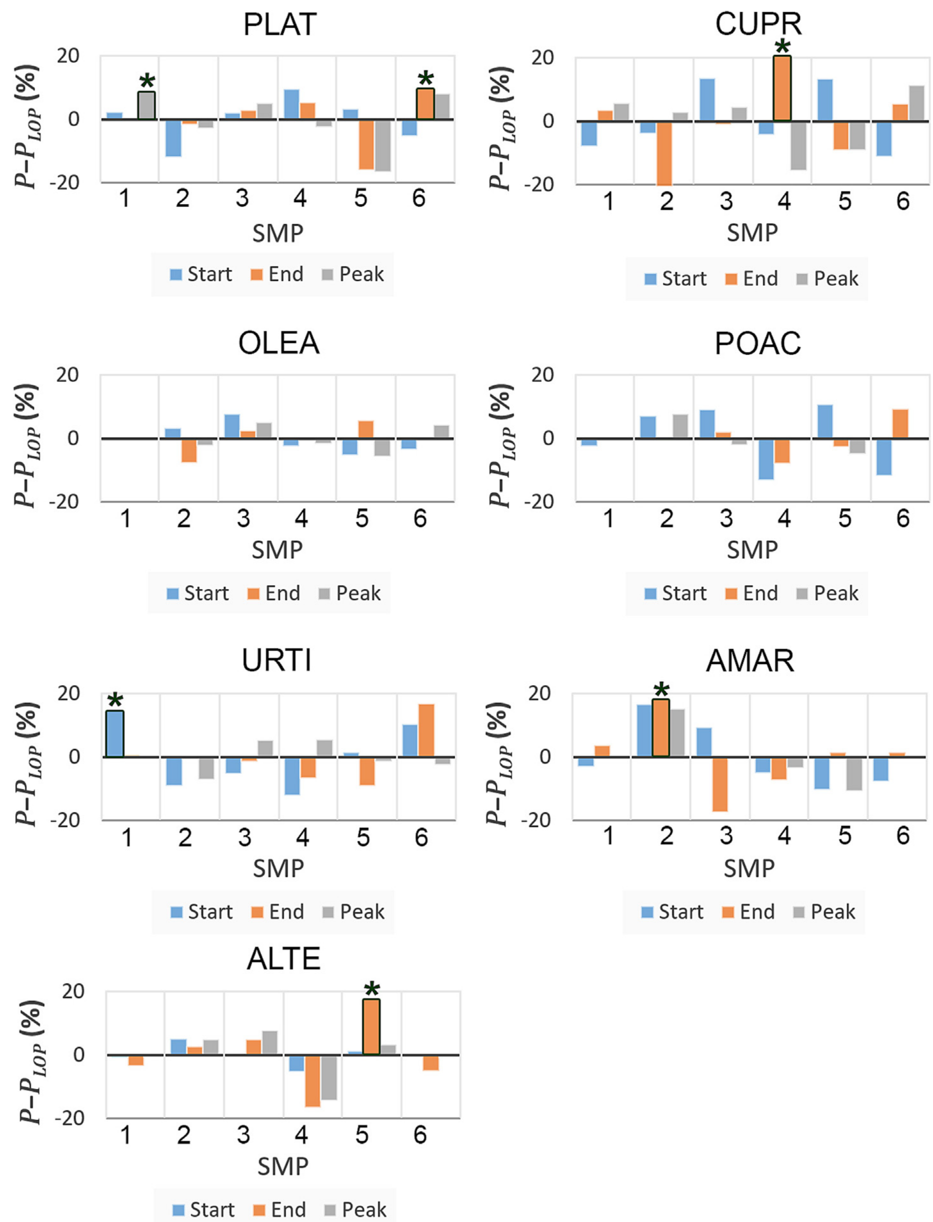

Fig. 9. Differences of sample proportions $P - P_{LOP}$ of each SMP for the different time parameters (Start, End and Peak) and taxon. P corresponds to the total of observed dates of occurrence of the time parameters, P_{LOP} collects all the dates belonging to the likely occurrence periods (LOPs) of each parameter. Asterisks indicate the cases for which the differences are statistically significant.

Table 5
Number of occurrences and percentage P (%) of each SMP for the observed Start dates of Urticaceae in the period 2001–2019 (19 days), number of days and percentage P_{LOP} (%) of each SMP for all the days of the corresponding LOP (57 days: from 20 to 76) in the period 2001–2019 (19 years), and value of the statistic Z comparing both percentages.

	Number of occurrences in 19 years	Number of *LOP* dates in 19 years (Total 1083 days)	*P* (%)	P_{LOP} (%)	*Z*
SMP-1	4	72	21	7	2.52
SMP-2	1	154	5	14	−1.12
SMP-3	3	227	16	21	−0.55
SMP-4	2	244	11	23	−1.25
SMP-5	4	213	21	20	0.15
SMP-6	5	173	26	16	1.23

as the least relevant in the concentrations of Urticaceae, *Olea*, Poaceae and Amaranthaceae. In reference to Cupressaceae and *Platanus*, the *PI* method highlights the high presence of these taxa in the SMP-3 and SMP-6 scenarios, in addition to the aforementioned SMP-1, in agreement with the high mean and median concentration values obtained.

The Performance Index complements the information provided by Fig. 7 in the sense that *PI* involves a sort of "pollen intensity" (Pollen Integral Season/Number of days in the season), and compares this "pollen intensity" for the days of each SMP with the averaged "pollen intensity". Fig. 10 shows how in some cases the "pollen intensity" is much higher under some SMP than the mean. The comparison involves intensity rather than simple concentration, which can be useful in relation to high allergenic situations. For instance, *Platanus* in SMP-1 appears very high in both Figs. 7 and 10. However, while Cupressaceae in SMP-1 achieves similar values than in SMP-3 and SMP-6 in Fig. 7, Fig. 10 is spotlighting how Cupressaceae pollen intensity is much higher under SMP-1 than under SMP-3 and SMP-6.

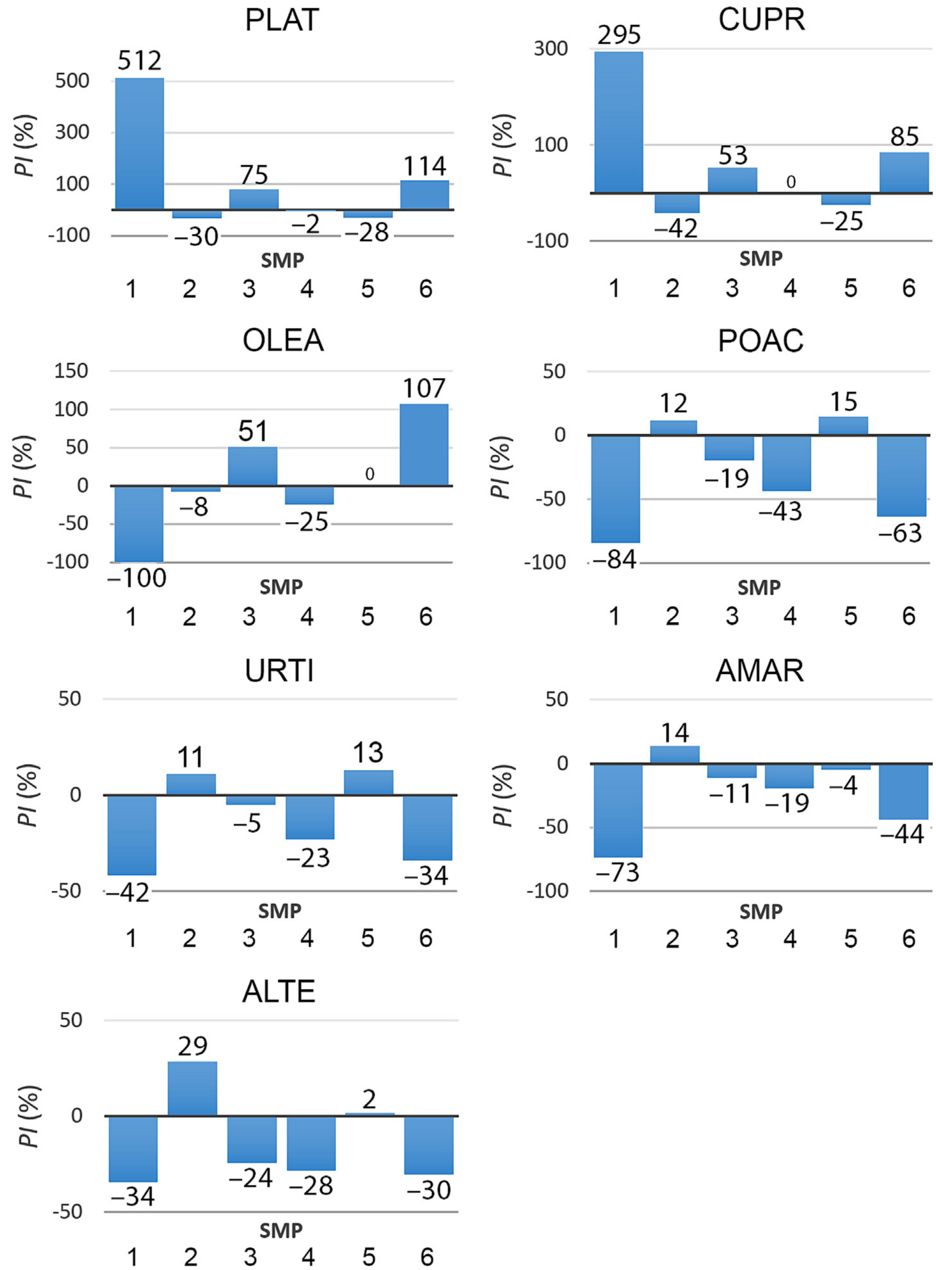

Fig. 10. Performance Index (*PI*) for each SMP and taxon.

Regarding the fungal spore *Alternaria*, the *PI* method does not highlight any of the synoptic patterns, except for the positive value of SMP-2. Therefore, it attributes similar concentration values in the different synoptic types, but higher in SMP-2, which is consistent with the fact that the mean and median *Alternaria* concentration values are the highest in this pattern that accumulates 45 % of days of high allergy risk (HC). It should also be noted that the SMP-2 and SMP-5 scenarios have registered an important percentage of days HC in *Platanus*, Poaceae, Urticaceae and *Alternaria* (Table 3).

As it is well known, the phenological parameters of plants, mainly woody plants, depend not only on the current year, but also on the conditions of the previous year. It is especially important for the start date of the pollen season, which is a very complex process also based on past conditions, mainly in perennial plants (Campoy et al., 2011; Luedeling et al., 2013). Despite the fact that the current synoptic condition is not the determining factor of the phenological moment of the plant, we found it interesting to look for possible relationships and include here those results with statistical significance (Fig. 9). The determination of time periods of likely occurrence (LOPs) of the time parameters Start, End and Peak have revealed that SMP-1 is the most likely to initiate the Urticaceae pollination as well as to provide the date of the peak for *Platanus*. On the other hand, the scenarios that favour the End are SMP-4 for Cupressaceae, SMP-2 for Amaranthaceae, and SMP-6 for *Platanus* (Fig. 9).

Platanus is the most abundant ornamental tree in Barcelona and presents significant allergy problems every spring (Puiggròs et al., 2015). The *Platanus* tree produces large amounts of pollen during its pollination period with an estimate of 3-10 $\times$ 10^6 pollen grains per inflorescence (Vrinceanu et al., 2021; Tormo Molina et al., 1996) and a threshold of clinical symptoms in sensitized persons of 50 Pollen m^{-3} (Cariñanos et al., 2020). These concentrations are widely exceeded by the values registered in Barcelona. *Platanus* pollen has been identified by the European Academy of Allergy and Clinical Immunology (EAACI) as an important allergen responsible for respiratory symptoms and was introduced as mandatory for pollen allergen screening in patients with possible allergic rhinitis in Europe (Bousquet et al., 2012). The SMP-1 scenario presented high mean values of this pollen, all them corresponding to high allergy risk (HC), concentrated in only 102 days in the 19-year period studied, and it was also the most probable scenario for the peak day. Considering that pollen particles behave in the atmosphere in a similar way than the particulate matter of the atmospheric aerosol (Sofiev et al., 2006, 2013), this result would coincide with the high values of daily mean particle number concentrations found by Salvador et al. (2021) in the urban background of the city of Madrid for this same synoptic type (SMP-1). In the analysis of this series, also in concordance with our results for *Olea* pollen, SMP-6 favoured the accumulation of pollutants, gases and particulate matter, emitted from local sources, and consequently the generation of high concentrations in the Madrid metropolitan area (Salvador et al., 2021).

We have not found a different behaviour in both concentrations and timing, depending on whether the pollen types are from trees or herbaceous plants, neither for the spore *Alternaria*, except for the case of the most significant SMPs influencing their presence in the air. For the three arboreal pollen types studied, scenarios SMP-3 and SMP-6 were relevant and also scenario SMP-1 for *Platanus* and Cupressaceae. For the herbaceous pollen types and the spore, scenarios SMP-2 and SMP-5 were relevant (except Amaranthaceae with only SMP-2).

The physical mechanisms that determine the influence of synoptic meteorology on airborne pollen are complex and involve processes ranging from the micro-scale to the synoptic scale. In this study we have focused on taxa of local origin, but long-distance contributions can also be important. In previous works, these external contributions were studied through the analysis of pollen types that are scarce in the study region, such as *Betula*, *Fagus* and *Ambrosia*. We were able to associate important peaks of *Ambrosia* with air-mass trajectories coming from North-eastern and Southern Europe, entering Catalonia through the northern Mediterranean region (Fernández-Llamazares et al., 2012). In the case of *Fagus* and *Betula*, episodes of long-range transport from Central Europe were identified, showing back-trajectories bypassing the Pyrenees through from its easternmost region (Alberes) or crossing them through the valley of the Garonne river (Belmonte et al., 2008; Izquierdo et al., 2011, 2017; Alarcón et al., 2022). The synoptic situations corresponding to the *Ambrosia* episodes were characterized by the presence of low pressures over the IP extending towards the Eastern Mediterranean, and high-pressure systems over Scotland and Eastern Europe. This scenario would correspond to the SMP-4 of the present study. In the case of *Betula* and *Fagus*, the synoptic situation showed high-pressure systems over the British Islands and the presence of low pressures over Eastern Mediterranean. In the present study these situations would correspond to types SMP-4 and SMP-6. However, these two synoptic types, SMP-4 and SMP-6, have turned out to be the least influential in the present study that deals with taxa predominantly of local origin. This could indicate that the local meteorology linked to each synoptic type is the most determining factor, rather than its associated transport pattern. Indeed, relative humidity and temperature are two variables that influence the release of pollen into the atmosphere: low relative humidity combined with high temperature favours the increase of airborne pollen. The duration of the insolation also influences the release of pollen and the wind speed is a determining factor in its transport and dispersal (Alba et al., 2000). The effect of rain simultaneous to pollination has mainly a washing effect by reducing the amount of pollen grains (Rodríguez-Solà et al., 2022). In another study we analysed the dynamics of the hourly concentrations during the episode corresponding to the absolute maximum of Total pollen recorded in Barcelona in 2015, in which 80 % of its total concentration was due to *Platanus* and *Pinus* pollen (Sicard et al., 2016, 2021). The analysis of the samples indicated that the correlation coefficient between the daily mean temperature and the daily total pollen concentration was 0.95, indicating a strong dependence of pollen release upon temperature. The correlation coefficient between the daily mean relative humidity and the daily Total pollen concentration was negative (-0.18) but much lower than the one for temperature. The correlation coefficient between daily wind speed and Total pollen concentration was 0.82, indicating a strong dependence of pollen release also upon wind speed. The synoptic chart for the peak day of the episode showed low pressures over the IP and the Western Mediterranean while high pressures moved northward, over the British Islands, a scenario that is similar to that corresponding to the SMP-5 type, linked in the present study to high concentrations of *Platanus* pollen in Barcelona. Therefore, the use of sea level pressure fields to characterize SMP seems to be a good option for this type of study, instead of trajectories or geopotential height fields at a given pressure level, useful to identify long-range transport episodes. They correctly depict the atmospheric circulation at relatively high tropospheric levels in most cases. But they are not appropriate for describing the main meteorological features that drive surface atmospheric circulations (Belis et al., 2019), which have been the most influential regarding pollen concentration in BCN.

5. Summary and conclusions

In this study we have established relationships between the occurrence of specific synoptic meteorological patterns and pollen/spore dynamics in an urban environment, focusing on the seven most allergenic taxa abundant in the study area. The city of Barcelona has been chosen as representative of an urban environment under a Mediterranean climate and due to its location in an emplacement with a great diversity of flora and vegetation. Cluster analysis of the mean sea level pressure fields has provided six synoptic meteorological scenarios, which we have characterized from the values of the local meteorological variables. The different statistical analyses that we have applied to the pollen/spore series obtained in Barcelona during the period 2001–2019 show that synoptic meteorology may be a relevant factor in the measured concentrations of some pollen/spores. In addition, and although without a direct cause-effect relationship, it can also influence the flowering timing. The following points can be highlighted:

- The synoptic type SMP-1, which occurred mainly in winter, coincided with the highest concentrations of Cupressaceae and *Platanus* pollen. SMP-1 was the less frequent of the patterns (4 %) and it was associated to atmospheric blockage on the Iberian Peninsula and situations of great atmospheric stability, favouring low temperatures, solar radiation and humidity and northwesterly winds in Barcelona. Instead, SMP-1 was also linked to the lowest values of the other pollen/spores. In particular, the pollen types Poaceae, Amaranthaceae and *Olea* are absent when this synoptic pattern occurs, partly due to the phenology of the species contained in these taxa.
- The synoptic situation, SMP-3, with the anticyclone over the Azores and the Atlantic low displaced to the north of the UK, which characterizes the weather in Barcelona with low pressures, low temperatures and solar radiation, and moderate winds from the west and southwest, was accompanied by high concentrations of Cupressaceae pollen, which is a tree that pollinates throughout the year although mainly in winter.
- The most frequent synoptic type, especially in spring and summer, SMP-2, produced sporadic episodes with concentrations considered to be of high risk of allergy of the herbs Urticaceae and Poaceae, and *Alternaria* fungal spore. Also, Amaranthaceae showed the highest percentage of days with concentrations of allergy risk under this scenario.
- SMP-1 was the most likely to initiate the Urticaceae pollination (Start) as well as to provide the date of the Peak for *Platanus*.
- The scenarios that favoured the End of pollination are SMP-4 for Cupresaceae, SMP-2 for Amaranthaceae, and SMP-6 for *Platanus*.
- The *Alternaria* spore was present in all synoptic types, although in higher concentrations during SMP-2 episodes.

Knowledge of the relationship between synoptic meteorology and airborne pollen/spore dynamics is useful to anticipate situations that may compromise health of the population and for the adoption of prevention measures by the competent authorities.

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CRediT authorship contribution statement

Marta Alarcón: methodology, original draft preparation, writing-reviewing.

Raul Rodríguez-Solà: methodology, figures, writing- reviewing.

Maria del Carme Casas-Castillo: methodology, figures, writing-reviewing.

Francisco Molero: synoptic meteorological patterns, writing- reviewing.

Pedro Salvador: synoptic meteorological patterns, writing- reviewing.

Cristina Periago: writing- reviewing.

Jordina Belmonte: pollen data, aerobiology, writing- reviewing.

Data availability

Data will be made available on request.

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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