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ORIGINAL PAPER

Determination of potential sources of *Quercus* airborne pollen in Córdoba city (southern Spain) using back-trajectory analysis

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Abstract The northern area of Córdoba province (southern Spain) is characterised by a high spatial distribution of *Quercus* species. In Córdoba city, high airborne *Quercus* pollen counts are detected during spring despite the low presence of *Quercus* populations in the Guadalquivir Valley, where this city is located. This study sought to clarify and identify the potential origin of the different *Quercus* peaks detected in this city and chart the possible relationship between *Quercus* pollen curves and air-mass movements. For this purpose, an integrated study of daily and intra-diurnal *Quercus* pollen counts and back-trajectory analysis was performed over the March–June period of the years 2006–2008. The application of cluster techniques to back trajectory enabled the identification of six different types of air-mass movement. As a function of frequency, two different air-mass groups were identified: the main group comprised Local, Slower Northwest and Mediterranean movements, characterised by higher frequencies; a second group consisting of North, Faster Northwest and Southwest trajectories occurred less frequently over the study period. Although a significant correlation was observed between *Quercus* airborne pollen counts recorded in Córdoba city and the influence of the Mediterranean air-mass movements, the strongest positive correlation was found between North and Northwest air-mass movements and daily *Quercus* pollen counts. These results would confirm both that the major *Quercus* pollen sources are located at different distances north of the city and a new pollen source is also located south of the province, beyond the Guadalquivir valley, related to the arrival of Mediterranean air masses. The northern source appears to be linked to regional transport and the southern source to long-range transport.

Keywords Oak pollen · Mediterranean · Transport · Synoptic conditions · HYSPLIT

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1 Introduction

The typical natural vegetation of Andalusia (southern Spain) essentially comprises Mediterranean forest and "dehesas", where the main tree genus is *Quercus*. Quite apart from their ecological importance, the acorn production of southern Mediterranean oak ecosystems is of vital economic importance, since acorns are a major component in the feeding systems of high-quality Iberian domestic pigs (García-Mozo et al. 2007a). The predominant Quercus species in Andalusia are cork oak (*Quercus suber* L.), kermes oak (*Quercus coccifera* L.), gall oak (*Quercus faginea* L.) and especially holm oak (*Quercus ilex* subsp. *ballota* (Desf. Samp). Airborne *Quercus* pollen is therefore detected in large amounts, especially in inland southern Spain (García-Mozo et al. 2002, 2008). Holm oak is the major flowering oak species in Andalusia and the main contributor to the *Quercus* pollen curve (Gómez-Casero et al. 2004, 2007).

Previous phenological studies indicated how the different species of oak trees growing in the Sierra Morena Mountains, located near Cordoba city, contributed to the *Quercus* pollen curve. The first flowering species was holm oak following of kermes oak and gall oak. Finally, in the month of May, the flowering of holm oak occurs contributing with a small peak to the curve (Gómez-Casero et al. 2007; García-Mozo et al. 2010).

Nevertheless, the *Quercus* pollen curve in Cordoba usually presents high pollen peaks not explicable in terms of weather-related factors and not matching the floral phenological data collected in the field (Gómez-Casero et al. 2007). Therefore, it is reasonably to hypothesise that a percentage of the *Quercus* pollen counts detected in the city may be under regional-/long-distance transport from sources located in the north of the province where the main *Quercus* populations are situated. In this case, we understand as regional-/long-distance transport the definitions proposed by Seinfeld and Pandis (2006), being defined regional scale for distances of up to 100 km and long scale for more than 100 km.

Different tools are currently used to analyse the spatial and temporal variability of atmospheric pollen, such as the air-quality and emergency dispersion modelling system (SILAM), which has been used for both source apportionment and forward dispersion simulations (Sofiev et al. 2006, 2008; Siljamo et al. 2007, 2008; Veriankaite et al. 2010). In this work, back-trajectory analyses were used. It provides information about the characteristics of air-mass movements over a region, in terms of their origin, horizontal pathways and altitude; with this information, it is possible to characterise the dominant type of air-mass movement over a given area (Jorba et al. 2004; Hondula et al. 2010). Back-trajectory analysis also provides detailed information on the path followed by an air mass until its arrival over the study area and is therefore a useful tool for a range of scientific applications relating to air-quality analysis (Borge et al. 2007; Toledano et al. 2009, Sprovieri et al. 2010).

In aerobiology, back-trajectory analysis helps to locate the origin of airborne biological particles detected at any given sampling point. As a result, recent studies have been able to provide detailed data on the long and regional origin of a number of pollen types in various climatic areas, including *Ambrosia* pollen in central Poland (Stach et al. 2007) and central northern Italy (Cecchi et al. 2007); *Betula* pollen in Denmark (Skjoth et al. 2008) and *Olea* pollen in southern Spain (Hernández-Ceballos et al. 2010a).

Several numerical models such as FLEXPART (Stohl et al. 1998) and WRF (Skamarock et al. 2005) have been developed for the computation of back trajectories. The HYSPLIT model (Draxler and Hess 1998) used in the present study has proved highly effective in studies focused on defining the pathway and possible long-range transport of air pollutants (Sánchez-Ccoyllo et al. 2006; Davis et al. 2010), aerosols (Petzold et al. 2009; Karaca et al. 2009). It has also been used to understand and analyse airborne pollen concentrations (Cecchi et al. 2007; Mahura et al. 2007).

The main objective of the present study was to identify the potential origin of *Quercus* pollen counts in the city of Córdoba and establish the relationship between air-mass movements and pollen counts. To this end, an analysis was made of 48-h back trajectories, computed using the HYSPLIT model, and of daily and intra-diurnal *Quercus* pollen counts over the March–June period 2006–2008.

2 Materials and methods

2.1 Area and climate

Córdoba province is situated in the central Andalusia region of southern Spain. The province is divided by

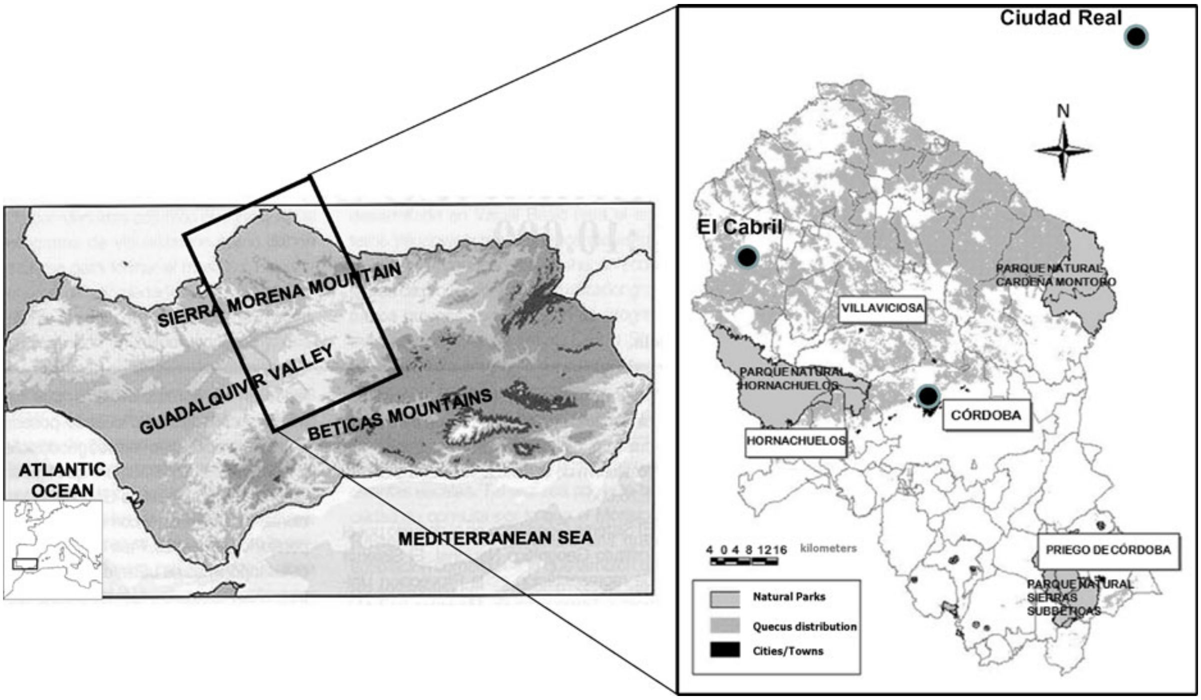

Fig. 1 **a** Area topography and **b** location of the study sites, representing grey area the Quercus crop distribution in Cordoba province

the Guadalquivir valley, where oaks are scarce and cereal and olive are the predominant crops. The valley is bounded to the north by the Sierra Morena mountains, where *Quercus* forests and "dehesas" are the main vegetation, and to the south by the Subbética Mountains, where olive groves predominate. The spatial distribution of *Quercus* population in the province of Córdoba, mainly in the north, is shown in Fig. 1.

Córdoba city (37°5′ N, 4° 45′ W) situated in the Guadalquivir valley at 120 m. above sea level (m.a.s.l) was considered as the main sampling point. In addition, *Quercus* pollen data from two other traps located in the north of the province were included in order to determine possible sources of airborne *Quercus* pollen in the city (Fig. 1). The first was a trap located at "El Cabril" reserve (38°4′ N, 5°24′ W, 450 m.a.s.l.) in the Sierra Morena mountains (80 km north-west of Córdoba city). The trap stands on the top of a hill inside the Hornachuelos Natural Park, 15 km from the nearest inhabited area. The second trap was located in the city of Ciudad Real (38°59′ N, 3°55′ W, 636 m.a.s.l.). This trap lies outside the region of Andalusia (130 km north-east of Córdoba city), on the Iberian Peninsula plateau, in the south of Castilla La Mancha, a region where "dehesa" formations also constitute the dominant ecological system.

Weather conditions in Córdoba city are mainly determined by its location within the Guadalquivir valley. The local climate is Mediterranean with continental influence, marked by considerable differences between the warm and cold seasons. Figure 2 shows monthly average temperature and relative humidity for the period 2000–2008 and charts monthly changes for each year of the study period 2006–2008, being obtained the weather data from Spanish Meteorological Agency (AEMET). As Fig. 2a and b show, the summer and winter are clearly defined, being the changes in relative humidity more pronounced than in temperature. In 2006, higher temperature and relative humidity values were recorded during spring and summer. In 2007, average temperatures were close to 8-year average; however, there were more marked differences in relative humidity, particularly in summer. Finally, temperature and relative humidity values during 2008 were in many months the lowest of the whole period.

Figure 2c shows the wind rose for Córdoba city for the period 2000–2008, indicating a clear valley

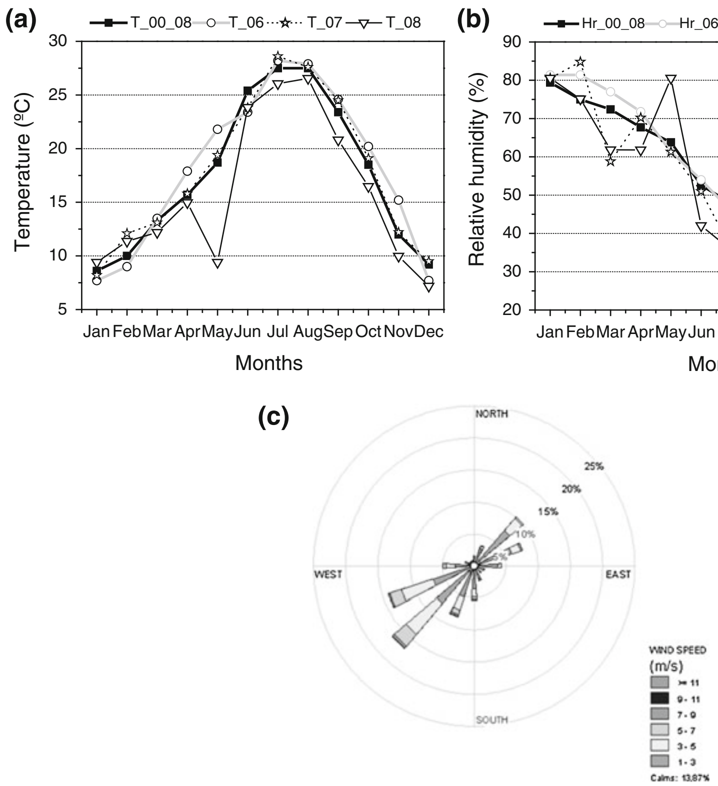

Fig. 2 Comparison of **a** temperature and **b** relative humidity monthly evolution at Cordoba city between 2006, 2007, 2008 and 2000–2008 period. **c** Rose wind for the 2000–2008 period

influence on surface dynamic; wind direction was limited to southwest–northwest (valley axis, Fig. 1). Wind speed was mostly below 5 m/s and rarely exceeded 9 m/s. The highest wind speed was observed in south-westerly flows, obtaining a total calm percentage (hourly data with wind speed less than 1 m/s) of 14% for the whole 2006–2008 period. The wind direction was mainly from the south-west, increasing in frequency and speed from March to June.

2.2 Airborne pollen counts

Daily and bi-hourly *Quercus* pollen count from 2006 to 2008 has been studied in this work. These data series have been obtained using Hirst-type volumetric spore traps (Hirst 1952). Standardised pollen data management has been processed following the rules laid down by the Spanish Aerobiology Network (REA) (Galán et al. 2007). For this study, the calculation of the 95 percentile (P95) has been used as the numerical limit to select the annual number of *Quercus* episode days, which represent the highest pollen concentrations detected in Córdoba city during each studied year.

2.3 Back-trajectory analysis

Back trajectories were computed using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model, developed by NOAA's Air Resources Laboratory (ARL) (Draxler et al. 2009). Kinematic back trajectories (3D) were considered the best option for representing air-mass pathways, since they enabled use of the vertical wind data included in the GDAS (Global Data Analysis System) meteorological files. This GDAS files have a temporal resolution of three hours, being the data gridded to 1°× 1 in latitude and longitude, including the upper level information in 23 pressure levels.

The validity of this model for computing back trajectories has been demonstrated in a number of studies (Lyamani et al. 2006; Borge et al. 2007; Yu et al. 2009; Hernández-Ceballos et al. 2010b in prep).

Here, air-mass movements were charted over a 48-h period, at a final height of 500 m above ground level (a.g.l) in order to ensure that the trajectory finished in the Atmospheric Boundary Layer (ABL). Similar back-trajectory characteristics were used by Hernández-Ceballos et al. (2010) in a study of the same area; the use, here, of a 48-h rather than 36-h period is associated with a minimal increase in computational error.

One aim of this study was to obtain an air-mass classification that could be related to daily airborne *Quercus* pollen counts. For this reason, one trajectory per day with an arrival time of 15 UTC over Córdoba city was calculated, being representative of the temporal range (between 12:00 UTC and 17:00 UTC) in which peak *Quercus* pollen counts are recorded (Galán et al. 1991; García-Mozo et al. 2007b). In addition, in order to correlate variations in air-mass movements with bi-hourly pollen counts, back trajectories were computed at different times for several episode days, using the same height and time values.

For the purposes of this study, a cluster was defined as a set formed by similar trajectories; each cluster represented a possible pattern of air-mass movement over Córdoba city. To compose each cluster, HYSPLIT has a module for applying cluster techniques based on variations in the Total Spatial Variance (TSV) between different clusters formed and on the spatial variance (SPVAR) between each cluster component (Draxler et al. 2009). The process consists in forming groups of trajectories which are associated with in the lowest increase in both indexes, retaining these associations throughout the process.

This enables the optimal number of clusters to be selected, i.e. the number of clusters that best represents the variability of a set of air-mass trajectories during a single period. Stunder (1996) associates this cluster number with the large increase in percentage TSV with respect to the number of clusters. Here, the optimal cluster number was the first associated with a TSV percentage variation above 40%.

3 Results

3.1 Air-mass classification

A total of 337 daily trajectories were computed over Córdoba city at 15 UTC from March to June during the period 2006–2008. To select the optimal cluster number of this set, the percentage variation in TSV over the final 30 steps was taken into account (Fig. 3a). Following the procedure outlined in Sect. 2.3, the optimal cluster number was set at six. The horizontal and vertical movements in each cluster are shown in Fig. 3b, which shows a single trajectory (centroid) as the average of the trajectories comprising the group.

These results enabled six air-mass types to be defined, coming from different areas, i.e. expanse in which the air mass was located 48 h prior its arrival over Córdoba city at 500 m.a.g.l (Fig. 3b). Two air masses originating in the Northwest were distinguished between them by the distance covered and by the speed of movement, since the time period was the same in both cases. One was associated with a long-distance displacement designated “Faster Northwest”,

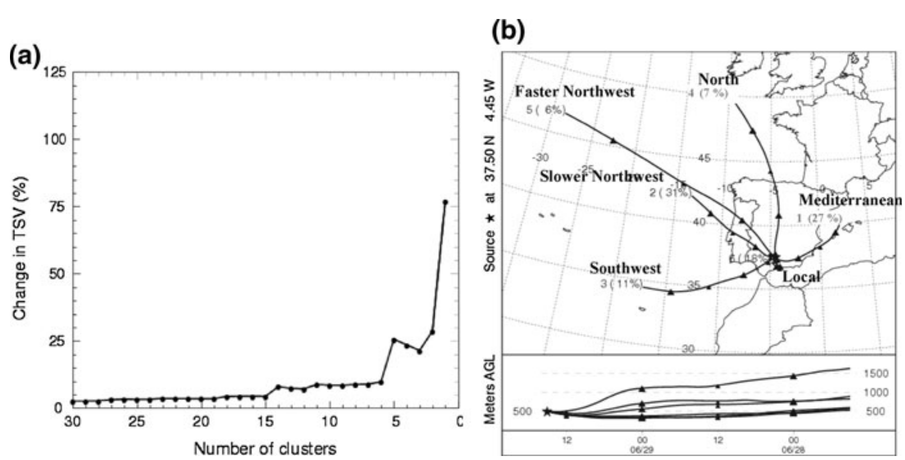

Fig. 3 **a** Variation of the Total Spatial Variance (TSV) versus cluster number in the final 30 steps and **b** Average cluster results (centroids). The right numbers in the centroids are the percentage of complete trajectories occurring in that cluster, and the left numbers are an identification number of the centroid

whilst the other is coming from an intermediate area closer to the Iberian Peninsula and was designated "Slower Northwest". The other faster advection type, designated "Northern", originated below the British Isles, with a trajectory from North to South of the Iberian Peninsula. Two air-mass clusters were discerned along the west–east axis of the Iberian Peninsula, one coming in from Atlantic, designated "Southwest" and the other from the Mediterranean ("Mediterranean") Finally, the smallest air-mass movement—travelling slowly over Córdoba province—was designated "Local".

The vertical movement of each air mass is also shown in Fig. 3b; the highest altitude pathway was associated with the Faster Northwest air-mass movement, which began at a height of up to 1,500 m. The lowest vertical development was recorded for Southwest, Mediterranean and Local movements, at altitudes below 500 m. North and Southwest air-mass movements were recorded at intermediate altitudes.

The two air masses most persistent over Cordoba city were the Mediterranean and Slower Northwest movements, with a frequency of 27 and 31%, respectively, being characterised the other types with values below 20%, as Local (18%), Southwest (11%), North (7%) and Faster Northwest (6%) (Fig. 3). Their monthly occurrence from March to June shows how the influence of the Mediterranean group was clearly more marked during April and June, whilst the Slower Northwest increased constantly in frequency until May, thereafter decreasing in June. Local and Southwest trajectories displayed a virtually constant frequency all months, whilst the North air-mass was more frequent in March and May and the Faster Northwest occurrence decreased from March to May, not being detected in June.

3.2 Changes in *quercus* pollen counts

Variations in daily average *Quercus* pollen counts in Córdoba city from March to June in 2006, 2007 and 2008 are shown in Fig. 4. Marked differences were observed between annual counts; the Annual Pollen Index (API), calculated as the sum of annual pollen grains, was 3,389 in 2006, 7,616 in 2007 and 12,484 in 2008.

With regard to pollen curve dynamics, annual differences are shown in Fig. 4. In 2006, *Quercus* pollen peaks were mainly observed during April, with daily peaks occasionally exceeding 200 grains/m^3; counts were lower in other months, dropping below 150 grains/m^3. In 2007, higher daily *Quercus* pollen counts were recorded from late March to mid-May, with two daily peaks more than 350 grains/m^3 in May and concentrations diminished during June. By contrast, *Quercus* pollen peaks during 2008 occurred

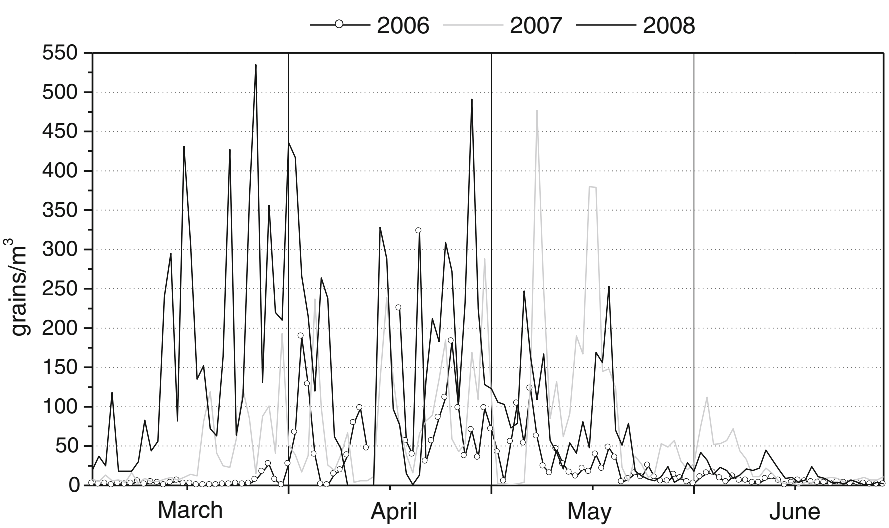

Fig. 4 *Quercus* pollen count daily average evolution from March to June in Cordoba monitoring site in 2006, 2007 and 2008. Grains/m^3: daily average pollen grains per m^3 of air

from March to April, when the highest daily counts of the whole study period were recorded (five peaks more than 400 grains/m^3).

Relationships between *Quercus* pollen counts and air masses identified over Córdoba city showed that the least frequent air-masses movements (North and Faster Northwest) were associated with the highest daily pollen counts (more than 90 pollen grains/m^3). The monthly results show how in March, the arrival of Faster Northwest air masses was associated with the highest *Quercus* pollen counts over Córdoba city, approaching 140 pollen grains/m^3, whilst the other trajectories were associated with daily counts of less than 60 pollen grains/m^3, the contribution of Mediterranean and Southwest trajectories being minimal.

In April, all air masses displayed a stronger influence on *Quercus* pollen counts in Córdoba city. North, Slower Northwest and Mediterranean air-mass movements were associated with daily values of over 120 pollen grains/m^3, whilst local circulations reached 90 pollen grains/m^3. On the other hand, the Faster Northwest circulation registered daily values less than 40 grains/m^3 and the Southwest advections of 45 pollen grains/m^3, being its maximum contribution to *Quercus* counts at Cordoba city.

In May, North air-mass movements were the major contributor to *Quercus* pollen counts in Córdoba city, with near of 140 pollen grains/m^3. However, the daily contribution associated to the other circulations was kept in daily values between 40 and 60 grains/m^3, excepting the Southwest advection with 30 grains/m^3. Finally, in June, the correlation between air-mass movements and pollen counts was much weaker, coinciding with the end of the flowering period. The strongest correlation ratio was observed for North air-mass movements, with a daily contribution approaching 80 pollen grains/m^3, whilst others types of movement contributed less than 20 pollen grains/m^3.

3.3 Episode analysis

Taking into account, each annual value of P95 in order to select *Quercus* episode days in Córdoba city (125 pollen grains/m^3 in 2006, 270 in 2007 and 420 in 2008), five days were identified as episode days in 2006, four in 2007 and five in 2008.

Relationships between daily back trajectories and each episode day revealed that all the air-mass movements identified, with the exception of Southwest (Sect. 3.1), are related with some of the high-pollen-count episodes. In order to provide a detailed description, one example of each case is analysed in depth below. However, no examples of Southwest transport were included because no *Quercus* pollen episodes were identified during this type of circulation.

For each episode, bi-hourly daily cycles and corresponding air-mass variability at specific times were analysed for Córdoba city. The same data were also analysed for El Cabril and Ciudad Real, in order to detect possible *Quercus* pollen transport from these areas to the city of Córdoba, as a means of identifying the potential location of *Quercus* pollen sources.

3.3.1 Episode analysis 20 April 2006, slow northwest air mass

A morning pollen peak at 6 UTC with 90 pollen grains/m^3 and increased counts from 16 UTC until the end of the day, reaching bi-hourly values of 80–90 pollen grains/m^3, were responsible for the daily pollen count recorded in Córdoba city during this episode day: 323 grains/m^3 (Fig. 5a). At El Cabril, the daily pollen count was 413 pollen grains/m^3, with a marked increase from 12 UTC until the end of the day. During this time, bi-hourly *Quercus* pollen counts exceeded 100 pollen grains/m^3 with two peaks of 200 pollen grains/m^3 at 16 and 22 UTC (Fig. 5a). In Ciudad Real, afternoon/evening counts increased at the same times as at El Cabril, though the increase was less marked; a daily peak was recorded at 2 UTC (120 pollen grains/m^3), and counts declined progressively until 12 UTC (Fig. 5a).

Back-trajectory analysis for that day showed a well-defined air-mass movement over all sampling stations during the day (Fig. 5b–d), identified as Slower Northwest (Fig. 3b). This homogeneity of the air-mass pathway was also observed in daily wind direction recorded in Córdoba city, which remained westerly. However, small variations observed in air-mass movements were probably responsible for the pollen peaks at each sampling site.

A relationship was observed between daily pollen cycles at El Cabril and Córdoba, suggesting an air-mass link between the two. A peak was detected at El Cabril at 2 UTC and then at 6 UTC in Córdoba city. Coinciding with a change in the air-mass pathway, a sharp increase was recorded at both El Cabril and

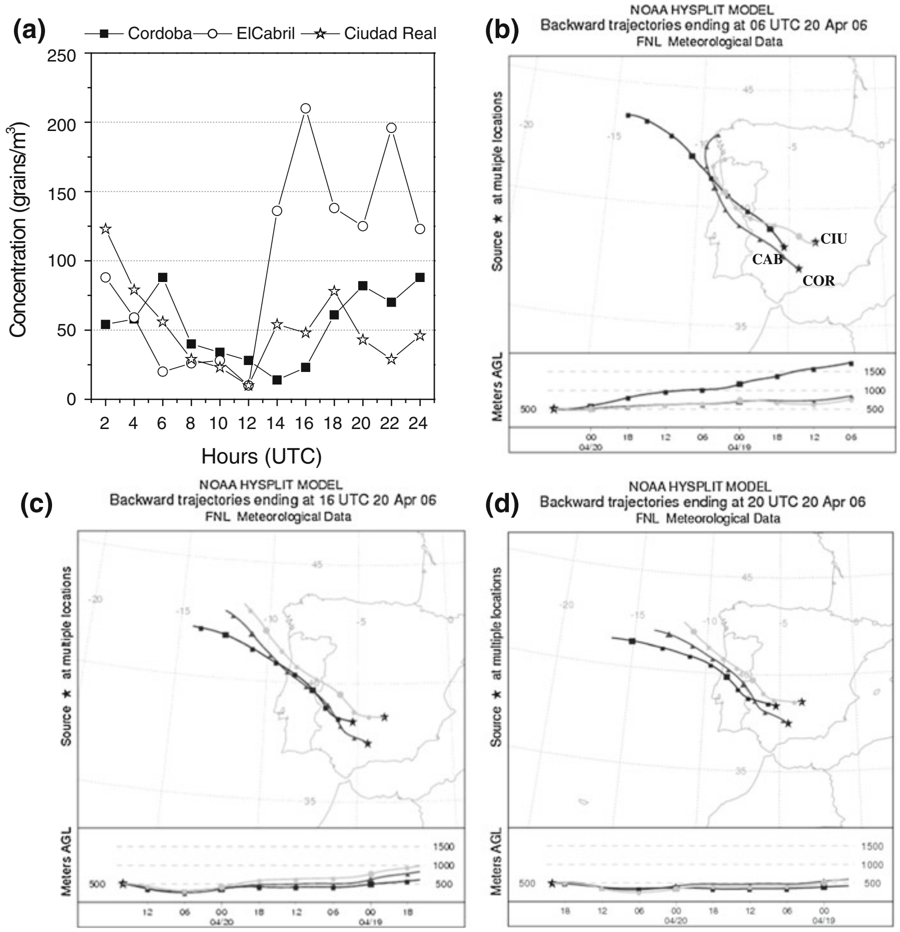

Fig. 5 a Bihourly *Quercus* pollen counts registered at Cordoba, El Cabril and Ciudad Real stations. (Average pollen grains per m^3 of air) and 48-h back-trajectory analysis at a height of 500 m and at **b** 06, **c** 16 and **d** 20 UTC on 20/04/06 in Córdoba (COR), El Cabril (CAB) and Ciudad Real (CIU) sites

Ciudad Real at 12 UTC, with pollen peaks being reported two hours later.

3.3.2 Episode analysis 17 May 2007, North air mass

The daily mean pollen count in Córdoba city was 379 pollen grains/m^3, with no marked peaks; in the course of the day, counts remained stable at between 40 and 80 pollen grains/m^3 (Fig. 6a). However, at El Cabril, daily peaks were identified at 6 UTC (130 grains/m^3) and at 10 UTC (140 pollen grains/m^3). Counts thereafter decreased 14 UTC until the end of the day, with values below 40 pollen grains/m^3 (Fig. 6a). During this episode day, no high pollen counts were recorded in Ciudad Real (Fig. 6a).

Air-mass movements originated in the north of the Iberian Peninsula (Fig. 6b–d), providing a clear example of North air-mass circulation (Fig. 3b). However, prior to arrival at each site, there was evidence of a deviation, as a result of which these movements came in from the east/northeast. This behaviour was confirmed by wind direction recorded at surface level and probably, together with the high vertical displacement, accounts for the absence of any correlation between counts at the various sampling sites, being probably associated El Cabril pollen peaks with the arrival of single air masses.

3.3.3 Episode analysis 13 March 2008, local air mass

The *Quercus* pollen count in Córdoba was 295 pollen grains/m^3, with a sudden, marked bi-hourly pollen peak of 200 pollen grains/m^3 at 4 UTC; thereafter,

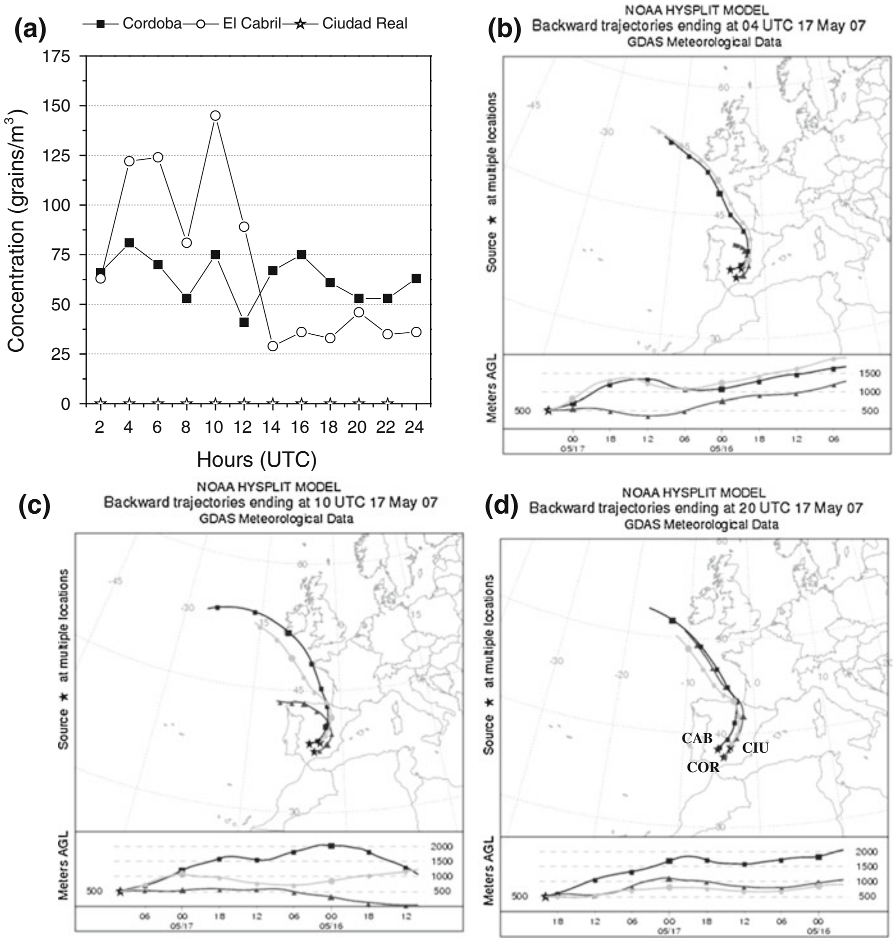

Fig. 6 **a** Bihourly *Quercus* pollen counts registered at Cordoba, El Cabril and Ciudad Real stations. (Average pollen grains per m^3 of air) and 48-h back-trajectory analysis at a height of 500 m and at **b** 04, **c** 10, and **d** 20 UTC on 17/05/07 in Córdoba (COR), El Cabril (CAB) and Ciudad Real (CIU) sites

values immediately dropped to below 50 grains/m^3 (Fig. 7a). This peak was not detected either at El Cabril (Fig. 7a) or at Ciudad Real (Fig. 7a), whose bi-hourly values remained below 10 pollen grains/m^3 throughout the day.

The pollen peak coincided with air-mass movements originating in the west of the Iberian Peninsula and remaining for a short time over the Córdoba area, as well as El Cabril and Ciudad Real (Fig. 7b). From 6 UTC, a well-defined and progressively developing circular movement was observed, arising in the west and moving north–south–north over Córdoba city, accompanied by a fall of vertical height (Fig. 7c, d). This coincided with a fall in pollen counts in Córdoba city (Fig. 7a). Wind direction in Córdoba city mirrored the behaviour of air mass, changing from east during the early part of the day to west/southwest thereafter.

3.3.4 Episode analysis 26 March 2008, faster Northwest air mass

Two marked peaks were detected in Córdoba city: at 6 UTC (300 pollen grains/m^3) and at 10 UTC (255 pollen grains/m^3), separate by a sudden, sharp dip (Fig. 7a). The daily pollen count was the highest for the whole period in Córdoba city, with 535 pollen grains/m^3. It should be noted, however, that pollen counts in Córdoba city were very low from 14 UTC onwards, with values dropping below 25 pollen grains/m^3 (Fig. 8a). Figure 8a also shows a relationship between daily counts in Córdoba and El Cabril, the two peaks occurring at the same time in both sites; though peak values were lower at El Cabril, pollen counts for the rest of the day were higher than in Córdoba. At Ciudad Real, pollen counts increased

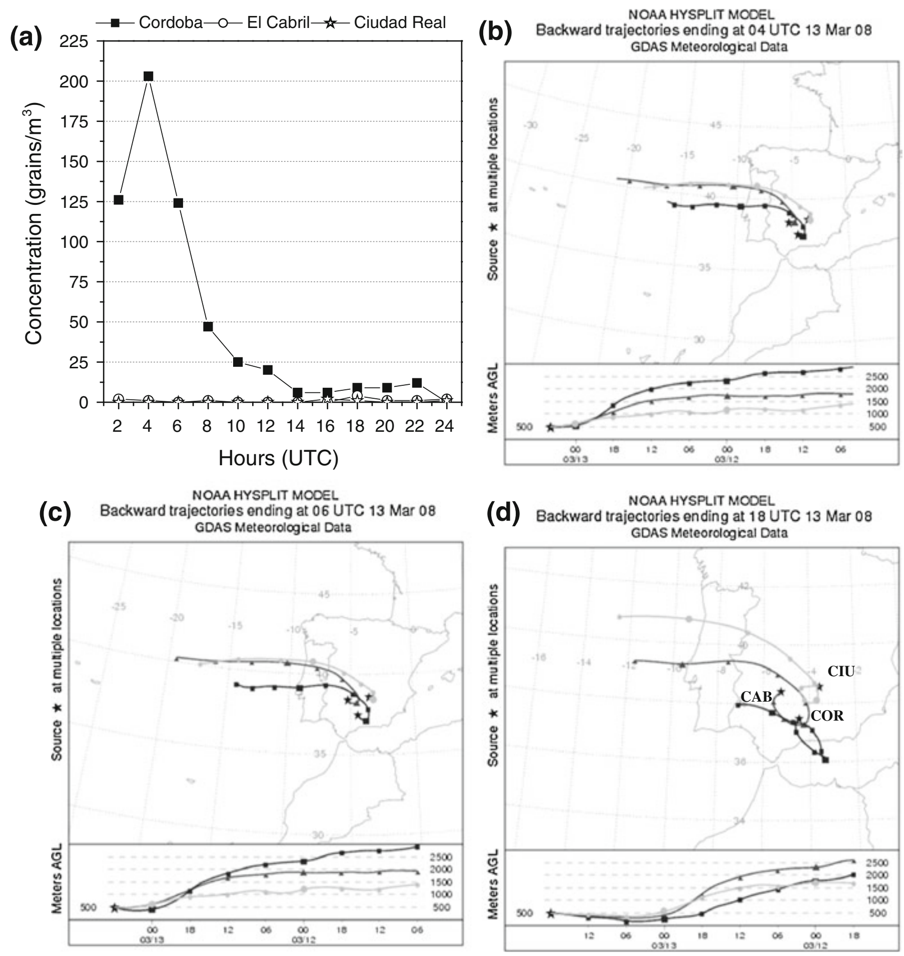

Fig. 7 **a** Bihourly *Quercus* pollen counts registered at Cordoba, El Cabril and Ciudad Real stations. (Average pollen grains per m^3 of air) and 48-h back-trajectory analysis at a height of 500 m and at **b** 04, **c** 06, and **d** 18 UTC on 13/03/08 in Córdoba (COR), El Cabril (CAB) and Ciudad Real (CIU) sites

from 6 UTC to 14 UTC, peaking at 14 UTC at around 150 pollen grains/m^3 (Fig. 8a).

Back-trajectory analysis indicated a constant Faster Northwest air-mass movement originating to the north-west of the Iberian Peninsula (Fig. 3b), with minimal changes in the course of the day (Fig. 8b, c, d). A similar uniformity was also apparent at surface level, with a constant arrival from the west/northwest. However, there was a marked change in wind speed, which increased from 1 m/s to 9 m/s in the middle of the day.

Given the homogeneity of the surface wind direction and the air-mass pathways, variability in pollen-peak timings was clearly the result of changing wind speeds (not shown). The sharp increase in wind speed from 12 UTC onwards would favour pollen dispersal, leading to lower airborne pollen counts (Fig. 8a). Wind speed would also account for the behaviour of pollen counts at Ciudad Real (Fig. 8a), where a sudden drop in counts coincided with increased wind speed.

3.3.5 Episode analysis 25 April 2008, Mediterranean air mass

A daily mean pollen count of 272 pollen grains/m^3 was recorded in Córdoba city, with two daily peaks: one at 6 UTC (115 pollen grains/m^3) and the other at 16 UTC (75 pollen grains/m^3), both followed by marked decrease in counts (Fig. 9a). At El Cabril, the pollen count remained fairly constant throughout the day, staying between 25 and 75 pollen grains/m^3 (Fig. 9a), having decreased from 14 UTC. At Ciudad Real, pollen counts remained below 50 grains/m^3, with a pollen curve similar to that observed in Córdoba (Fig. 9a).

Air-mass movement was virtually constant throughout the day, originating over the Mediterranean and

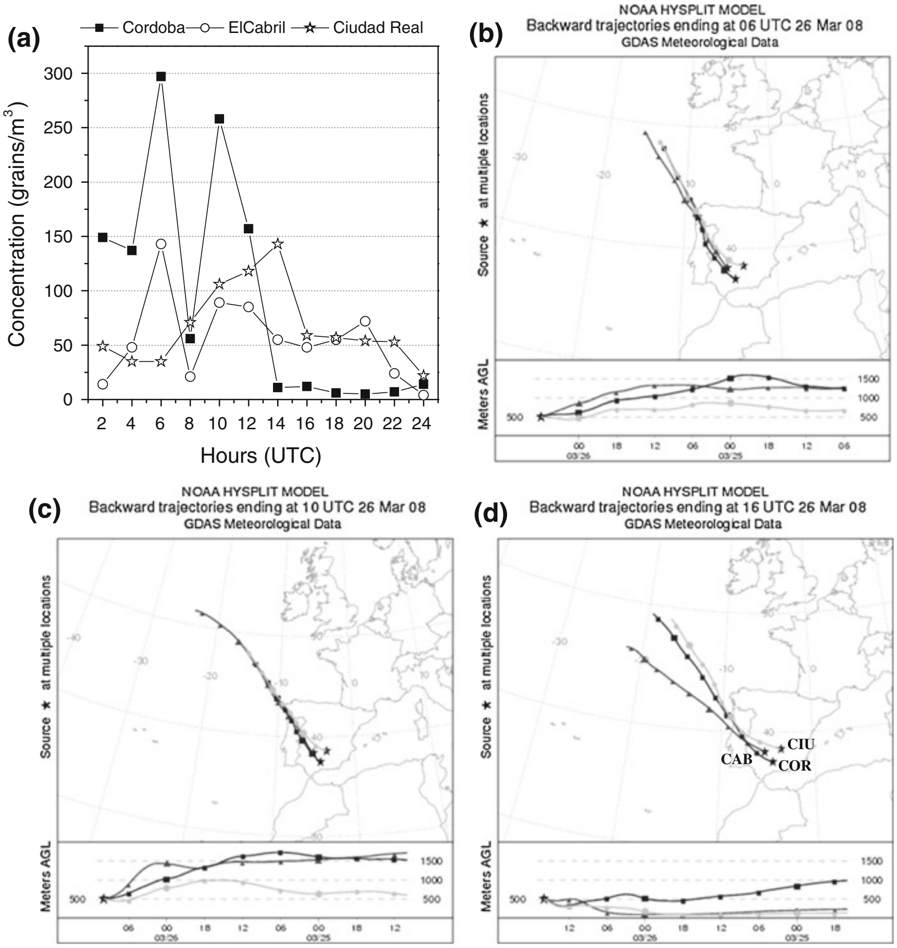

Fig. 8 **a** Bihourly *Quercus* pollen counts registered at Cordoba, El Cabril and Ciudad Real stations. (Average pollen grains per m^3 of air) and 48-h back-trajectory analysis at a height of 500 m and at **b** 06, **c** 10, and **d** 16 UTC on 26/03/08 in Córdoba (COR), El Cabril (CAB) and Ciudad Real (CIU) sites

moving inland along the natural channels linking the Guadalquivir valley to the coast (Fig. 9 b, c, d). Surface winds, however, were less constant, westerly winds backing to south/southwest by the end of the day (not shown). This change in wind direction coincided with a drop in pollen counts, first at Córdoba and, then, two hours later at El Cabril, suggesting a possible connection between these pollen-monitoring sites and the minimal contribution of the Southwest flow to *Quercus* counts.

4 Discussion

Previous aerobiological and phenological studies of *Quercus* in this area report high local airborne *Quercus* pollen counts, deriving mainly from holm oak stands (Gómez-Casero et al. 2007; García-Mozo et al. 2007a). Research indicates that holm-oak flowering is highly dependent on temperature (García-Mozo et al. 2002, 2008). Even so, the atmospheric dynamics of airborne *Quercus* pollen remain quite unclear. For that reason, daily and intradiurnal *Quercus* pollen counts and 48-h back trajectories over Córdoba city were analysed here, in an attempt to identify their main origin. In addition, pollen data and back trajectories from northern areas were studied to identify potential pollen transport between these areas and Córdoba city that might influence the pollen counts recorded.

Quercus pollen episode days were identified using the statistical 95th percentile value (P95), which is

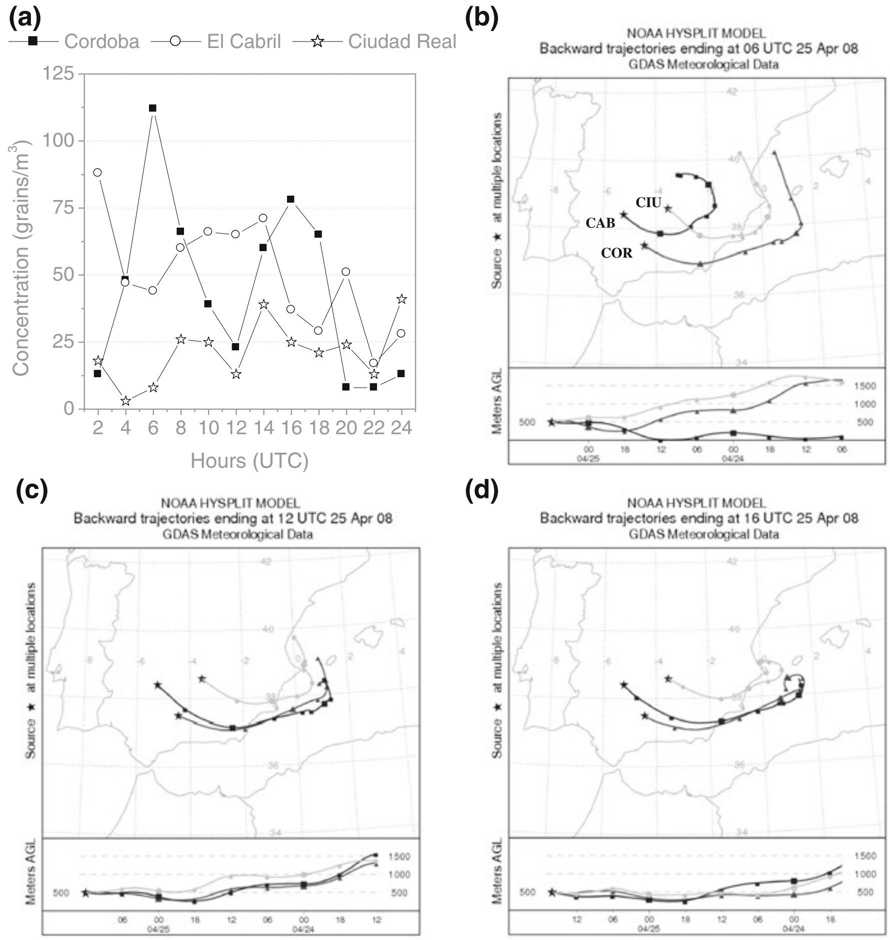

Fig. 9 **a** Bihourly *Quercus* pollen counts registered at Cordoba, El Cabril and Ciudad Real stations. (Average pollen grains per m^3 of air) and 48-h back-trajectory analysis at a height of 500 m and at **b** 06, **c** 12, and **d** 16 UTC on 25/04/08 in Córdoba (COR), El Cabril (CAB) and Ciudad Real (CIU) sites

generally used to highlight maximum or anomalous values in a temporal data series (Mitsakou et al. 2008; Adame et al. 2010). The annual calculation of this value and its comparison with daily data series for each year enables faster identification of anomalous values relating to high pollen counts. This method is more effective than that used in other studies those selecting episode days on a purely subjective basis, thus hindering the comparison of episode days between different periods and areas (Stach et al. 2007; Mahura et al. 2007).

The analysis of air-mass movements as a means of determining the origin of airborne pollen counts recorded in a given area has been validated for a range of climate areas and pollen types, including grass pollen in the United Kingdom (Smith et al. 2005), *Ambrosia* pollen in Poland (Smith et al. 2008), *Betula* pollen in Denmark (SkjØth et al. 2008) and *Celtis* and *Nothofagus* pollen in Buenos Aires (Gassmann and Pérez 2006).

The value of the HYSPLIT model to determine back trajectories has previously been evaluated for this kind of research (Sauliene and Veriankaite 2006; Cecchi et al. 2007; Mahura et al. 2007). However, as it is reflected in Veriankaite et al. (2010) and Hernández-Ceballos et al. 2010b in prep), the accuracy of the HYSPLIT results is mainly conditioned by the horizontal spatial resolution of the meteorological data used to calculate back trajectories. For this reason, it is necessary to take into account the relationship between the spatial resolution of the meteorological data and the scale of the atmospheric transport distance consider in each study. In this case, the use of GDAS files, with a resolution of 111 km, could be considered suitable to study the regional (up to 100 km) and long-range (more than 100 km) transport, defined in (Seinfeld and Pandis 2006), of *Quercus* pollen over Cordoba city.

In addition, it has to be considered the difficult and complex to quantify the airflow patterns over mountains, the anabatic or katabatic flows that have this type of atmospheric transport model (Pérez-Landa et al. 2007a, b). Both mountain winds are mainly observed under fair-weather conditions and denote an upslope (downslope) wind driven by heating (cooling) at the slope surface with respect to the surrounding air, respectively, having a wind speeds range often between 3–5 m/s and a spatial development conditioned by the characteristic of the mountain, such a high and cover. Taking into account the orographic conditions of this area, with mountains with height less than 1,000 m, the influence of these flows over air-mass transport is limited. In addition, the use of GDAS files to calculate back trajectories does not allow to consider these mountains flows, due to its spatial resolution is not enough to detect the development and behaviour of these.

Motivated by these limitations, different ways have been used to account the uncertainty of back trajectories. In this sense, Smith et al. (2005) used clusters of trajectories (trajectories situated directly north, south, east and west of the central parcel) in order to identify anomalies in the trajectory analysis. In Stach et al. (2007) used ensembles based on nine trajectories with receptor points placed 16 km apart. Over this study area, Hernández-Ceballos et al. (2010a) examined the behaviour of trajectories at different altitudes from 100 m to 800 m, selecting 500 m a.g.l as representative height. This last study, therefore, allows the used of back trajectories at this region, in order to identify the potential origin of *Quercus* pollen counts over Cordoba city.

The result obtained here for air-mass movements over Córdoba city at 500 m between March and June largely agrees with the findings of previous studies of seasonal air-mass changes at the mouth of the River Guadalquivir in southern Andalusia (Toledano et al. 2009; Hernández-Ceballos et al. 2010b in prep). Results for monthly air-mass frequency over Córdoba city varied considerably over the study months. Two different air-mass groups were identified as a function of frequency: the main group comprised Local, Slower Northwest and Mediterranean movements, characterised by higher frequencies; a second group consisting of North, Faster Northwest and Southwest trajectories occurred less frequently over the study period.

The main air-mass movements recorded here agree with the synoptic configurations prevailing from March to June over the Iberian Peninsula as a whole (López Ontiveros and 2003). This period is characterised by the progressive minimisation of unstable synoptic conditions and the increasing prevalence of stable conditions as summer approaches, leading to a gradual decreased in air-mass movements, evident in the monthly frequencies obtained for each air-mass type. A drop in frequency was observed in the air-mass movements with a greater displacement—particularly for North and Faster Northwest movements—whilst shorter-range movements (Local and Mediterranean) recorded a progressive increase in frequency. Similar air-mass behaviour has been reported by Jorbá et al. (2004), in a classification and seasonal analysis of air-mass movements in the north-eastern Iberian Peninsula.

Previous aerobiological and phenological studies carried out on *Quercus* pollen dynamic in the city of Cordoba, indicated that, even the main part of the pollen curve corresponds to the flowering time of *Quercus* species in that area, there are also high pollen peaks not explicable in terms of weather-related factors and not matching the floral phenological data collected in the field (Gómez-Casero et al. 2007). Joint analysis of air-mass movements and *Quercus* pollen counts revealed strong relationships. The influence of these movements on pollen counts was particularly apparent from the data recorded in March of each year; in March 2008, higher *Quercus* counts coincided with the dominance of northerly air masses, whilst in 2006 and 2007, peak pollen counts declined, coinciding with the maximum influence of Southwest and Mediterranean air-mass movements.

The results obtained for daily *Quercus* pollen counts associated to each air-mass type relate to the *Quercus* pollen spatial distribution over the Andalusia region. The arrival of Southwest air masses was associated with the lowest pollen counts in Córdoba city, due to the minimal presence of *Quercus* in the Guadalquivir valley, whilst the arrival of northerly air-mass movements (North, and Faster and Slower Northwest) was associated with the highest daily pollen counts over Córdoba city; Mediterranean and Local movements also formed part of this latter group.

The relationship between air-mass movements and daily *Quercus* pollen recorded at Cordoba city allows us to identify two *Quercus* pollen sources: the most influential source was located in the northern area of Córdoba with pollen grains transported to the city by North and Northwest air-mass movements; a secondary source was situated in southern Andalusia, beyond the Guadalquivir valley, and pollen was transported by Mediterranean air-mass movements. Monthly data showed that the northern source contributed to pollen counts over the whole study period, whilst the southern source mainly contributed to counts in April and May.

Given the distance of these two sources from Córdoba city, two types of pollen transport must be involved. The northern source was linked with regional transport, and the southern source with long-range transport. Mediterranean air-mass movements and long-regional would account for the influence of *Quercus* sources in the Andalusian Mediterranean area on counts in Córdoba city, since pollen is transported through natural channels, over a large cultivated area. The effectiveness of these natural channels has already been reported for airborne *Olea* pollen content (Hernandez-Ceballos et al. 2010a).

However, the contribution of Local air masses to daily *Quercus* counts also confirmed the influence of sources closer to Córdoba city. Local circulation sweeps over the area north of the city, where there is a *Quercus* forest, and, therefore, the influence of these air-mass movements is thus largely determined by their pathway. This was evident on the 13/03/2008 episode day, when a decrease in pollen counts coincided with the development of a local air mass moving in from the south—where *Quercus* is relatively scarce—towards Córdoba city.

Comparative analysis of daily pollen cycles at the three sampling sites (Córdoba, El Cabril and Ciudad Real) indicated that *Quercus* pollen is transported between the Córdoba and El Cabril areas (northern area of Cordoba province), and that transport is clearly governed by Local air-mass type. No clear correlation was detected between Córdoba city and Ciudad Real area, indicate that the transport from northern areas would be a regional transport and that the Sierra Morena mountain chain would act as a geographical barrier, minimising the influence of *Quercus* sources located in the Iberian Peninsula plateau.

Back-trajectory analysis indicated that high-pollen-count episodes were mainly associated with air-mass movements arising in the north of the province, confirming the major contribution of northern *Quercus* sources to pollen counts in Córdoba city. A secondary southern pollen source was also identified with a minor contribution to the city's *Quercus* pollen count. This type of analysis is a valuable tool for pollen-forecasting purposes in Córdoba city, since episodes of this kind are to be expected whenever similar air-mass movements are identified.

5 Conclusions

(1) The application of cluster techniques to a set of back trajectories enabled identification of six different types of air-mass movements, whose monthly frequency over the study period was governed by temporal variations in the synoptic pattern influential over the Iberian Peninsula: one air-mass movement was identified as coming from the north, two from the north-west (designated Faster and Slower), two along the west–east axis of the Iberian Peninsula (designated Mediterranean and Southwest) and finally, a Local air-mass movement associated with the lowest displacement. As a function of frequency two different air-mass groups are identified: the main group comprised Local, Slower Northwest and Mediterranean movements, characterised by higher frequencies; a second group consisting of North, Faster Northwest and Southwest trajectories occurred less frequently over the study period.

(2) In terms of the API values associated with each air-mass type, the Mediterranean and Slower Northwestern movements contributed most to airborne *Quercus* pollen counts recorded in Córdoba city. However, joining air-mass frequency and daily pollen counts, the North and the Faster Northwest movements were associated with the highest daily counts. A lower contribution was observed for Local air masses, and finally, the arrival of Southwest air masses

exerted the least influence on *Quercus* pollen counts in Córdoba city.

(3) The correlation between air-mass movements and pollen counts helped to identify two *Quercus* pollen sources: the most influential source was located in the north of Córdoba province, and pollen was transported over a regional distance to the city by North and Northwest air-mass movements; a secondary source was situated in southern Andalusia, beyond the Guadalquivir valley, and pollen was transported over a longer distance by Mediterranean air-mass movements. In addition, the monthly data showed that the northern source contributed to pollen counts over the whole study period, whilst the southern source mainly contributed to counts in April and May.

References

Adame, J. A., Bolívar, J. P., & De la Morena, B. A. (2010). Surface ozone measurements in the southwest of the Iberian Peninsula (Huelva, Spain). *Environmental Science and Pollution Research, 17*, 355–368.

Borge, R., Lumbreras, J., Vardoulakis, S., Kassomenos, P., & Rodríguez, E. (2007). Analysis of long-range transport influences on urban PM10 using two-stage atmospheric trajectory clusters. *Atmospheric Environment, 41*, 4434–4450.

Cecchi, L., Torrigiani Malaspina, T., Albertini, R., Zanca, M., Ridolo, E., Usberti, I., et al. (2007). The contribution of long-distance transport to the presence of *Ambrosia* pollen in central northern Italy. *Aerobiologia, 23*, 145–151.

Davis, R., Normile, C., Sitka, L., Hondula, D., Knight, D., Gawtry, S., et al. (2010). A comparison of trajectory and air mass approaches to examine ozone variability. *Atmospheric Environment, 44*, 64–74.

Draxler, R. R., & Hess, G. D. (1998). An overview of the HYSPLIT_4 modelling system for trajectories, dispersion, and deposition. *Australian Meteorology Magazine, 47*, 295–308.

Draxler, R.R., Stunder, B., Rolph, G., & Taylor, A. (2009). HYSPLIT_4 User's Guide. NOAA Air Resources Laboratory. http://www.arl.noaa.gov/documents/reports/hysplit_user_guide.pdf. Accessed 14 April 2010.

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 de Publicaciones de la Universidad de Córdoba, Córdoba, Spain. ISBN 978-84-690-6353-8.

Garcia-Mozo, H., Dominguez-Vilches, E., & Galan, C. (2007). Airborne allergenic pollen in natural areas. *Annals of Agricultural and Environmental Medicine, 14*, 109–115.

García-Mozo, H., Galán, C., Aira, M. J., Belmonte, J., Díaz de la Guardia, C., Fernández, D., et al. (2002). Modelling start of oak pollen season in different climatic zones in Spain. *Agricultural and Forest Meteorology, 110*, 247–257.

García-Mozo, H., Gómez-Casero, M. T., Dominguez, E., & Galán, C. (2007). Influence of pollen emission and weather-related factors on variations in holm-oak (*Quercus ilex* subsp. ballota) acorn production. *Environmental and Experimental Botany, 61*, 35–40.

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

García-Mozo, H., Mestre, A., & Galán, C. (2010). Phenological trends in southern Spain: A response to climate change. *Agricultural and Forest Meteorology, 150*, 575–580.

Gassmann, M. I., & Pérez, C. F. (2006). Trajectories associated to regional and extra-regional pollen transport in the southeast of Buenos Aires province, Mar del Plata (Argentina). *International Journal of Biometeorology, 50*, 280–291.

Gómez-Casero, M. T., Hidalgo, P., García-Mozo, H., Domínguez, E., & Galán, C. (2004). Pollen biology in four Mediterranean *Quercus* species. *Grana, 43*, 22–30.

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

Hernández-Ceballos, M.A., García-Mozo, H., Adame, J.A., Domínguez-Vilches, E., De la Morena, B.A., Bolívar, J.P., et al. (2010a). Synoptic and meteorological characterization of olive pollen transport in Córdoba province (Southwestern Spain). *International Journal of Biometeorology*. doi: 10.1007/s00484-010-0306-4.

Hernández-Ceballos, M.A., Adame, J.A., Bolívar, J.P., & De la Morena, B.A. (2010b). The climatology of air masses in southwestern Europe from 1997 to 2007. In prep.

Hirst, J. (1952). An automatic volumetric spore-trap. *Annals of Applied Biology, 36*, 257–265.

Hondula, D. M., Sitka, L., Davis, R. E., Knight, D. B., Gawtry, S. D., Deaton, M. L., et al. (2010). A back-trajectory and air mass climatology for the Northern Shenandoah Valley, USA. *International Journal of Climatology, 30*, 569–581.

Jorba, O., Pérez, C., Rocandenbosch, F., & Baldasano, J. M. (2004). Cluster Analysis of 4-Day Back Trajectories Arriving in the Barcelona Area (Spain) from 1997 to 2002. *Journal of Applied Meteorology, 43*, 887–901.

Karaca, F., Anil, I., & Alagha, O. (2009). Long-range potential source contributions of episodic aerosol events to PM10 profile of a megacity. *Atmospheric Environment, 43*, 5713–5722.

López Ontiveros, A. (coord). (2003). *Geografía de Andalucía*. Editorial Ariel Geografía.

Lyamani, H., Olmo, F. J., Alcántara, A., & Alados-Arboledas, L. (2006). Atmospheric aerosols during the 2003 heat wave in southeastern Spain I: Spectral optical depth. *Atmospheric Environment, 40*, 6453–6464.

Mahura, A. G., Korsholm, U. S., Baklanov, A. A., & Rasmussen, A. (2007). Elevated birch pollen episodes in Denmark: contributions from remote sources. *Aerobiologia, 23*, 171–179.

Mitsakou, C., Kallos, G., Papantoniou, N., Spyrou, C., Solomos, S., Astitha, M., et al. (2008). Saharan dust levels in Greece and received inhalation doses. *Atmospheric Chemistry and Physics, 8*, 7181–7192.

Pérez-Landa, G., Ciais, P., Gangoiti, G., Palau, J. L., Carrara, A., Gioli, B., et al. (2007a). Mesoscale circulations over complex terrain in the Valencia coastal region, Spain–Part 2: Modeling CO2 transport using idealized surface fluxes. *Atmospheric Chemistry and Physics, 7*, 1851–1868.

Pérez-Landa, G., Ciais, P., Sanz, M. J., Gioli, B., Miglietta, F., Palau, J. L., et al. (2007b). Mesoscale circulations over complex terrain in the Valencia coastal region, Spain–Part 1: Simulation of diurnal circulation regimes. *Atmospheric Chemistry and Physics, 7*, 1851–1868.

Petzold, A., Rasp, K., Weinzierl, B., Esselborn, M., Hamburger, T., Dornbrack, A., et al. (2009). Saharan dust absorption and refractive index from aircraft-based observation during SAMUM 2006. *Tellus, 618*, 118–130.

Sánchez-Ccoyllo, O. R., Silva Dias, P. L., Fátima Andrade, M., & Freitas, S. R. (2006). Determination of O3-, CO- and PM10- transport in the metropolitan area of Sao Paulo, Brazil though synoptic–scale analysis of back-trajectories. *Meteorology Atmospheric and Physics, 92*, 83–93.

Sauliene, I., & Veriankaite, L. (2006). Application of backward air mass trajectory analysis in evaluation airbone pollen dispersion. *Journal of Environmental engineering and landscape management, 14*(3), 113–120.

Seinfeld, J. H., & Pandis, S. N. (2006). *Atmospheric Chemistry and Physics: From air pollution to climate change*. New York: John Wiley and Sons.

Siljamo, P., Sofiev, M., Severova, E., Ranta, H., & Polevova, S. (2007). On influence of long-range transport of pollen grains onto pollinating seasons. In C. Borrego & E. Renner (Eds.), Developments in Environmental Science, 6. *Air Polution Modelling and its Applications XVIII*, 708–716.

Siljamo, P., Sofiev, M., Severova, E., Ranta, H., Kukkonen, J., & Polevova, S. (2008). Sources, impact and exchange of early-spring birch pollen in the Moscow region and Finland. *Aerobiologia, 24*, 211–230.

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Wang, W., et al. (2005). A description of the Advanced Research WRF Version 2. NCAR Tech Notes-468 + STR. http://www.mmm.ucar.edu/wrf/users/docs/arw_v2.pdf. Accessed 30 April 2010.

SkjØth, C., Sommer, J., Brandt, J., Hvidberg, M., Geels, C., Hansen, K., et al. (2008). Copenhagen–a significant source of birch (Betula) pollen? *International Journal of Biometeorology, 52*(6), 453–462.

Smith, M., Emberlin, J., & Kress, A. (2005). Examining high magnitude grass pollen episodes at Worcester, United Kingdom, using back-trajectory analysis. *Aerobiología, 21*, 85–94.

Smith, M., SkjØth, C. A., Myszkowska, D., Uruska, A., Malgozata, P., Stach, A., et al. (2008). Long-range transport of *Ambrosia* pollen to Poland. *Agriculture and Forest Meteorology, 148*, 1402–1411.

Sofiev, M., Siljamo, P., Ranta, H., & Rantio-Lehtimäki, A. (2006). Towards numerical forecasting of long-range air transport of birch pollen: theoretical considerations and a feasibility study. *International Journal of Biometeorology, 50*, 392–402.

Sofiev, M., Siljamo, P., Ranta, H., Linkosalo, T., Jaeger, S., Jaeger, C., et al. (2008) From Russia to Iceland: an evaluation of a large-scale pollen and chemical air pollution episode during April and May, 2006. *Aerobiological Monographs*, Vol. 1, in press.

Sprovieri, F., Hedgecock, I. M., & Pirrone, N. (2010). An investigation of the origins of reactive gaseous mercury in the Mediterranean marine boundary layer. *Atmospheric Chemistry and Physics, 10*, 3985–3997.

Stach, A., Smith, M., SkjØth, C., & Brandt, J. (2007). Examining *Ambrosia* pollen episodes at Poznan (Poland) using back-trajectory analysis. *International Journal of Biometeorology, 51*, 275–286.

Stohl, A., Hittenberger, M., & Wotawa, G. (1998). Validation of the Lagrangian particle dispersion model FLEXPART against large scale tracer experiments. *Atmospheric Environment, 32*, 4245–4264.

Stunder, B. (1996). An assessment of the Quality of Forecast Trajectories. *Journal of Applied Meteorology, 35*, 1319–1331.

Toledano, C., Cachorro, V. E., de Frutos, A. M., Torres, B., Berjon, A., Sorribas, M., et al. (2009). Airmass classification and Analysis of Aerosols Types at El Arenosillo. *Journal of Applied Meteorology and Climatology, 48*, 962–981.

Veriankaite, L., Siljamo, P., Sofiev, M., Sauliene, I., & Kukkonen, J. (2010). Modelling analysis of source regions of long-range transported birch pollen that influences allergenic seasons in Lithuania. *Aerobilogia, 26*, 47–62.

Yu, S. C., Mathur, T., Kang, D. W., Schere, K., & Tong, D. (2009). A study of the ozone formation by ensemble back-trajectories-process analysis using the Eta-CMAQ forecast model over the northeastern US during the 2004 ICARTT period. *Atmospheric Environment, 43*, 355–363.