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ORIGINAL PAPER

Cluster analysis of intradiurnal holm oak pollen cycles at peri-urban and rural sampling sites in southwestern Spain

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Abstract The impact of regional and local weather and of local topography on intradiurnal variations in airborne pollen levels was assessed by analysing bi-hourly holm oak (*Quercus ilex* subsp. *ballota* (Desf.) Samp.) pollen counts at two sampling stations located 40 km apart, in southwestern Spain (Cordoba city and El Cabril nature reserve) over the period 2010–2011. Pollen grains were captured using Hirst-type volumetric spore traps. Analysis of regional weather conditions was based on the computation of backward trajectories using the HYSPLIT model. Sampling days were selected on the basis of phenological data; rainy days were eliminated, as were days lying outside a given range of percentiles (P95–P5). Analysis of cycles for the study period, as a whole, revealed differences between sampling sites, with peak bi-hourly pollen counts at night in Cordoba and at midday in El Cabril. Differences were also noted in the influence of surface weather conditions (temperature, relative humidity and wind). Cluster analysis of diurnal holm oak pollen cycles revealed the existence of five clusters at each sampling site. Analysis of backward trajectories highlighted specific regional airflow patterns associated with each site. Findings indicated the contribution of both nearby and distant pollen sources to diurnal cycles. The combined use of cluster analysis and meteorological analysis proved highly suitable for charting the impact of local weather conditions on airborne pollen-count patterns. This method, and the specific tools used here, could be used not only to study diurnal variations in counts for other pollen types and in other biogeographical settings, but also in a number of other research fields involving airborne particle transport modelling, e.g. radionuclide transport in emergency preparedness exercises.

Keywords Holm oak · Daily cycles · Cluster analysis · Meteorological conditions · Iberian Peninsula

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Introduction

Pollen grains are among the most common allergens, especially those released in large amounts from wind-pollinated plants into the atmosphere. The analysis of variations in airborne pollen-counts over time provides valuable information for the investigation and treatment of pollen allergies, which can have a major impact on human health (Pérez-Badia et al. 2010a; Cariñanos and Casares-Porcel 2011). In this sense, models as the NOAA HYSPLIT (Skjøth et al. 2012; Fernández-Rodríguez et al. 2014) or SILAM (Veriankaite et al. 2009; Prank et al. 2013) have been widely used in aerobiology studies.

Airborne pollen counts typically vary throughout the year, from day to day and in the course of a single day. These variations are governed by biological factors—e.g. flowering phenology and pollen-release patterns—but also by weather-related factors such as temperature, rainfall, relative humidity and wind behaviour (Muñoz Rodriguez et al. 2010; Ben Sidel et al. 2014). Detailed knowledge of the varying impact of these factors in the course of a season, a week or even a single day, is particularly useful for agricultural, forestry and environmental purposes. This knowledge will also help to improve the quality of life of people (treat and avoid symptoms) who suffer from allergy.

There has been considerable aerobiological research into seasonal and daily variations in pollen-count patterns and their causes (Sahney and Chaurasia 2008; Scheifinger et al. 2013). Although fewer studies have addressed diurnal variations, a number of papers report that each pollen taxon displays specific diurnal patterns, reflecting not only its own genetic response to environmental conditions but also variations in weather conditions in the course of the day (Pérez-Badia et al. 2010b; Fernández-Rodríguez et al. 2014).

Since the impact of weather conditions on diurnal pollen cycles varies from one region to another, the extrapolation of findings is of limited validity (Sanchez-Mesa et al. 2005). Local relief is known to influence temporal and spatial variations in surface weather conditions (Hernández-Ceballos 2012), which in turn affect pollen counts; variations in the wind regime (direction and speed), for example, exert a varying effect on the transport, accumulation and dispersal of airborne particles (Im and Yenigun 2005; Bouchlaghem et al. 2007). Moreover, weather conditions may change considerably in the course of the day, leading to diurnal variations in pollen counts which may differ in intensity and timing even over short distances (Hernández-Ceballos et al. 2010). The definition of a single diurnal pollen pattern for a whole region is therefore a complex undertaking, given the marked impact of local relief and the attendant variation in surface weather conditions (e.g. local winds, atmospheric stability) on diurnal variations in pollen counts.

Considering these points, the present study aims to examine the impact of the natural and local atmospheric environment (relief and weather conditions) on pollen dynamics. To this purpose, this work focused on the cluster analysis of intradiurnal variations in airborne holm oak (*Quercus ilex* subsp. *ballota* (Desf.) Samp.) pollen counts at two sampling sites located in southwestern Iberian Peninsula (Cordoba and El Cabril) located 40 km apart: a peri-urban area and a natural reserve.

The selection of holm oak, the most abundant tree species in southern Spain, is based on its considerable ecological and economic importance, since it is a mainstay of the Mediterranean forest and "dehesa" ecosystems (García-Mozo et al. 2007a). The holm oak produces large amounts of pollen during the spring, and is the major contributor to the *Quercus* pollen curve (García-Mozo et al. 2002; 2008; Gómez-Casero et al. 2007). On the other hand, cluster analysis technique, based on Ward's hierarchical method, was used here to obtain groups (clusters) of elements (in this case, daily cycles) with similar temporal behaviour of holm oak. This technique is usually used to extract patterns that help simplify and understand a large quantity of information. In aerobiology, this tool has been used before (Oteros et al. 2012).

The specific goals addressed were as follows:

1) To examine the impact of local relief on diurnal variations in pollen counts in a small sampling area
2) To determine the influence of local weather conditions (temperature, humidity and wind speed and direction) and regional meteorological factors (air-mass movements) on diurnal pollen cycles
3) To model diurnal pollen cycles for each sampling site based on cluster analysis of bi-hourly counts

Materials and methods

Study area

The study was performed at two sampling sites: one located in a peri-urban area (Cordoba city) and the other in a rural environment, El Cabril nature reserve in Cordoba province (southern Iberian Peninsula, hereafter IP) (Fig. 1). Cordoba city is located in the centre of the province (37°50′N, 4°45′W), while El Cabril reserve (surface area 1200 ha, 15 km from the nearest village) lies in the northwest of the province (38°4′N, 5°24′W). A 3D figure of the topographical relief at both sites is shown in the Supplementary information (https://cesiumjs.org/index.html), with the aim to help to perceive the differences between both sites.

The El Cabril reserve ranges in altitude from 450 to 600 m a.s.l.; it has a sub-humid Mediterranean climate with virtually no rainfall in summer (June–August). Data for the last 50 years indicate a mean annual rainfall of 700 mm and a mean temperature of 16.8 °C. Cordoba city is situated at an altitude of 123 m a.s.l. and has a Mediterranean climate with some continental features; the annual average temperature is 17.8 °C and the mean annual rainfall is 621 mm.

Aerobiological and phenological data

Data series for *Quercus* pollen counts in 2010 and 2011 were obtained at both sampling sites using Hirst-type volumetric spore traps (Hirst 1952). Sampling and bi-hourly and daily data management were carried out in accordance with Spanish Aerobiology Network (REA) protocols (Galán et al. 2007), in compliance with the minimum requirements laid down by the European Aeroallergen Network (Galán et al. 2014). For bi-hourly and daily data, the appropriate correction factor was applied, taking into account sampling time and microscope field size (Galán et al. 2007). Holm oak phenological data were obtained in the field, using the floral phenophases recommended by Gómez-Casero et al. (2007).

Meteorology: observational database and computation of air masses

Meteorological data were provided by surface weather stations located at the University of Cordoba campus, the site of

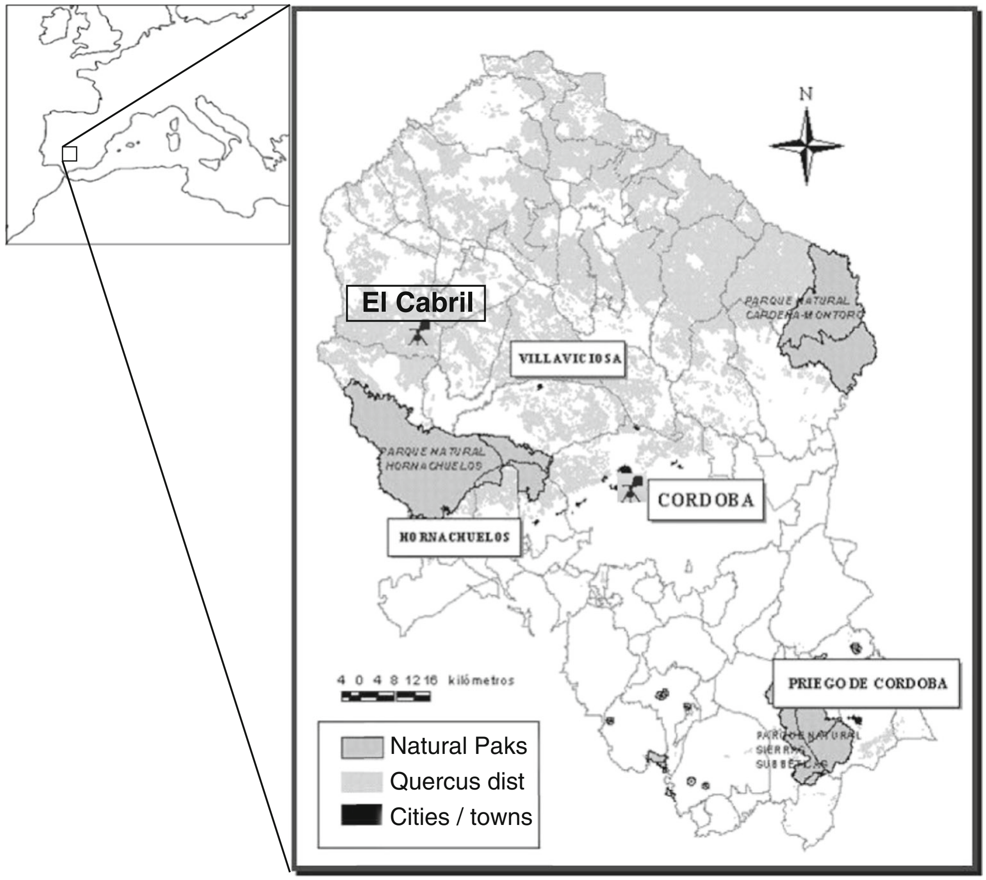

Fig. 1 Location of study sites. *Quercus* distribution in Cordoba province shown in *grey*

the Cordoba spore trap and by another station located 10 m from the spore trap in El Cabril. Both stations provide hourly weather data. The weather variables analysed were temperature (°C), relative humidity (%), wind direction (°) and wind speed (m/s). In both cases, the meteorological station is located at a height of 10 m a.g.l.

The HYSPLIT model (Draxler et al. 2014) developed by NOAA's Air Resources Laboratory (ARL) was used to calculate air mass trajectories. GDAS (Global Data Analysis System) meteorological files, with a spatial resolution of 111 km, were used to compute bi-hourly kinematic 3D backward trajectories covering 48 h periods, at a final height of 500 m at the Cordoba and El Cabril sites. The same method has been used previously in this region to investigate pollen counts (Hernández-Ceballos et al. 2010, 2011).

Data analysis: methodology and cluster analysis

The start date of the *Quercus* pollen season was defined as the first day on which ≥1 pollen grain/m^3 was recorded, with subsequent 5 days recording one or more pollen grains/m^3; the end date was the last day on which 1 pollen grain/m^3 was recorded and when lower or equal counts (0–1 pollen grain/m^3) were recorded on subsequent days (Garcia-Mozo et al. 2009).

Selection of the days on which to record pollen counts took into account a number of factors: 1) analysis of field phenological data at both sampling sites in order to determine which part of the *Quercus* curve corresponded to holm oak pollination; 2) discarding of airborne pollen counts recorded on rainy days (>0 mm/day) and 3) discarding of days with daily pollen counts lying outside the percentiles 95 to 5, with a view to identifying and removing outliers in the time series. The combination of these criteria ensured that the days selected provide a range of pollen-count values suitable for the purpose of the study. Results were expressed as bi-hourly pollen counts, since these data provide greater accuracy (Šikoparija et al. 2011).

Cluster analysis is used in order to minimise subjectivity when classifying a set of "objects" into groups (clusters). It serves to generate systematic structures (patterns) that help to simplify and understand a large amount of information by grouping similar objects together. Statistical parameters are used to define the groups, by minimising the differences among individual elements within a cluster and maximising the differences between clusters.

Although two different clustering algorithms are used in grouping analysis, "hierarchical" and "non-hierarchical" clustering (Everitt 1980), Ward's hierarchical method was used here, since no previous knowledge was available regarding the number of clusters required to summarise pollen-count variability. Analysis started by taking each day as a separate cluster, and then combining clusters sequentially, reducing the number of clusters at each step until only one cluster remained. Using this method, information is quantified as the sum of squared distances of each element with respect to the centroid of the cluster to which it belongs. The accuracy of the values was previously tested using data from earlier daily and seasonal pollen analyses (Oteros et al. 2012).

In order to determine the degree to which meteorological variables (temperature, relative humidity and wind direction and speed) were associated with pollen-count variability, the correlation coefficient (significance level 0.05) was obtained for each sampling site.

Results

Annual analysis

The daily behaviour of airborne holm oak pollen counts at Cordoba and El Cabril over the study period is shown in Fig. 2. Table 1 also shows a general statistical summary of both pollen seasons in each sampling site. The pollen season in Cordoba was twice as long as that of El Cabril, where it started 2/3 weeks later. Data showed that pollen season start- and end-dates varied considerably between years and between sampling sites. In 2011, for example, the flowering period started nearly 3 weeks earlier than in 2010 at both sampling sites.

Mean temperatures in 2010 were similar for the two sites (around 15 °C), whereas in 2011 the mean temperature was considerably higher in Cordoba (22 °C) than in El Cabril (17 °C). Marked differences in relative humidity were observed between sampling sites and study years, with values ranging from 89 % at El Cabril in 2010 and 52 % in Cordoba in 2010. Wind speeds were similar at the two sites, ranging between 2 and 2.5 m/s. Rainfall in 2010–11 (Fig. 2) was heavier and more frequent in Cordoba (146.30 mm) than at El Cabril (71.6 mm).

Daily pollen cycles and weather patterns

Applying the method described under "Data analysis: methodology and cluster analysis" to the daily time series for holm oak pollen counts in Cordoba and El Cabril (Fig. 2), daily cycles were calculated on the basis of 51 days in Cordoba (25 in 2010, 26 in 2011) and 31 days in El Cabril (13 in 2010, 18

Fig. 2 Trends in daily holm oak pollen counts and daily rainfall

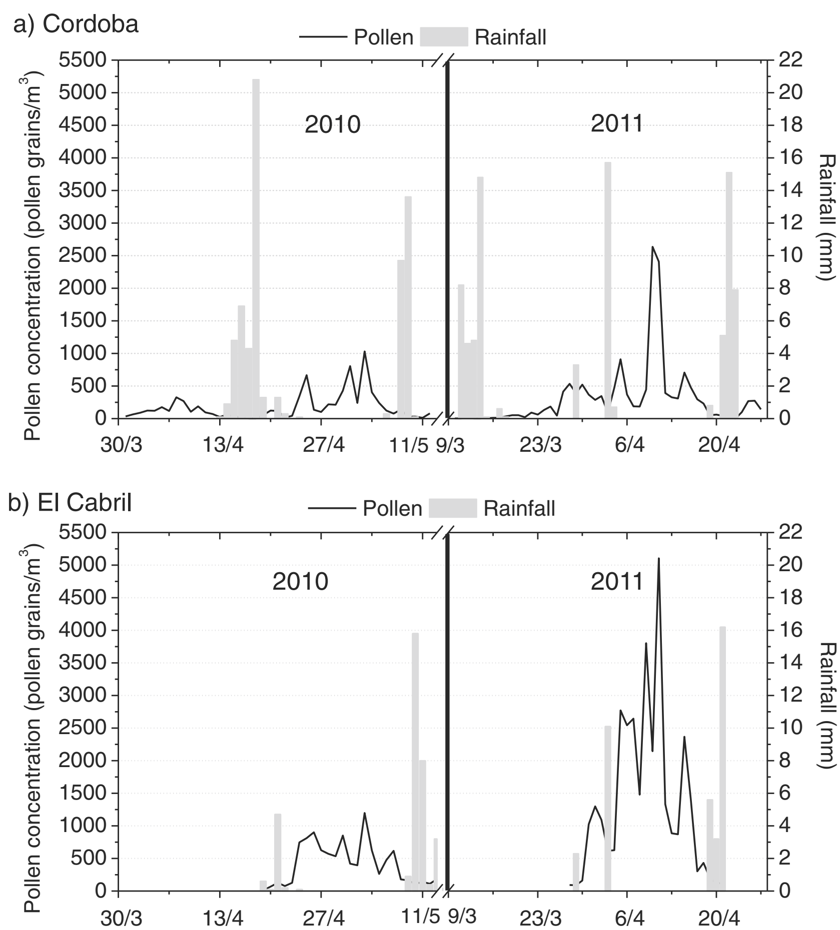

Table 1 Annual pollen index per each pollen type, mean, standard deviation (SD), maximum value (Max), minimum value (Min), and percentile 95th and 5th. Principal pollination period: start date, end date and length (number of days)

Location	Year	Total	Mean	SD	Max	Min	P95	P5	Start date	End date	Length (days)
Cordoba	2010	4725	173	214	1032	3	632	11	30 Mar	12 May	44
	2011	7947	372	540	2635	2	984	21	19 Mar	27 Apr	40
El Cabril	2010	7271	401	323	1198	11	890	70	19 Apr	14 May	26
	2011	27181	1341	1282	5105	88	3595	97	28 Mar	21 Apr	24

in 2011). Table 1 shows the corresponding values of each percentile (95th and 5th) taken as reference for each pollen season and site.

In Cordoba, the peak bi-hourly pollen count ranged between 350 and 400 pollen grains/m^3, and was generally recorded at night (00:00–06:00 UTC); daytime values varied around 200–300 pollen grains/m^3. By contrast, pollen counts at El Cabril peaked at over 1400 pollen grains/m^3 between 14:00 and 00:00 UTC, recording a progressive decrease until 12:00 UTC and a sharp increase of around 1000 pollen grains/m^3 from 14:00 UTC (Fig. 3).

Weather patterns varied considerably between sampling sites in both study years (Fig. 3). Daily variations in temperature and relative humidity were more marked in Cordoba than at El Cabril (Fig. 3a). Although maximum humidity values were similar at both sites (around 90 %), minima were lower in Cordoba (25 % vs. 50 % at El Cabril). Minimum temperatures were similar at both sites (around 10 °C), but maxima were higher in Cordoba (around 30 °C). In Cordoba, peak pollen counts coincided with maximum humidity values and lower temperatures, while in El Cabril the reverse pattern was observed.

Analysis of daily variations in surface winds (Fig. 3b) revealed different patterns for both speed and direction at the two sampling sites. In Cordoba, the arrival of easterly flows predominated in the morning and at midday, with speeds of up to 4 m/s. Later in the day, the arrival of westerly flows (16:00–23:00 UTC) coincided with a small increase and subsequent levelling-off of pollen counts. In El Cabril, wind-related factors appeared to have a more marked influence on pollen patterns: from morning to early afternoon, the arrival of easterly flows coincided with minimum counts, while the switch from easterly to westerly winds coincided with an increase in pollen counts. Maximum wind speeds were recorded during the transition from easterly to westerly winds, with values of around 3 m/s.

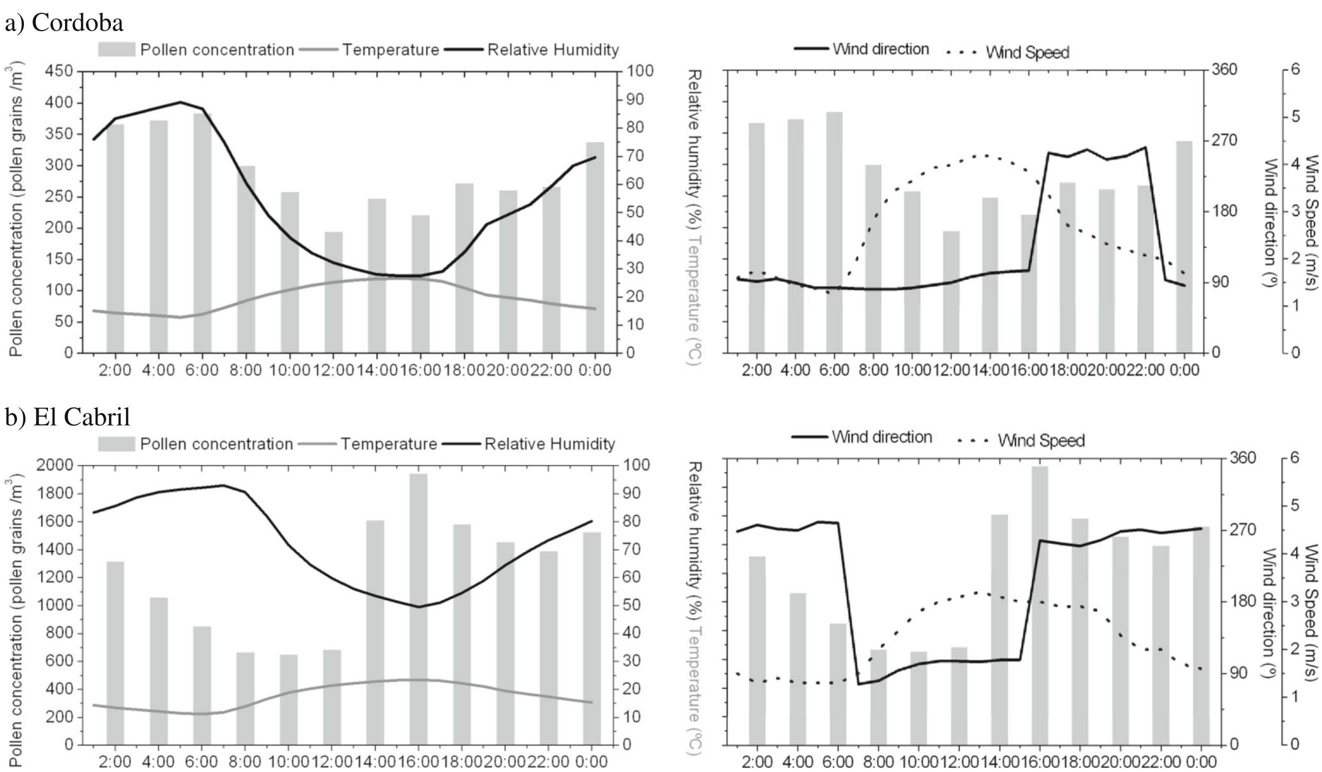

Fig. 3 Variations in mean diurnal pollen counts and weather patterns at Cordoba and El Cabril sites over the sampling period (2010–2011)

In Cordoba, inverse correlations were recorded between pollen counts and both temperature and wind speed, whereas pollen counts correlated positively with relative humidity. The correlation test (significance level 0.05) indicated significant dependence of pollen counts on weather patterns (Table 2). For El Cabril, counts correlated positively with temperature but negatively with relative humidity. Here, the *p* value indicated the independence of each variable with respect to pollen counts. A positive correlation was observed between pollen counts and wind direction at both sampling sites, though it was considerably stronger at El Cabril (Table 2).

Cluster analysis

The dendrogram resulting from hierarchical clustering in Cordoba and El Cabril is shown in Fig. 4. Application of Ward's method to the complete diurnal holm oak pollen cycle indicated that the optimal number of groups to be used was five at each sampling site.

Once clusters had been defined, the relevant bi-hourly pollen counts were examined as a function of relative humidity, temperature, wind speed and direction. At both sites, the period when peak bi-hourly counts were recorded was used for reference purposes, given the importance of pollen peaks in aerobiological analysis. Each cluster therefore represented a different pollen-behaviour situation, reflecting the exposure of pollen to different weather conditions.

Cordoba

Diurnal pollen counts and weather patterns for the five clusters identified in Cordoba are shown in Fig. 5. The results confirmed a marked variation in the timing of the bi-hourly peak. For C2 and C5, peak counts—with differing values—were recorded at night; values decreased progressively thereafter until midday. In C4, clear elevated peaks were evident from 14:00–18:00 UTC; while in C1, peaks were observed at the end of the day. C3 displayed varying trends, with two clear peaks: at 06:00 and 00:00 UTC.

Daily variations in temperature and humidity were similar in terms of trends for all five clusters, though differing in both intensity and range. Maximum humidity values were recorded at 04:00–06:00 UTC, while minima were observed at 14:00–16:00 UTC; temperature displayed the reverse trend.

Table 2 Correlation coefficient and *p* value at a 0.05 significance level (in brackets) between pollen and meteorological parameters at two sampling sites

	Temperature	Relative humidity	Wind speed	Wind direction
Cordoba (Pollen)	−0.9 (0,0)	0.9 (0,0)	−0.9 (0,0)	0.2 (0,34)
El Cabril (Pollen)	0.5 (0,12)	−0.6 (0,06)	0.2 (0,53)	0.6 (0,07)

Temperature patterns varied between clusters, in terms of both range (maximum-minimum) and absolute maximum and minimum values. Maximum temperatures ranged between 30 °C (C2) and 22 °C (C1), while minima varied between 10 °C (C1) and 19 °C (C5); temperature ranges were between 16 °C (C2) and 11 °C (C5).

Relative humidity patterns displayed greater inter-cluster variation. Range always exceeded 40 %, the widest range being recorded for C3 (71 %) and the narrowest for C4 (41 %). Strikingly, the peak value for relative humidity was close to 100 % (C3). In C2 and C5, a sharp decrease was recorded at the end of the day, becoming more marked as the day progressed.

Wind direction displayed similar behaviour in C1, C2 and C5: easterly winds arriving earlier in the day rapidly gave way to westerly flows in the afternoon and evening. The transition was most prolonged in C1 (lasting from 15:00 to 00:00 UTC), but lasted for only a few hours in C2 (18:00–22:00 UTC) and C5 (20:00–22:00 UTC). The switch from easterly to south-westerly was more gradual in C3, where it was also recorded in the morning (10:00 UTC) and lasted until afternoon (19:00 UTC). Contrasting behaviour was noted for C4, with westerly winds blowing in twice in the course of the day (morning and afternoon), interspersed with easterly winds from 10:00 to 14:00 UTC.

Wind speed differed in terms of both pattern and intensity. While maximum values were recorded in the middle of the day for all clusters, peak values remained stable in C1, C2 and C5, whereas a clear peak was observed in C3 and C4, in which the highest wind speeds were also recorded (5.3 m/s). The narrowest range of wind speeds (less than 3.5 m/s) was observed in those clusters displaying a plateau. In C5, wind speed increased sharply towards the end of the day, rising from 0.5 to 2.8 m/s.

El Cabril

Diurnal pollen counts and weather patterns for the five clusters identified in El Cabril are shown in Fig. 6. Peak pollen counts were recorded in the afternoon/evening (C1, C2 and C4) and early at night (C3 and C5), although intensities varied. Maximum peaks at night were always observed at 00:00 UTC. In C5, a sharp increase led to the highest pollen count recorded at El Cabril (6500 pollen grains/m3), while in C3 counts increased gradually from midday onwards, peaking at 2400 pollen grains/m3. Afternoon peak values displayed similar timing: counts declined throughout the morning until 12:00 UTC, rising thereafter from 14:00 UTC to peak at 16:00 UTC. The maximum peak was highest in C4 (4000 pollen grains/m3). Thenceforth, counts decreased progressively, with a second low peak early at night.

Relative humidity curves differed more than temperature curves. Temperature patterns and intensity were similar in all

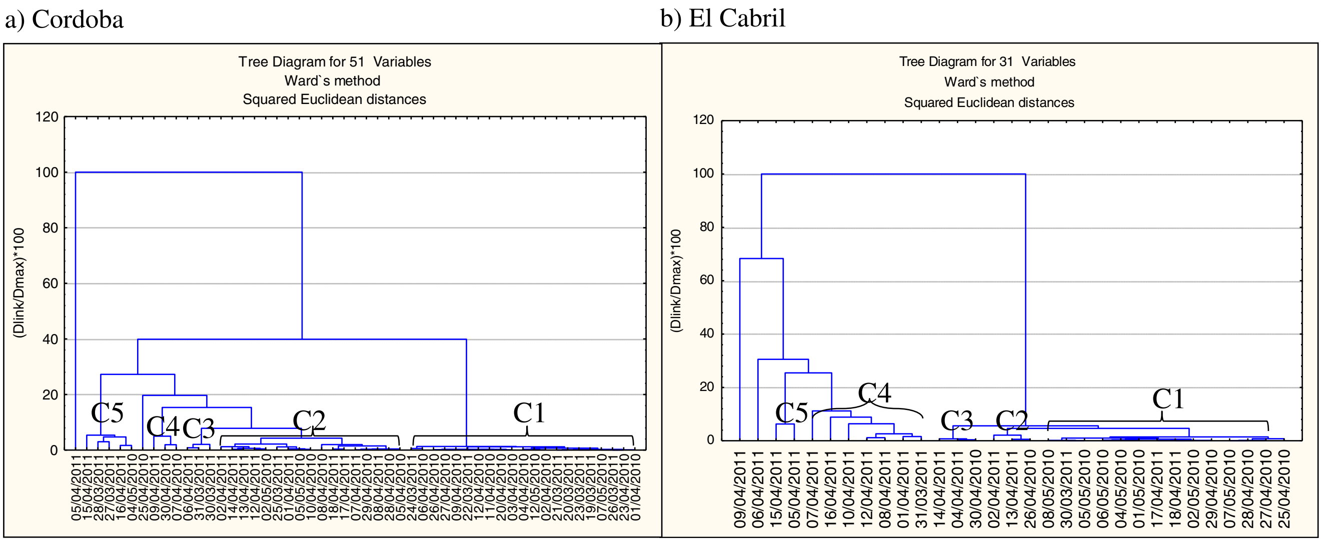

Fig. 4 Hourly frequency distribution of peak holm oak pollen counts in Cordoba and El Cabril, 2010–2011

five clusters. Peak values were recorded at 15:00 UTC, and ranged between 24.8 and 26.5 °C, while minima were observed at 06:00 UTC and varied from 11.2 to 13.1 °C. Differences between maximum and minimum humidity levels were more marked: peak values, recorded at 07:00 UTC, ranged from 82 to 99 %, while minima—observed between 14:00 and 16:00 UTC—varied between 31 and 47 %.

Winds were predominantly easterly and westerly. In both C3 and C4, easterly winds prevailed during the central hours of the day, and westerly winds in the afternoon/evening and at night. A progressive change from easterly to westerly winds over the course of the day was observed in C1 and C5. The cluster in which curves differed most was C2, with constant easterly flows during the day, changing to southwesterly flows only between 17:00 and 21:00 UTC.

All clusters except C4 displayed a plateau for wind speed, at below 3 m/s, maximum values remaining steady from midday to late evening. By contrast, C4 displayed a clear peak at above 3 m/s, followed by a progressive decline until night.

Regional air-mass patterns

Surface weather conditions over a given period of a time in a given area are largely governed by air-mass patterns. A simple way to identify differences between periods in terms of atmospheric configuration (air-mass patterns) is by computing backward trajectories, since these are the footprint of its impact on a certain region (Jorba et al. 2004). The back trajectory is the pathway previously travelled by the air mass before arriving at a certain point (Doty and Perkey 1992). Depending on the meteorological file (horizontal resolution) and the set-up used to calculate back trajectories (i.e. time covered, final vertical height and so on), either synoptic or regional configurations can be analysed.

Here, the computation of back trajectories focused on determining the degree of similarity between the regional patterns associated with each cluster (weather variables and holm oak pollen counts) in Cordoba and El Cabril. With this aim, a set of 48 h bi-hourly back trajectories with a final height of 500 m were calculated for each day of each cluster (Fig. 4). The representativeness of back trajectories in this region had previously been tested in various studies (Hernández-Ceballos et al. 2010; 2012). The mean trajectory associated with each cluster at Cordoba and El Cabril is shown in Fig. 7.

Findings for Cordoba indicated the main advection of flows from the north (C1, C2, C3, C5) with variations in both origin and pathway. C3 was related to air masses arising to the northwest of the IP that rapidly crossed the centre of the peninsula; C1 and C5 displayed a shorter continental movement of air masses from the north to the south of the IP. C2 was also linked with air masses coming from the north but with a movement over the eastern IP and a final easterly advection over the sampling area. Finally, C4 displayed a shorter air mass displacement from east to west in the southern IP and performed a previous clockwise movement, thus reaching the sampling area from the northwest.

Findings for El Cabril indicated a greater variability of air-mass origins and pathways, displaying the advection of northerly (C1), northwesterly (C5), easterly (C4) and southerly flows (C2, C3). C1 was characterised by the direct advection of northern flows crossing the centre of the IP, while C5 displayed the impact of fast-moving air masses from the northwest. C4 was associated with air masses coming from the centre of the IP and recording a clockwise displacement from north to east. A similar air-mass movement was displayed by C3 and C2, starting to the southeast and moving into the sampling area from the south.

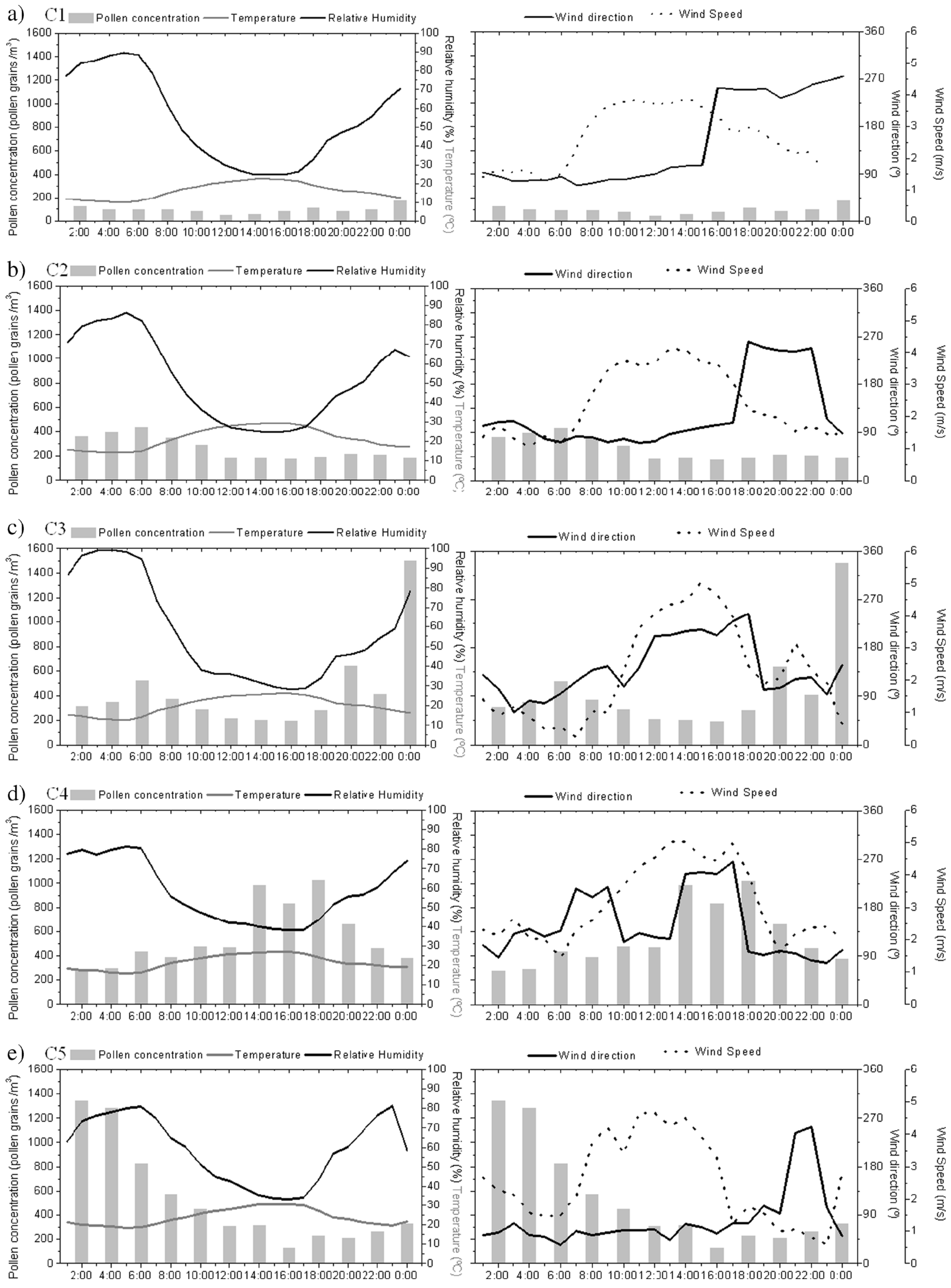

Fig. 5 Diurnal pollen counts and weather patterns for the five clusters identified in Cordoba

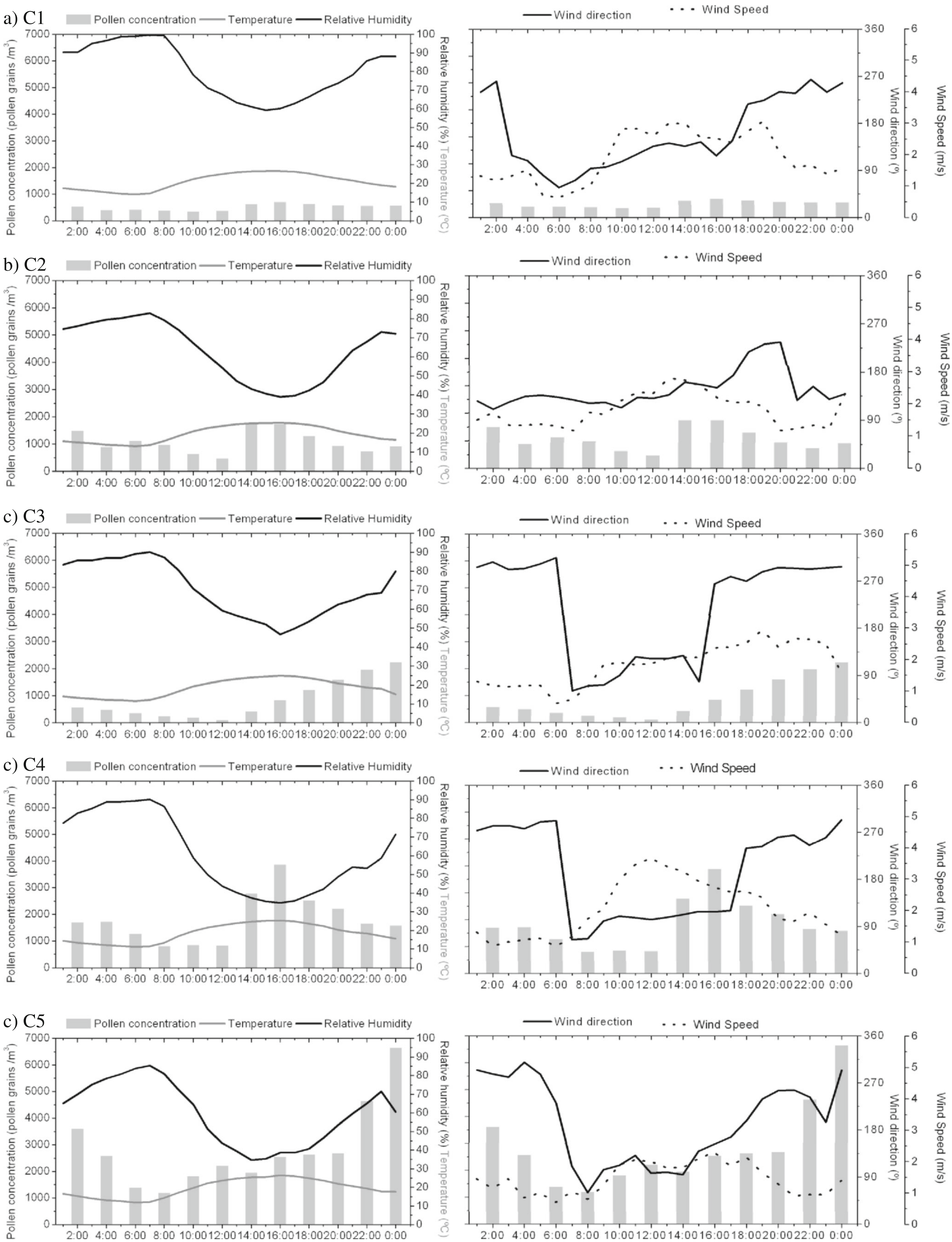

Fig. 6 Diurnal pollen counts and weather patterns for the five clusters identified at El Cabril

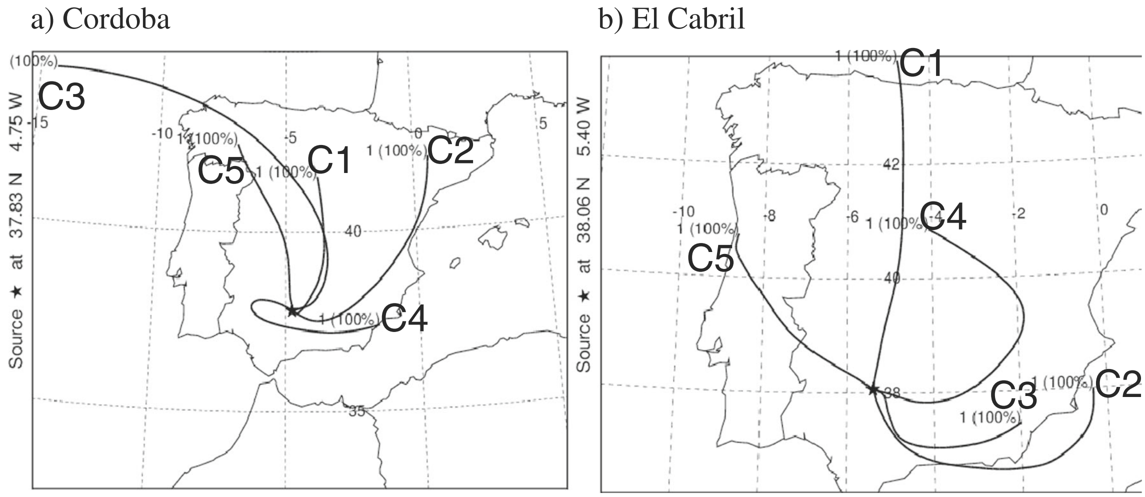

Fig. 7 Average air masses (*centroids*) obtained for each holm oak pollen cluster. The left number (*1*) is the identification of the centroid, while the right percentage (*100 %*) refers the relative frequency of trajectories

Discussion

This study sought to characterise diurnal holm oak pollen-count patterns at two sampling sites that, though near each other, were environmentally different, and to identify the relief features and weather-related parameters most influencing variations in these patterns.

The method used to select the days to be included for characterisation purposes proved suitable. Calculation of the statistical percentile values P5 and P95 as thresholds enabled faster identification of outlier high and low values. This technique has already been successfully used in earlier aerobiological research to identify the numerical limit of outliers (Mitsakou et al. 2008), as an alternative to subjective estimation. Inclusion of outlier days could influence the computation of diurnal cycles, and thus considerably modify the results.

Application of cluster analysis revealed the existence of five diurnal curves for each sampling site, differing in both timing and intensity. Findings confirmed that there was no single, common diurnal pattern for holm oak pollen counts at either site, and highlighted the impact of local relief, which gave rise to marked differences, even between sites located close to each other. The identification of different behaviour patterns confirms the results of earlier aerobiological research in the region that highlighted the need for a fuller understanding of diurnal pollen patterns as a response to local environmental factors (García-Mozo et al. 2007a, b).

Analysis of bi-hourly holm oak dynamics indicated a considerable difference between sampling sites with regard to the timing of peak pollen counts. In Cordoba, peaks were observed at night and in the early morning, whereas in El Cabril they were recorded in the afternoon and early night. These patterns contradict the findings reported for *Quercus* pollen counts in Cordoba by Galán et al. (1991) and in El Cabril by García-Mozo et al. (2007b), which indicated that peaks occurred between 12:00 and 17:00 UTC. However, similar patterns have been observed in the central Spanish city of Toledo (Pérez-Badia et al. 2010b). The occurrence of peaks outside this period is typically attributable to pollen transported from non-local sources (Hernández-Ceballos et al. 2010), thus confirming the influence of holm oak sources located outside the city on pollen counts. This result is also supported by the fact that large differences are observed between peak intensity, and this difference cannot be entirely associated with the population density of holm oak in local sources due to both areas present a similar density (50 tree/ha), and hence, a similar production (source) of pollen.

Analysis of meteorological data confirmed the influence of local and regional weather conditions on diurnal pollen-count patterns in both sampling sites. The computation of backward trajectories revealed the existence of different regional atmospheric patterns associated with each cycle. Results highlighted the impact of northerly flows at both sites, though more frequently in Cordoba, while the advection of southerly flows was a noteworthy feature only at El Cabril. These patterns agree with the findings of earlier analyses of air-mass movements and *Quercus* pollen counts in Cordoba city (Hernández-Ceballos 2011); pollen counts were influenced in Cordoba by sources to the north, while counts at El Cabril were in part attributable to southerly flows transporting pollen from southern areas of the province.

Previous research has shown that peak counts recorded at night are largely due to pollen transported from distant areas (Pérez-Badia et al. 2010a, b). In Cordoba, the highest bi-hourly night-time holm oak pollen counts (from 22:00 to 08:00 UTC) were associated with the advection of northerly (C1, C3, C5) and easterly flows (C2), while at El Cabril they were linked with the arrival of air masses from the northwest (C5) and south (C3). Given the distribution of holm oak pollen sources in the province, it can be inferred that the counts recorded in

Cordoba city reflect the impact both of nearby sources on the outskirts of the city (local transport) and of sources located further away, in the north of the province (mesoscale transport). For El Cabril, pollen counts are influenced by the arrival of southerly air masses bringing pollen grains from southern sources (mesoscale transport – C2 and C3) combined with the impact of nearby sources (local transport).

Due to differences in relief, regional patterns had a different impact on surface weather conditions at each site. Cordoba is located in the Guadalquivir valley and El Cabril in a mountainous area. The local wind patterns recorded were typical of each sampling site (Hernández-Ceballos et al. 2011); the channelling of winds due to specific relief features was reflected in the diurnal curves. The variability observed in certain daily pollen cycles suggests the effect of local/ mesoscale winds, such as mountain breezes, as noted by Hernández-Ceballos et al. (2014), although further research is needed to confirm this influence. Here, analysis of pollen cycles in conjunction with surface wind data revealed only a limited influence of air-mass flows at both sites. There was no clear surface wind direction that might account for maximum or minimum holm oak pollen counts. Analysis of wind speed and direction provides information on pollen transport, and hence on contributions from other close or distant sources, but does not take local pollen emission into account.

In the early morning and at night, with less vertical air movement and lower horizontal wind speeds, a large proportion of previously airborne pollen grains fall to the ground. This would account for the strong negative correlation between pollen counts and wind speed. In Toledo, a positive correlation has been reported between pollen- counts and temperature, both being highest at midday and through the afternoon (Pérez-Badia et al. 2010a, b). A similarly positive correlation with temperature was observed for El Cabril, whereas in Córdoba a strong negative correlation was recorded. These findings highlight the limitations of extrapolating data to different areas, and the need to take into account the combined impact of local relief, local pollen-source locations and local weather conditions.

Access to a database of bi-hourly holm oak counts facilitated the charting of diurnal pollen patterns in Cordoba province. Moreover, the use of two sampling sites enhanced the quality of the analysis by allowing the influence of weather conditions on curves to be compared. Earlier, both features had helped to provide a detailed analysis of diurnal *Quercus* pollen dynamics, to account for pollen content characteristics and to better understand the influence of weather conditions on diurnal variations in pollen counts. The present findings can be taken into account when producing pollen forecasts for this region, and the methods used here can also be applied to the analysis of other pollen type in other areas, with a view to obtaining as much information as possible regarding pollen levels in order to limit the exposure of allergy sufferers.

Conclusions

The findings of this study revealed differences in diurnal holm oak pollen dynamics between sampling sites only 40 km apart in southern Spain, highlighting the impact of local weather conditions and land relief. Differences were observed in the overall diurnal cycle (2010–2011), with peak counts at night in Cordoba and at midday in El Cabril. Cluster analysis clearly identified the influence of relief and weather conditions on diurnal airborne pollen dynamics. Five different patterns were identified, reflecting differences in regional (air-mass analysis) and local weather conditions (temperature, relative humidity and wind). Results indicated the involvement of both nearby and distant pollen sources, thus stressing the combined influence of pollen transport and local production that must be taken into account in order to account for pollen behaviour. This method, and the specific tools used here, could be applied in other research fields, for example to study radionuclide transport.

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References

Ben Sidel FF, Bouziane H, Trigo MM, El Haskouri F, Bardei F, Redouane A, Kadiri M, Riadi H, Kazzaz M (2014) Airborne fungal spores of Alternaria, meteorological parameters and predicting variables. Int J Biometeorol. doi:10.1007/s00484-014-0845-1

Bouchlaghem K, Mansour FB, Elouragini S (2007) Impact of a sea breeze event on air pollution at the eastern Tunisian coast. Atmos Res 86: 162–172

Cariñanos P, Casares-Porcel M (2011) Urban green zones and related pollen allergy: a review. Some guidelines for designing spaces with low allergy impact. Landsc Urban Plan 101:205–214

Doty KG, Perkey DJ (1992) Sensitivity of trajectory calculations to the temporal frequency of wind data. Mon Weather Rev 121:387–401

Draxler RR, Stunder B, Rolph G, Stein A, Taylor A (2014) HYSPLIT4 user's guide. NOAA Tech. Memo. ERL ARL-230, NOAA Air Resources Laboratory, Silver Spring

Everitt BS (1980) Cluster analysis, 2nd edn. Heineman Educational Books, London

Fernández-Rodríguez S, Skjøth CA, Tormo-Molina R, Brandao R, Caeiro E, Silva-Palacios I, Gonzalo-Garijo A, Smith M (2014)

Identification of potential sources of airborne Olea pollen in the southwest Iberian Peninsula. Int J Biometeorol 58:337–348

Galán C, Tormo R, Cuevas J, Infante F, Domínguez E (1991) Theoretical daily variation patterns of airborne pollen in the southwest of Spain. Grana 30:201–209

Galán C, Cariñanos P, Alcázar P, Dominguez E (2007) Management and quality manual. Spanish aerobiology network (REA). Servicio Publicaciones Universidad de Córdoba, Córdoba, ISBN 978-84-690-6353-8

Galán C, Smith M, Thibaudon M, Frenguelli G, Oteros J, Gehrig R, Berger U, Clot B, Brandao R, EAS QC Working Group (2014) Pollen monitoring: minimum requirements and reproducibility of analysis. Aerobiologia. doi:10.1007/s10453-014-9335-5

García-Mozo H, Galán C, Aira MJ, Belmonte J, Díaz de la Guardia C, Fernández D, Gutierrez FJ, Trigo MM, Domínguez E (2002) Modelling start of oak pollen season in different climatic zones in Spain. Agric For Meteorol 110:47–257

García-Mozo H, Gómez-Casero MT, Dominguez E, Galan C (2007a) Influence of pollen emission and weather-related factors on variations in holm-oak (Quercus ilex subsp. ballota) acorn production. Environ Exp Bot 61:35–40

García-Mozo H, Dominguez-Vilches E, Galan C (2007b) Airborne allergenic pollen in natural areas: Hornachuelos Natural Park, Cordoba, southern Spain. Ann Agric Environ Med 14:1–63

García-Mozo H, Galán C, Belmonte J, Bermejo D, Díaz de la Guardía C, Elvira B, Gutiérrez M et al (2008) Regional phenological models to forecast the start and peak of *Quercus* pollen season in Spain. Agric For Meteorol 148:372–380

Garcia-Mozo H, Galán C, Belmonte J, Bermejo D, Candau P, Díaz de la Guardia C, Elvira B et al (2009) Predicting the start and peak dates of the Poaceae pollen season in Spain using process-based models. Agric For Meteorol 149:256–262

Gómez-Casero MT, Galán C, Domínguez-Vilches E (2007) Flowering phenology of Mediterranean *Quercus* species in different locations (Córdoba, SW Iberian Peninsula. Acta Bot Malacitana 32:127–146

Hernández-Ceballos MA (2012) Caracterización meteorológica y modelización de Andalucía occidental (Meteorological characterization and modelling of southwestern Andalucia). Ph.D. thesis, University of Huelva, Huelva, p 284, ISBN:978-84-15147-73-2

Hernández-Ceballos MA, García-Mozo H, Adame JA, Domínguez-Vilches E, De la Morena BA, Bolívar JP, Galán C (2010) Synoptic and meteorological characterisation of olive pollen transport in Córdoba province (south-western Spain). Int J Biometeorol 55:17–34

Hernández-Ceballos MA, García-Mozo H, Adame JA, Domínguez-Vilches E, De la Morena BA, Bolívar JP, Pérez-Badía R, Galán C (2011) Determination of potential sources of Quercus airborne pollen in Córdoba city (southern Spain) using back-trajectory analysis. Aerobiologia 27:261–276

Hernández-Ceballos MA, Skjøth CA, García-Mozo H, Bolívar JP, Galán C (2014) Improvement in the accuracy of back trajectories using WRF to identify pollen sources in southern Iberian Peninsula. Int J Biometeorol. doi:10.1007/s00484-014-0804-x

Hirst J (1952) An automatic volumetric spore-trap. Ann Appl Biol 36: 257–265

Im U, Yenigun O (2005) An application of a puff dispersion model on power plant emissions in Yatagan region, Turkey. Int J Environ Pollut 23:314–324

Jorba O, Perez C, Rocadenbosch F, Baldasano JM (2004) Cluster analysis of 4-day back trajectories arriving in the Barcelona area, Spain, from 1997 to 2002. J Appl Meteorol 43:887–901

Mitsakou C, Kallos G, Papantoniou N, Spyrou C, Solomos S, Astitha M, Housiadas C (2008) Saharan dust levels in Greece and received inhalation doses. Atmos Chem Phys 8:7181–7192

Muñoz Rodriguez AF, Palacios I, Molina R (2010) Influence of meteorological parameters in hourly patterns of grass (Poaceae) pollen concentrations. Ann Agric Environ Med 17:87–100

Oteros J, García-Mozo H, Hervás-Martínez C, Galán C (2012) Year clustering analysis for modelling olive flowering phenology. Int J Biometeorol. doi:10.1007/s00484-012-0581-3

Pérez-Badia R, Rapp A, Morales C, Sardinero S, Galán C, García-Mozo H (2010a) Pollen spectrum and risk of pollen allergy in central Spain. Ann Agric Environ Med 17:139–151

Pérez-Badia R, Vaquero C, Sardinero S, Galán C, García-Mozo H (2010b) Intradiurnal variations of allergenic tree pollen in the atmosphere of Toledo (Central Spain). Ann Agric Environ Med 17:37–43

Prank M, Chapman DS, Bullock JM, Belmonte J, Berger W, Dahl A et al (2013) An operational model for forecasting ragweed pollen reléase and dispersion in Europe. Agric For Meteorol 182–183:43–53

Sahney M, Chaurasia S (2008) Seasonal variations of airborne pollen in Allahabad, India. Ann Agric Environ Med 15:287–293

Sánchez-Mesa JA, Brandao R, Lopes L, Galán C (2005) Correlation between pollen counts and symptoms in two different areas of the Iberian Peninsula: Cordoba (Spain) and Evora (Portugal). J Investig Allergol Clin Immunol 15:112–116

Scheifinger H, Belmonte J, Buters J, Celenk S, Damialis A, Dechamp C, García-Mozo H, Gehrig R et al (2013) Monitoring, modelling and forecasting of the pollen season. In: Sofiev M, Bergman K-C (eds) Allergenic pollen. Springer, Dordrecht, pp 71–127, ISBN 978-94-007-4880-4

Šikoparija B, Pejak-Šikoparija T, Radišić P, Smith M, Galan C (2011) The effect of changes to the method of estimating the pollen count from aerobiological samples. J Environ Monitor 13:384–390

Skjøth CA, Sommer J, Frederiksen L, Gosewinkel Karlson U (2012) Crop harvest in Denmark and Central Europe contributes to the local load of airborne Alternaria spore concentrations in Copenhagen. Atmos Chem Phys 12:11107–11123

Veriankaite L, Siljamo P, Sofiev M, Sauliene I, Kukkonen J (2009) Modelling analysis of source regions of long-range transported birch pollen that influences allergenic seasons in Lithuania. Aerobiologia 26:47–62