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Airborne pollen parameters and their relationship with meteorological variables in NE Iberian Peninsula

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Abstract The present study explores the role of the meteorological variability in the pollen production and the timing of the airborne pollen season by analysis of the correlation between precipitation, insolation and temperature and the main standardised airborne pollen parameters of 22 taxa collected at 6 localities in Catalonia (NE Spain). The pollen parameters included in the study were: Annual Pollen Integral and the Start, End and Length of the Main Pollen Season. Considering that the Main Pollen Season of most of the taxa in Catalonia lasts from spring to summer or autumn, correlations between the pollen parameters and winter (from December to March) values of meteorological variables were calculated. Correlations between Monthly Pollen Integral and monthly values of the meteorological variables were also calculated. The results obtained report the synchronism registered in the variations of pollen concentration with precipitation (negative), insolation (positive) and temperature (positive). Temperature was the meteorological variable that showed a greater influence in the pollen production and the timing of the pollen season, being insolation the least one. The Start of the Main Pollen Season was the pollen parameter more correlated with the meteorological variables, especially with winter temperatures.

Keywords Aerobiology · Plant phenology · Meteorological variability · Spain

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1 Introduction

Biological particles are present in the atmosphere in form of pollen grains, fungal spores, bacteria, viruses and fragments of plants, fungi and animals. Matthias-Maser et al. (2000) suggested that the proportion by volume of the total airborne particulate matter made up by biological material in remote continental, populated continental and remote maritime environments is, respectively, 28, 22 and 10%. Pollen has a very important role to trigger allergic respiratory

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diseases. Human health is directly affected by the presence of high concentrations of pollen in the atmosphere (Traidl-Hoffmann et al. 2003), which varies according to climate, geography and vegetation. Data on the presence and prevalence of allergenic airborne pollens obtained from both aerobiological studies and allergological investigations allow the design of pollen calendars with the approximate flowering period of the plants in the sampling area. Europe is a geographically complex continent with a widely diverse climate and a wide spectrum of vegetation. Forecasting of how much pollen will be produced in a given season and when it will become available for release into the atmosphere is of crucial importance. The environmental drivers controlling the dynamics of pollen season must be known to implement pollen production and transport in the simulation models (Duhl et al. 2013). The amount of pollen collected at a sampling station is dependent, first, on the amount of emission sources in the surrounding regions and, second, on the weather, that affects the strength and timing of the emissions as well as the atmospheric transport (Zhang et al. 2013). Different techniques have been used in the modelling of airborne pollen: regression analyses (Stach et al. 2008a), multivariate statistical methods (Makra et al. 2006), Lagrangian modelling (Kuparinen et al. 2007; Izquierdo et al. 2015b), large eddy simulation (Chamecki et al. 2009), mesoscale and long-range transport models (Pasken and Pietrowicz 2005; Siljamo et al. 2008; Sofiev et al. 2006; Belmonte et al. 2008).

Many studies have been conducted to examine pollen of different species and its relationship with meteorological variables. In these studies maximum, minimum and mean temperature, relative humidity, precipitation, wind speed, wind direction, sea level pressure, sunshine hours and dew point temperature were correlated with daily pollen concentrations (e.g. Galán et al. 2000; Stefanic et al. 2005; Weryszko-Chmielewska et al. 2006). Temperature was the most important factor in the timing of flowering in winter- and spring-blooming temperate tree species, while in species that bloom during other times photoperiod is also an important determinant of flowering time (Frenguelli and Bricchi 1998; García-Mozo et al. 2002). Flowering in temperate grass species was generally determined by both photoperiod and temperature, although in Mediterranean grasses, the photoperiod requirement is low (Heide 1994). The magnitude of pollen produced in a given season is mainly a function of precipitation in some tree and grass species, and of both temperature and precipitation in others (Recio et al. 2010; García-Mozo et al. 2006). Haroon and Rasul (2008) studied the meteorological factors affecting pollen concentration in Islamabad (Pakistan) and concluded that meteorological variables affect pollen concentration in the atmosphere in two moments: production and dispersion.

Some authors predicted onset and duration of the *Ambrosia* pollen season in Lyon (France) by applying statistical approaches based on meteorological data (Laaidi et al. 2003). Grinn-Gofron and Bosiacka (2015) determined the functional relationships between composition of atmospheric bioaerosols and meteorological factors using canonical correspondence analysis. Piotrowska and Kubik-Komar (2012) investigated the pattern of the birch atmospheric pollen seasons in Lublin (Poland) in the period 2001–2010. Their statistical analysis showed that minimum temperature of February and March and total rainfall in June in the year preceding pollen release had the greatest effect on the birch atmospheric pollen season and that low temperatures in February promoted the occurrence of high pollen concentrations. Piotrowska-Weryszko (2013) reported on the effect of the meteorological factors on the *Alnus* pollen season in Lublin (Poland). Stach et al. (2008a) emphasised how important is the weather during the few weeks or months preceding pollination for grass pollen production in Poznan (Poland). Zhang et al. (2015) designed a pollen production model for California taking into account that for tree and grass species that typically flower between March and June, temperature is the main driver controlling the timing of pollen release, while precipitation (and temperature, for some species) controls the magnitude of pollen produced. Galán et al. (2000) found that the most important meteorological parameter influencing Urticaceae pollen counts in spring in Southern Spain was temperature, while rain did not appear to be significant.

The aim of this study is to investigate the influence of meteorology on the airborne pollen dynamics through correlation analysis between precipitation, insolation and temperature and Annual Pollen Integral, Monthly Pollen Integral, the dates of Start and

End of the pollination season and the Length of the pollination season of 22 taxa collected at 6 localities in Catalonia (NE Spain) during the 18-year period 1994–2011.

2 Data and methodology

2.1 Pollen records

Airborne pollen data were recorded by the Aerobiological Network of Catalonia (XAC) at six stations located in Barcelona (BCN) and Bellaterra (BTU) over an 18-year period, from 1994 to 2011, and in Girona (GIC), Lleida (LLE), Manresa (MAN) and Tarragona (TAU) over a 16-year period from 1996 to 2011.

Daily samples were obtained from Hirst samplers (Hirst 1952), the standardised method in European aerobiological networks (Galán et al. 2014), and analysed following the standardised Spanish method (Galán et al. 2007). 22 pollen taxa were considered of high interest due to their abundance, landscape importance and/or allergenic significance: *Alnus*, *Ambrosia, Artemisia*, *Betula*, *Castanea*, Chenopodiaceae/Amaranthaceae, *Corylus*, Cupressaceae, *Fagus*, *Fraxinus*, *Olea*, *Pinus*, *Pistacia*, *Plantago*, *Platanus*, Poaceae, Polygonaceae, total *Quercus, Quercus* deciduous type (which includes *Q. canariensis* Willd., *Q. faginea*, Lamk., *Q. humilis* Mill., *Q. petraea* (Matt.) Liebl., *Q. pyrenaica* Willd., *Q. robur* L. and exceptionally the evergreen species *Q. suber* L.), *Quercus* evergreen type (which includes *Q. ilex* L. and *Q. coccifera* L.), *Ulmus* and Urticaceae (de Bolòs and Vigo 1990).

The pollen parameters included in this study were: Annual Pollen Integral (APIn, sum of the mean daily pollen concentrations in a year), Monthly Pollen Integral (MPIn, sum of the mean daily pollen concentrations in a month), the dates of Start and End of the Main Pollen Season and the Length (number of days between the Start and the End). The Main Pollen Season (MPS) has been established as the period beginning the date (Start) in which the sum of the daily mean pollen concentrations reaches 2.5% of the annual sum until the date (End) in which the sum reaches 97.5% (Andersen 1991).

2.2 Area under study

Catalonia is located in the north-east of the Iberian Peninsula. The six localities having the most complete airborne pollen series for the period 1994–2011 (BCN, BTU, GIC, LLE, MAN and TAU) were chosen for this study. Figure 1 shows the area under study and the six sampling stations of the Aerobiological Network of Catalonia.

The climate in Catalonia is governed by processes linked to mid-latitude circulation patterns, but also by phenomena with subtropical characteristics. Its climatic diversity is strongly influenced by the Mediterranean Sea and the orography. The Pyrenees, all 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. At the same time, the effects of the Mediterranean perturbations are limited to the coast line and have less effect than expected inland because they are reduced by the Littoral and Pre-littoral chains than run parallel to the coast from north to south in Catalonia. Also, the Iberian Peninsula lessens the intensity of rainfall generated by westerlies that arrive from the Atlantic reaching the Spanish Mediterranean littoral. Consequently, only north-western Catalonia remains significantly affected by Atlantic perturbations.

The Littoral (where BCN and TAU are) and Pre-littoral areas (with BTU and GIC) are governed mainly by Mediterranean advection, where the effect of frontal passages coming from the Atlantic is less significant. The central basin (with LLE and MAN) is protected against the Mediterranean advection by the Littoral and Pre-littoral chains and also against northern outbreaks by the Pyrenees. Furthermore, fronts coming from the Atlantic are weakened by their trajectory across the Iberian Peninsula. Table 1 shows geographical and climatic information about the 6 localities of Catalonia included in this study.

2.3 Meteorological data

Meteorological data were provided by the Servei Meteorològic de Catalunya (SMC). Daily values of precipitation (PRE), insolation (INS), maximum temperature (T_{max}) and minimum temperature (T_{min}) were recorded at the closest meteorological stations to airborne sampling sites (all of them are 5–15 km away). From T_{max} and T_{min}, the mean daily

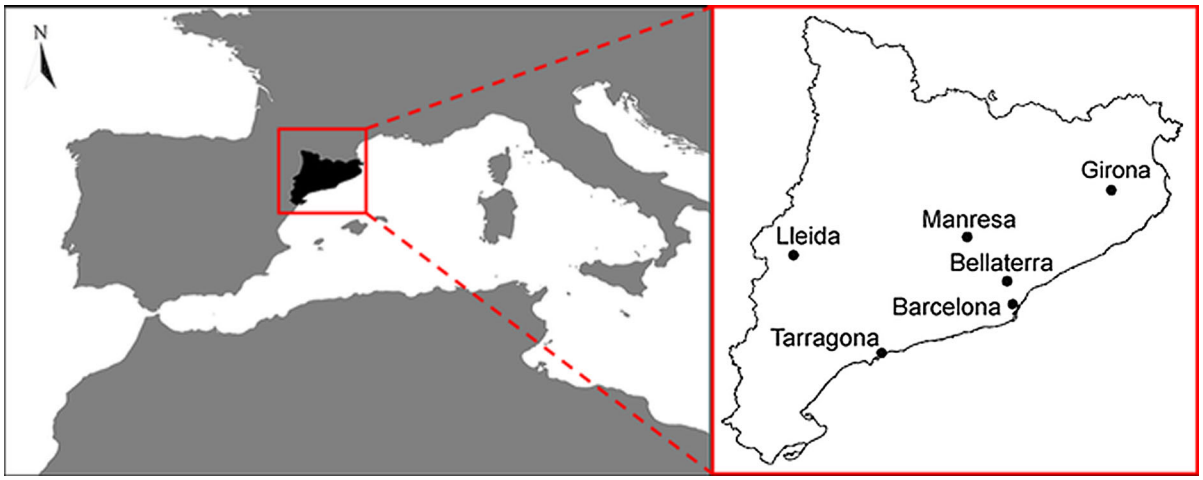

Fig. 1 Area under study and sampling stations of the Aerobiological Network of Catalonia (XAC)

Table 1 Information about the 6 monitoring sites, including geographical location (altitude, latitude and longitude), and climatic characteristics (mean annual temperature and total annual rainfall) during the years included in the study

Station	Geographical characteristics			Climatic characteristics	
	Altitude (m.a.s.l)	Latitude	Longitude	Mean annual temperature (°C)	Total annual precipitation (mm)
Barcelona	93	41°24′N	02°11′E	15.8	602
Bellaterra	245	41°33′N	02°07′E	15.6	562
Girona	98	41°59′N	02°60′E	16.1	702
Lleida	202	41°37′N	00°37′E	14.7	319
Manresa	291	41°44′N	01°50′E	14.9	597
Tarragona	44	41°07′N	01°15′E	16.4	551

temperature (T_{mid}) was computed. Some missing data reduced quite a bit our database: years 1999, 2008 and 2009 in LLE for precipitation; year 1997 in BCN, 1996 in BTU and 1999 in LLE for temperature; years 2000 and 2001 in GIC for temperature and precipitation and year 2004 in GIC for insolation.

2.4 Statistical methods

Spearman's rank correlation coefficient was applied to measure the relationship pollen data (APIn, MPIn, Start, End and Length of the MPS) and the meteorological variables (PRE, INS, T_{max}, T_{min} and T_{mid}). Considering that the MPS of most of the taxa in Catalonia lasts from spring to summer or autumn, correlations between the pollen parameters characterising the MPS (APIn, Start, End and Length of the MPS) and winter (from December to March) values of meteorological variables were calculated. Correlations between MPIn and monthly values of the meteorological variables were also calculated.

The Spearman correlation was used because it is considered more robust and resistant to outlying data than the conventional Pearson correlation coefficient (Wilks 2011; Fernandez-Llamazares et al. 2012). Two levels of significance were considered: $p < 0.01$ and $p < 0.05$.

3 Results and discussion

Table 2 shows the mean values of APIn for each individual pollen taxon and for total pollen (expressed in pollen day m^{-3}) collected at the six sampling stations for the period 1994–2011 or 1996–2011 and the mean value of the APIn of each taxon considering

Table 2 Mean values of Annual Pollen Integral (APIn) for each individual pollen taxon and for total pollen (expressed in pollen day m^{-3}) collected at the 6 sampling stations for the period 1994–2011 or 1996–2011

	Barcelona BCN	Bellaterra BTU	Girona GIC	Lleida LLE	Manresa MAN	Tarragona TAU	Catalonia
Alnus	159	149	703	517	154	85	295
Ambrosia	8	11	8	5	5	3	7
Artemisia	145	166	85	378	182	227	197
Betula	196	183	302	72	141	131	171
Castanea	252	165	551	70	102	179	220
Chenop/Amar.	530	483	426	4133	958	590	1187
Corylus	227	224	531	103	204	982	379
Cupressaceae	6889	6592	6750	8160	7981	9015	7565
Fagus	18	19	74	19	18	14	27
Fraxinus	281	272	1779	266	404	352	559
Olea	1234	1088	869	2153	2375	3081	1800
Pinus	4783	8067	6864	2614	6797	4142	5545
Pistacia	73	120	65	77	181	116	105
Plantago	392	979	703	982	3774	516	1224
Platanus	15915	4108	5186	1710	5367	1337	5604
Poaceae	1119	1496	2096	2304	2389	1233	1773
Polygonaceae	78	77	131	136	73	79	96
Total *Quercus*	4911	7208	15,618	3665	5065	3961	6738
Q. deciduous t.	1007	2247	5528	749	1228	633	1899
Q. evergreen t.	3904	4961	10,090	2916	3837	3328	4839
Ulmus	128	268	108	67	309	284	194
Urticaceae	2889	2173	3193	1050	3282	3401	2665
Other taxa	2520	5936	9456	3457	3794	3146	4718
Total pollen	42,747	39,784	55,498	31,938	43,555	32,874	41,066

See also in the last column the average value of the 6 stations

Catalonia as a whole. The 22 pollen taxa considered in this paper are the most abundant in the sampling stations of Catalonia and accounted for 83–94% of total pollen recorded. The 22 taxa have different roles in the environments. Most of them (15) are trees/shrubs and the rest (7: *Ambrosia*, *Artemisia*, Chenopodiaceae/Amaranthaceae, *Plantago*, Poaceae, Polygonaceae and Urticaeae) are herbs. They are taxa especially important in the natural landscape (*Alnus*, *Artemisia*, *Betula*, *Castanea*, *Corylus*, *Fagus*, *Fraxinus*, *Pinus*, *Pistacia*, Poaceae, *Quercus* and *Ulmus*) and or in the urban areas, due to the use as ornamental plants (*Betula*, Cupressaceae, *Fraxinus*, *Olea*, *Platanus*, *Ulmus*) and their capacity to leave in ruderal areas (Chenopodiaceae/Amaranthaceae, Polygonaceae, Urticaeae).

As shown, Cupressaceae, Total *Quercus*, *Platanus, Pinus* and *Quercus* evergreen type are the main contributors to the pollen spectra. Here, they are cited in decreasing order of importance taking into consideration the mean APIn for Catalonia, but at each locality they are also situated in the positions 1–5 in order of importance, with the only exception of *Platanus* that in Girona, Lleida and Tarragona is located between positions 6 and 8. Cupressaceae and *Platanus* are planted as ornamental trees in urban and urbanised areas, and this is the main cause of their abundance in the airborne spectra. *Quercus* (evergreen and deciduous type) and *Pinus* are the main trees in the Catalan landscapes; moreover, sometimes they are also planted in the cities as ornamental. Regarding pollen taxa from herbaceous plants, the main contributors are from the Urticaceae family, containing ruderal plants usually abundant in urban and urbanised areas, the Poaceae family, present everywhere although specially abundant in grasslands and open landscapes, and *Plantago*, a genus of plants abundant in grasslands. Also important to be cited is the Amaranthaceae family (here cited as Chenopodiaceae/Amaranthaceae pollen type), composed by

ruderal plants and plants from dry and salty environments included littoral landscapes.

Girona is the locality showing the highest APIn, followed by Manresa, Barcelona, Bellaterra, Tarragona and Lleida. This means that the localities with higher precipitation (Table 1) show higher pollen counts and those continental meteorological conditions (Lleida) contribute to lower pollen counts.

The significant correlations between pollen counts (MPIn and APIn) and precipitation (PRE), insolation (INS) and maximum (T_{max}), minimum (T_{min}) and mean (T_{mid}) temperatures for each taxon in each station are summarised in Table 3 and commented in the following sections. Besides the 22 individual pollen taxa, we also considered the total pollen counts. Then, the number of total correlations is 22 pollen taxa + total pollen = 23 × 6 locations = 138.

3.1 Correlations between MPIn and monthly values of the meteorological variables

Correlations between MPIn (sum of the mean daily pollen concentrations in a month) and monthly values of the meteorological variables were calculated in order to explore the immediate effect of meteorological variables on the pollen counts (follow the round symbol in Table 3). The table included as Online Resource 1 shows the significant correlations between MPIn and monthly values of meteorological variables (precipitation, insolation and temperature) obtained for each taxon in each station.

Only negative significant correlations between MPIn and monthly PRE (total amount of precipitation during a month) were obtained and represent 13% of the cases (18/138). This result could be explained as a washing out effect of the airborne pollen by precipitation. Several authors have published about the direct negative effect that precipitation has on the amount of pollen collected during the pollination season (Frei 1998; Jato et al. 2002; Díaz de la Guardia et al. 2003; Peternel et al. 2004; Green et al. 2004; Janati et al. 2004; Khwarahm et al. 2014; De Linares et al. 2017; Vélez-Pereira 2017). Recio et al. (2010) gives also an explanation to this negative correlation, expressing that the content of water in the soil facilitates the vegetative growth better than the flowering. The negative association of pollen counts and precipitation could also be explained by the phenological pattern of the plants flowering out of the rainy season. The pollen taxon most affected by PRE is Poaceae, with negative significant correlations in BTU, GIC and TAU, possibly due to the long pollination period what gives more opportunities to coincide with rains. This is in concordance with the bibliography, as seven of the ten papers above cited refer to Poaceae pollen. The locality giving a higher number of significant results MPIn/PRE is GIC. This location is the one showing highest annual precipitations but also the highest amount of total pollen during the year. This is not contradictory because the pollen production in GIC is very high for some taxa (*Castanea*, *Alnus*, *Betula*, *Fraxinus*, *Quercus*) that are very abundant in the region. On the other hand, the effect of the washout by precipitation, as we see in our results, has an immediate effect reducing the monthly pollen levels in GIC.

The significant correlations between MPIn and monthly INS (sum of daily sunshine hours during a month) represented 11% of the total correlations (15 over 138) and were mostly positive (13 over 15). This result confirms that pollen production and release are enhanced by sunlight and that this effect is relatively immediate because it affects the pollen production in the forthcoming days. Only *Castanea* in BCN and MAN presented negative correlations, while in GIC (where *Castanea* APIn is the highest of all the stations) the correlation was positive.

On the other hand, 7 of the 22 taxa showed no correlation with either, PRE or INS: *Ambrosia*, *Betula*, *Fagus*, *Pistacia*, Total *Quercus*, *Quercus* evergreen type and *Urticaceae*. The pollen concentrations of *Ambrosia*, *Fagus* and *Pistacia,* with short pollination periods, are usually low in the atmosphere of Catalonia and, in the case of the two first taxa and *Betula* their presence have been related to long-range transport episodes (Fernández-Llamazares et al. 2012; Belmonte et al. 2008; Izquierdo et al. 2015b). Regarding Total *Quercus*, *Quercus* evergreen type and *Urticaceae,* the lack of correlations could be due to the non-synchronous occurrence of their long pollination period and the seasonal variations of meteorological variables. *Pinus* is the pollen type most influenced by INS (BTU, GIC and LLE), followed by Chenopodiaceae/Amaranthaceae, *Olea* and *Plantago* (BTU and LLE). BTU and LLE are the localities giving a higher number of significant correlations MPIn/INS. There is a lack of bibliography relating airborne pollen counts and INS. Again, Poaceae is the pollen type more studied. The authors Kizilpinar et al. (2011) and

Table 3 Significant correlations between pollen counts (●: MPIn and ■: APIn) and precipitation (PRE), insolation (INS) and maximum (T_{max}), minimum (T_{min}) and mean (T_{mid}) temperatures for each taxon. MPIn is correlated with monthly values, and APIn is correlated with winter (from December to March) values of meteorological variables

BCN | BTU | GIC | LLE | MAN | TAU

	PRE		INS		T MAX		T MIN		T MID	
	N	P	N	P	N	P	N	P	N	P
Alnus	●				■					
Ambrosia										
Artemisia	●	■■						■		■
Betula			■			●●				●●
Castanea	●		●●	●						
Chenop/Amar.	●	■	■	●●		●	●	●●	●	●
Corylus	●●					●●	■	●		●●
Cupressaceae	●	■	■		■		■■■		■	●●
Fagus					■■■	●●●		●	■■	●●●
Fraxinus	●	■			■■	●●	■	●●	■■	●●
Olea	●	■■		●●	■	●		●		●●●●
Pinus	●●	■■		●●●	■	●●		●		●
Pistacia						●				●●
Plantago		■	■	●●		●		●●		●
Platanus	●	■■		■	■	●●		●■		●■
Poaceae	●●●		■	●	■	●				●●■
Polygonaceae	●		■			●●				
Total *Quercus*		■■	■	■	■■	●●●			■	
Q. deciduous t.		■■■	■	●	■■■	●●●			■	●
Q. evergreen t.		■■			■	●●●		●		●
Ulmus	●						■	■	■	
Urticaceae			■			●●		●		●●
Total pollen	●	■■■		●	■■	●●●		●		●●

Khwarahm et al. (2014) show a strong positive correlation of grass pollen with INS.

The significant correlations between MPIn and monthly values of T_{max}, T_{min} and T_{mid} are always positive, except for Chenopodiaceae/Amaranthaceae in TAU, possibly because autumn, when temperatures are decreasing, is the period of the year with highest pollen counts of this taxon in TAU. The significant correlations with T_{max} represent 25% of total correlations (34 over 138), 11% of total for T_{min} (15 over 138) and 23% for T_{mid} (30 over 138). *Alnus, Ambrosia*, *Artemisia*, *Castanea* and *Ulmus* showed no correlation with temperature.

Temperature is, together with precipitation, one of the common parameters studied, and it is cited to show a positive correlation with pollination intensity (Teranishi et al. 2000; Ziska and Caulfield 2000; Rasmussen 2002; Ribeiro et al. 2003; Peternel et al. 2004; Green et al. 2004; Ziello et al. 2012; Fernández-Llamazares et al. 2014; Khwarahm et al. 2014; Janati et al. 2017).

3.2 Correlations between APIn and winter values of meteorological variables

Considering that the pollination season of most of the taxa in Catalonia occurs between spring and summer or autumn, correlations between APIn and winter (from December to March) values of meteorological variables were calculated (follow the squared symbol in Table 3). The table included as Online Resource 2 shows the significant correlations between APIn and winter values of meteorological variables (precipitation, insolation and temperature) obtained for each taxon in each station. The results are commented and discussed in the following paragraphs.

APIn and winter PRE correlated always positively and represented 16% of the total possible correlations

(22 over 138). This means that high (low) amounts of winter PRE induced high (low) pollination in the following spring to autumn. Half of the taxa (11/22) showed no correlation in any of the stations (*Alnus*, *Ambrosia*, *Betula*, *Castanea*, *Corylus*, *Fagus*, *Pistacia*, Poaceae, Polygonaceae, *Ulmus* and Urticaceae). Here, it is necessary to take into account that the precipitation regime of the previous year may also influence the pollen production in the following year of some trees, e.g. *Betula* (Stach et al. 2008b; Nielsen et al. 2010). Another argument is that woody and herbaceous species respond differently to precipitation, trees being more related to conditions prior to flowering and herbaceous plants responding more immediately to the precipitation events (Cariñanos et al. 2004; Galán et al. 2016). In our study, this argument is the explanation for trees and shrubs pollinating during winter and very early spring (*Alnus*, *Ulmus*, Cupressaceae and *Corylus*) and herbaceous plants with a long-lasting pollination (Urticaceae, Poaceae, *Plantago*, Chenopodiaceae/Amaranthaceae) giving very few, if any, correlations. Spring flowering trees (*Pinus*, *Platanus*, *Quercus*, and *Olea*) correlate with winter PRE while those pollinating in summer (*Castanea*) doesn't. A different explanation for the lack of correlations is for plants that are scarce in the territory (*Betula* and *Fagus*) and arrive mainly through long-range transport (Belmonte et al. 2008; Izquierdo et al. 2017). In this study, they have shown only 1 correlation.

Quercus deciduous type was the taxon which presented positive correlations with winter PRE in a greater number of stations (BTU, GIC and MAN), as well as Total Pollen (BCN, BTU, MAN). On the other hand, BCN was the station in which a greater number of taxa presented positive correlations (Cupressaceae, *Olea*, *Pinus*, *Plantago*, Total *Quercus*, *Q*. evergreen type and total pollen) with winter precipitation, followed by BTU (*Olea*, *Pinus*, Total *Quercus*, *Q*. deciduous type, *Q*. evergreen type and total pollen). Garcia-Mozo et al. (2006) also found that PRE during the month prior to the *Quercus* pollination period makes the greatest contribution to pollen production. On the contrary, Fernández-Martínez et al. (2012) found that the amount of PRE and its temporal distribution barely influenced airborne pollen production.

The significant correlations between APIn and winter INS are positive or negative depending on the taxa and the sampling station, but represent only 8% (11 of 138) of the total possible correlations. Only 10 of the 22 taxa show some significant correlation, mostly negative (9 of 11). Only *Platanus* in GIC and Total *Quercus* in TAU were positive. It can be because *Platanus* and deciduous *Quercus* pollen type pollinate by the end of winter–beginning of spring and more sunny winters can contribute to better pollinations. The negative correlations could be explained by the fact that the pollen production is favoured by winter precipitation, as we saw previously, and rainy winters probably lead to fewer hours of sunshine, together with the fact that most of the taxa pollinate from spring on, far from the effect of winter INS. There is a second possible explanation for that and it is that, in the recent years, end of winter coincides with a notable increase of temperatures and plants become exhausted before. MAN is the locality showing a higher number of correlations, all negative, 6 for winter INS (Chenopodiaceae/Amaranthaceae, *Plantago*, Poaceae, Polygonaceae, Total *Quercus* and *Q*. deciduous type). The coincidence between the stabilisation of the INS values once winter is over with the beginning of the pollination of these taxa can be the explanation for this negative relationship.

The significant correlations between APIn and winter temperatures were mostly negative. Regarding T_{max}, they represented 14% (19 over 138) and were negative in all cases, while positive and negative correlations were obtained for T_{min} (7% in total, 9 over 138; 4% negative) and T_{mid} (8% in total, 11 over 138; 7% negative). The positive correlations corresponded to *Artemisia* in LLE, *Platanus*, in BCN, and Poaceae and *Ulmus* in BTU. As LLE is the locality with the highest *Artemisia* APIn and BCN the one with the highest *Platanus* APIn, these results could be representative, showing that the higher the minimum winter temperature the higher the pollen production in the year. In the case of *Artemisia*, López et al. (2017) have found that, although the pollination takes place from summer to autumn, it is more intense when winters are warmer. Other interesting results are obtained for TAU and the taxon *Corylus*, and for TAU and MAN for Cupressaceae and *Fraxinus*, all negative with, at least, winter T_{min}. In the case of *Corylus* and Cupressaceae TAU is the site presenting highest APIn and pollination occurs mostly during winter, thus meaning that low temperatures favour the pollination. *Fraxinus* results need deeper consideration. It is difficult to

stablish a general interpretation of the relationship between APIn and temperature because of the variability of results obtained (Jato et al. 2004).

Summarising, APIn was specially influenced by winter precipitation and winter maximum temperature. The positive correlations between APIn and winter precipitation indicate the positive effect of precipitation during the winter months before the flowering period on the annual pollen production for most of the taxa. This result agree with those obtained by Izquierdo et al. (2015a) reporting the negative correlation between Seasonal Pollen Integral and Northern Hemisphere teleconnection patterns (NAO, AO and WeMO indices) and the positive effect of precipitation on the annual pollen during the negative phase of the three climatic indices. In accordance with this study, we have obtained a link between higher rainfall in winter and increased pollen production for the following taxa: *Artemisia*, Chenopodiaceae/Amaranthaceae, Cupressaceae, *Fraxinus*, *Olea*, *Pinus*, *Plantago*, *Platanus*, *Quercus*, *Quercus* deciduous type, *Quercus* evergreen type, as well as for total pollen.

3.3 Influence of meteorological variables in the Start, End and Length of the Main Pollen Season

The influence of precipitation, insolation and temperature in the timing of pollen season was evaluated by analysing the dates of Start and End of the Main Pollen Season (MPS) and the Length (number of days between the Start and the End). The significant correlations between phenology (Start, End and Length of the MPS) and precipitation (PRE), insolation (INS) and maximum (T_{max}), minimum (T_{min}) and mean (T_{mid}) temperatures for each taxon are summarised in Table 4. The number of total correlations is 22 pollen taxa $\times$ 6 locations = 132.

These results are commented and discussed in the following paragraphs.

3.3.1 Precipitation

Precipitation has a little influence on the main parameters that characterise the MPS. Regarding the sign of the correlations, they are positive or negative depending on the taxon and the sampling station.

Significant correlations between Start and winter precipitation accounted around 8% of total correlations. Positive correlations were obtained for *Artemisia*, Chenopodiaceae/Amaranthaceae, Cupressaceae, *Olea, Plantago*, *Platanus*, Poaceae and Polygonaceae, while negative correlations were obtained for *Alnus*, *Ambrosia* and *Quercus* deciduous (see the table included as Online Resource 3).

Fewer significant correlations were obtained with End, around 6% of total correlations. Significant correlations were negative for *Olea*, *Pistacia*, Poaceae, *Quercus* and *Quercus* evergreen type, while positive correlations were obtained for *Artemisia* and *Ulmus* (see the table included as Online Resource 4).

Significant correlations between Length and winter precipitation accounted 14% of total correlations. Correlations were negative for *Alnus*, *Artemisia*, Chenopodiaceae/Amaranthaceae, *Olea*, *Pinus*, *Pistacia*, *Platanus*, Poaceae, *Quercus*, *Quercus* deciduous type, *Quercus* evergreen type and Urticaceae, and positive for *Fagus*, *Plantago* and *Ulmus* (see the table included as Online Resource 5).

The winter PRE gave a highest number of positive correlations (8) with Start and the highest number of negative correlations with Length. This is consistent with the results already indicated in this paper for PRE as a washing out agent. With regard to Start, our result is also in accordance with Vélez-Pereira (2017) who found that precipitation in the same day had a relevant effect in eliminating the low concentration levels of Urticaeae, Poaceae and Chenopodiaceae/Amaranthaceae pollen.

3.3.2 Insolation

Evenly with precipitation, the significant correlations with winter values of insolation were positive or negative depending on the taxa and the sampling station, but represented only 4–7% (5–9 over 132). Thereby, we can conclude that insolation has little effect over the timing of the pollen season. Significant correlations between Start, End and Length of the MPS and winter values of insolation for each taxon in each station can be found in tables included as Online Resource 3, 4 and 5.

Table 4 Significant correlations between phenology (●: Start, ■: End and ▲: Length) and winter (from December to March) values of precipitation (PRE), insolation (INS) and maximum (T_{max}), minimum (T_{min}) and mean (T_{mid}) temperatures for each taxon

BCN | BTU | GIC | LLE | MAN | TAU

	PRE		INS		T MAX		T MIN		T MID	
	N	P	N	P	N	P	N	P	N	P
Alnus	●	▲	▲		● ●		● ●		● ●	▲
Ambrosia	●		●			●		■		● ■
Artemisia	▲	● ■ ■	●	▲			● ▲		▲	
Betula					●		●		●	
Castanea								●		●
Chenop/Amar.	▲	●	■	▲	●	▲		▲	●	▲
Corylus							●		●	
Cupressaceae		●				▲		■ ▲		■
Fagus		▲	▲	▲	▲ ▲		▲		▲	●
Fraxinus					●		●		● ■	
Olea	■ ▲ ▲	●		▲	● ●	■ ▲ ▲ ▲	●	▲	● ●	▲ ▲ ▲
Pinus	▲			■	● ● ● ●	▲ ▲ ▲	●	▲	● ● ● ■	▲ ▲ ▲
Pistacia	▲ ▲	■	■		● ● ● ■		● ●		● ● ●	▲
Plantago		● ▲	■ ▲ ▲	●	● ●	■	●		● ●	■ ▲
Platanus	▲ ▲	●	■		● ● ● ■	▲ ▲	●		● ● ●	▲ ▲
Poaceae		● ■		■	●	▲		▲	●	
Polygonaceae		●			●	■ ▲	●	▲	●	■ ▲
Total *Quercus*	■ ▲			▲	● ● ●	▲ ▲			● ●	▲ ▲
Q. deciduous t.	▲ ▲	●			● ●	▲	●		● ●	▲
Q. evergreen t.	■ ▲ ▲		●		● ● ●	▲	■		●	
Ulmus		■ ▲	●					▲		
Urticaceae	▲				● ● ●				● ●	

3.3.3 Temperatures

Significant correlations between the Start of the MPS and winter temperatures represented 20% (79 over 396) and were mostly negative (74 over 79), meaning that high (low) winter temperatures in Catalonia coincide with earlier (later) pollination. Only *Ambrosia* in LLE, *Castanea* in GIC and *Fagus* in BCN showed positive correlation. According to Piotrowska and Kubik-Komar (2012), in temperate climate regions, air temperature recorded at the end of winter and early spring has the greatest effect on the Start of the MPS. Other studies have established that temperature is the main factor controlling the start of the MPS (Frei 1998; Laaidi 2001; Root et al. 2003; Fernández-Martínez et al. 2012). The different behaviour of the Start for *Ambrosia* and *Fagus* with temperatures could be explained since these taxa are scarce in Catalonia and long-range transport from other regions could mask correlations. Different studies of transport episodes of *Ambrosia* (Belmonte et al. 2000; Fernández-Llamazares et al. 2012) and *Fagus* (Belmonte et al. 2008) from Central Europe to Catalonia have been documented. On the other hand, *Ambrosia* and *Castanea* are usually airborne in summer and thus easily not affected by winter temperatures. Significant correlations between the Start of the MPS and winter values of maximum (T_{max}), minimum (T_{min}) and mean (T_{mid}) temperatures for each taxon in each station can be found in the table included as Online Resource 3.

Significant correlations between the End of the PS and winter values of maximum (T_{max}), minimum (T_{min}) and mean (T_{mid}) temperatures represented only 4% (14 over 396) meaning that winter temperatures have little influence on the end of the MPS. Significant correlations between the End of the MPS and winter values of maximum (T_{max}), minimum (T_{min}) and mean (T_{mid}) temperatures for each taxon in each station can be found in the table included as Online Resource 4.

Significant correlations between the Length of the MPS and winter values of maximum (T_{max}), minimum (T_{min}) and mean (T_{mid}) temperatures represented 11% (45 over 396) and were mainly positive (39 over 45), meaning that high (low) winter temperatures in Catalonia enlarge (shorten) the pollination season. Negative correlations corresponded to *Fagus* (4) and *Artemisia* (2). This result can be explained by the combined effect of the negative correlation between Start and winter temperature and the no correlation between End and winter temperature: high winter temperatures advance the Start but not affect the End, and thus an enlargement of the MPS is expected. Significant correlations between the Length of the PS and winter values of maximum (T_{max}), minimum (T_{min}) and mean (T_{mid}) temperatures for each taxon in each station can be found in the table included as Online Resource 5.

4 Conclusions

In this study, a correlation analysis between precipitation, insolation and temperature and the main airborne pollen parameters (MPIn. APIn and Start, End and Length of the Main Pollen Season) of 22 taxa collected at 6 aerobiological stations in Catalonia (NE Spain) have been performed in order to determine the effect of meteorological variability on their dynamics.

A summary of the main results is shown in Tables 3 and 4. Regarding the pollen type, *Olea* and *Pinus* show a higher number of significant correlations (30), followed by *Platanus* (27), *Quercus* deciduous type (23), *Plantago* (22) and Total *Quercus* (22). On the other hand, *Ambrosia* is the only pollen type that shows no correlation between meteorological variables and the amounts of pollen (APIn and MPIn), while *Castanea* and *Corylus* are the taxa presenting the least number of correlations (only 2) between the parameters that characterise the Main Pollen Season and the meteorological variables.

The pollen parameter with the highest number of significant correlations with the meteorological variables was MPIn (104), followed by Start (95), Length (73), APIn (67) and End (28).

Temperature was the meteorological variable that showed a major influence in the pollen production and in the timing of the pollen season. Maximum (104) and mean (94) temperature presented the greatest number of significant correlations, followed by precipitation (74), minimum temperature (50) and insolation (45).

A clear positive correlation has been detected between the pollen production and the winter precipitation for most of the pollen taxa included in this study. In addition, the pollen season seems to advance its start and extend its length in years with warm winters. Nevertheless, the end of the pollen season does not seem clearly influenced by winter weather.

Results show that airborne pollen levels and its dynamics are influenced by meteorological conditions. Improving knowledge about the influence of meteorology on the pollen dynamics is essential to improve modelling and obtain better forecast of the start and the severity of the pollen season. Most of the results obtained in this study corroborate results shown by other researchers; however, there are some limitations due to the time resolution of the data (monthly and yearly) used in our work. Therefore, more research is needed for better comprehend the interaction between meteorology and airborne pollen levels and its dynamics. For a future research, the results regarding correlations between temperature and pollen concentrations may improve by splitting the annual period in two sections, one since the beginning of the pollination until the peak date and the other from this moment to the end of the pollination. This will be the case for most taxa pollinating between spring and summer.

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