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Causes of increased pollen exposure during Saharan-Sahel dust intrusions☆

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ABSTRACT

Airborne particulate matter such as mineral dust comes mainly from natural sources, and the African regions of Sahara and Sahel originate large amounts of the aerosols dispersed worldwide. There is little knowledge about the influence of dust episodes on airborne pollen concentrations, and although the centre and southeast of the Iberian Peninsula are frequently affected by dust intrusions, until now, no specific works have analysed the effect of these episodes on airborne pollen concentrations in these areas. The aims of this study were to analyse the simultaneous occurrence of airborne pollen peaks and Saharan-Sahel dust intrusions in the central and south-eastern Iberian Peninsula, and to study the weather conditions – air mass pathways and conditions of air temperature, relative humidity and atmospheric pressure – that influence the airborne pollen concentrations during dust episodes. The results showed that the rise in airborne pollen concentrations during dust episodes is apparent in inland Iberian areas, although not in coastal areas in the southeast where pollen concentrations are even observed to decrease, coinciding with prevailing easterly winds from the sea. Total pollen concentrations and specific pollen types such as *Olea*, Poaceae and *Quercus* showed an increase in the central Iberian Peninsula during dust episodes when two meteorological phenomena concur: 1) prevailing winds from extensive areas of major wind-pollinated pollen sources over a medium or short distance (mainly from western and southwestern areas); and 2) optimal meteorological conditions that favour pollen release and dispersal into the atmosphere (mainly high temperatures and subsequently low humidity in central areas). Both conditions often occur during the Saharan-Sahel dust intrusions in the centre. Maximum pollen peaks are therefore most likely to occur during dust episodes in the central Iberian Peninsula, thus dramatically increasing the risk of outbreaks of pollinosis and other respiratory diseases in the population.

1. Introduction

Airborne particulate matter derives mainly from natural sources, and the arid regions of the North of Africa are the main source of mineral dust of desert origin dispersed throughout the Northern Hemisphere (Ginoux et al., 2012; Middleton and Kang, 2017). Mediterranean countries are severely affected by Saharan-Sahel dust episodes (Gobbi et al., 2019; Kallos et al., 2007), and the Iberian Peninsula is located in one of the main transport pathways of desert African dust (Salvador et al., 2014; Valenzuela et al., 2012). However, the Saharan-Sahel dust contribution is not homogeneously distributed throughout the Iberian territory, where the central and southern areas suffer the greatest incidence of dust episodes (Querol et al., 2019; Russo et al., 2020).

Saharan-Sahel dust episodes have a significant impact on air quality, and constitute the largest source of PM_{10} in regional background measurements in southern Mediterranean areas; peak desert contributions may represent up to 80% of the total PM_{10} mass (Pey et al., 2013). Most of the exceedances of the daily European limit for particulate matter are caused by Saharan-Sahel dust episodes (Querol et al., 2009). The negative effects of respirable fraction of the particulate matter (PM_{10}, $PM_{2.5}$ and PM_1) on public health are well known (Karanasiou et al., 2012), and mineral dust is specifically responsible for the increased risk

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of respiratory and cardiovascular diseases and other health disorders (Goudie, 2014; Soleimani et al., 2020), and even for higher mortality rates (Díaz et al., 2017; Stafoggia et al., 2016). The health effects of mineral dust may also be further aggravated by other particles transported by air mass movements from desert areas, e.g. bioaerosols such virus, bacteria, spores or pollen grains (Griffin, 2007), and the allergenic potential of pollen and spores may trigger allergic reactions in the sensitized population.

Respiratory diseases related to pollen allergy are one of the main public health concerns in industrialised countries (Kim et al., 2013). Approximately a quarter of the European population is affected by pollinosis, and this rate is expected to rise in the coming decades due to the increase of pollen releasing and allergen sensitisation in the climate change context (Baldacci et al., 2015; European Academy of Allergy and Clinical & Immunology, 2015). Pollen exposure is increasing for some biological pollutants in cities (Lake et al., 2017; Lara et al., 2020), but particular meteorological events during high pollen days have been observed to produce the most severe asthma outbreaks associated with extreme episodes such as thunderstorms, dust intrusions or episodes of heavy rainfall (Rabiee et al., 2018; Silver et al., 2018; Thien et al., 2018).

There is little available knowledge on the effect of phenomena such as dust intrusions on airborne pollen levels in the Mediterranean area. Past research has revealed an increase in pollen diversity and pollen load for specific taxa (Cariñanos et al., 2004; García-Mozo et al., 2017; Oduber et al., 2019), but we do not have a comprehensive understanding of the meteorological conditions that regulate the pollen contribution during these intrusions. Previous studies carried out in the Macaronesian and Temperate regions documented the specific transport routes of bioaerosols such as pollen and spores as well as other drivers of pollen release such as temperature during African intrusions (Grewling et al., 2019; Izquierdo et al., 2011). Grewling et al. (2019) reported that several types of pollen and spores are transported together by air masses from North Africa. Dust intrusions also influenced the occurrence of other pollutants in the atmosphere (Salvador et al., 2019). The concomitant presence of inorganic and biological agents in the urban atmosphere has a negative impact on public health during Saharan-Sahel dust episodes.

Although the centre and southeast of the Iberian Peninsula are frequently affected by Saharan-Sahel dust intrusions (Negral et al., 2012; Russo et al., 2020), until now, no specific works have analysed the effect of these episodes on airborne pollen concentrations in these areas. In this work we tested several hypotheses in these Iberian Mediterranean areas in order to pose the following questions: 1) Do Saharan-Sahel dust intrusions cause a significant increase in airborne pollen concentrations? 2) What is the main geographic scale (short-, medium- or long-distance) of the airborne transport of the highest pollen concentrations? 3) Do other meteorological factors besides air mass movements (e.g. air temperature, relative humidity …) affect the pollen release during Saharan-Sahel dust intrusions?

In this context, the aims of this study were therefore: firstly, to analyse the simultaneous occurrence of airborne pollen peaks and Saharan-Sahel dust intrusions and compare this situation with the pollen concentrations in the days before and after the dust intrusions in the central and south-eastern Iberian Peninsula; secondly, to study the weather conditions – namely prevailing winds and air mass pathways – that favour high pollen concentrations during dust episodes in relation to the distribution of the pollen sources, and variations in other meteorological variables such as air temperature, relative humidity and atmospheric pressure.

2. Materials and methods

2.1. Data collection

The study was carried out along a corridor from the south-eastern to the central Iberian Peninsula in order to analyse airborne pollen concentrations in an important gateway for African air masses. Air quality stations were used in the study area, based on measurements of thoracic fraction of particulate matter (PM_{10}) and biological particles (pollen grains).

Pollen data were recorded in six pollen stations from the centre to the southeast: Talavera de la Reina, Toledo and Albacete in the region of Castilla-La Mancha (central Spain) and Lorca, Murcia and Cartagena in the Region of Murcia (south-eastern Spain) (additional information about the pollen stations in Supplementary Materials, Table S1 and Figures S1-S3). Daily pollen concentrations measured in pollen grains per cubic metre of air (pollen grains/m^3) were recorded continuously (except for data during missed periods without sampling in Talavera and Albacete, Table S1) using a Hirst-type volumetric sampler during the period 2009–2019. Aerobiological sampling and pollen quantification and identification were done following the minimum recommendation in the standardised procedure proposed by the International Association for Aerobiology and the European Aerobiology Society (Galán et al., 2014). The pollen count was monitored according to a periodic quality control procedure to ensure the quality and comparability of the pollen data (Oteros et al., 2013). Pollen sampling was carried out using a 7-day recording volumetric spore trap (Lanzoni VPPS-2000, Bologna, Italy) based on the Hirst design (Hirst, 1952) following standardised rules (EN 16868, 2019). The flow rate of this device is 10 l/min and bioaerosols were trapped on an adhesive-coated Melinex® strip (Burkard Manufacturing Co. Ltd., Rickmansworth, UK). Daily samples were analysed under ×400 magnification (light microscope), analysing four longitudinal sweeps per slide, following the standardised recommendations (Galán et al., 2014). The aerobiological datasets were managed using the 'AeRobiology' R package (Rojo et al., 2019) implemented in R Software (R Core Team, 2020).

Information on the characterization of the Saharan-Sahel dust intrusions was supplied by the Spanish Ministry for Ecological Transition and the Demographic Challenge (MITECO, www.miteco.gob.es), and was generated from different air quality stations run by the regional governments and the European Monitoring and Evaluation Programme (EMEP). In Spain, this network of air quality stations is organized into different regions to characterize dust episodes following geographic criteria. This geographic division serves as the basis for the alert systems developed by the Spanish government in compliance with European rules (Viana et al., 2010). The region of Castilla-La Mancha (central Spain) belongs to the central division while the Region of Murcia belongs to the south-eastern division (although also the eastern division was considered in the descriptive study of dust episodes) (Figure S1). The background monitoring stations in these areas continuously collect data on particulate matter (PM_{10}) to evaluate the real impact of African dust intrusions that have been previously identified based on remote sensing and meteorological criteria, as described below (additional information about the background monitoring stations used to define the desert dust intrusions in Supplementary Materials, Table S2). Meteorological data were provided by the Spanish Meteorological Agency (AEMET).

2.2. Definition of desert dust intrusions

The identification of African dust episodes is provided by the Spanish Ministry for Ecological Transition and the Demographic Challenge (MITECO), which has established an updated alarm system for dust intrusions from the Saharan-Sahel region into Spanish territory. The methodology is detailed and explained below. However, since the definition of the desert intrusions used in this work is based on processed data published by the national government, the methodological details may be consulted in the published works (Querol et al., 2009; Salvador et al., 2013) whose methodological procedure has been used as a reference method in European policies (European Commission, 2011). Two approaches were followed to define both the occurrence of the dust episodes and the intensity of the episodes.

Dust episodes are identified by applying different coupled models and meteorological information in order to identify the dust episodes, independently of their intensity (Pey et al., 2013). The following models analyse dust concentrations and air mass movements in the area of the Iberian Peninsula-North Africa: (1) the daily interpretation of the back-trajectories computed by the HYSPLIT model (Hybrid Single-Particle Langrangian Integrated Trajectory, http://ready.arl.noaa.gov/HYSPLIT.php) developed by the NOAA's Air Resources Laboratory (ARL) (Stein et al., 2015); (2) various aerosol forecast maps showing dust estimation using remote sensing data such as the NAAPS-NRL model (http://www.nrlmry.navy.mil/aerosol/), the SKIRON dust model (http://forecast.uoa.gr/dustindx.php), BSC-DREAM8b (http://www.bsc.es/ess/bsc-dust-daily-forecast) and the NMMB-BSC-dust model (https://dust.aemet.es/forecast/nmmb-bsc-dust-forecast-sconc); (3) the selected background air quality stations at ground level that measure surface PM_{10}, as described above. Finally, synoptic conditions using NCEP/NCAR reanalysis (https://psl.noaa.gov/data/composites/hour/) are used to verify some specific unclear cases. These steps on the definition of dust episodes are followed by the Spanish government who provides official data of daily dust events, following the standardised procedure referenced above.

The intensity of the dust episodes was calculated based on a statistical procedure of the PM_{10} time series measured at ground level. The aim of this data processing was to discriminate local or regional dust amounts from the long-range dust transported from the Saharan-Sahel region. The daily local background PM_{10} concentrations were calculated as the 30 days moving the 40th percentile for PM_{10} levels, removing the days with Saharan-Sahel dust intrusion. The difference between this baseline level and the daily dust concentrations during the dust episodes was the amount of dust assumed by the long-range transport according to the methodology proposed by Escudero et al. (2007), which is an official method used in European regulations (Viana et al., 2010).

2.3. Analysis of air mass movements

A complete backward trajectory analysis was carried out during the dust episodes between February and October 2009–2019, in Talavera de la Reina, Toledo and Albacete (central Iberian Peninsula) and Lorca, Murcia and Cartagena (south-eastern Iberian Peninsula). The 3-hourly trajectories for each dust episode were calculated with the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT). The meteorological data from the database of the Global Data Analysis System was used at a spatial resolution of 1°. HYSPLIT trajectories were computed 48 h back in time for three specific heights: 500 m, 1000 m and 2000 m above ground level. A cluster analysis was performed of the backward trajectories for each site using the trajectories computed at lower levels (500 m) (Makra et al., 2010). The clustering method used to classify the air trajectories was Euclidean distance. A constant number of four clusters was calculated for each site to easily differentiate prevailing directions from the results of the clustering analysis. The 'splitr' (Iannone, 2020) and 'openair' (Carslaw and Ropkins, 2012) R packages implemented in R Software (R Core Team, 2020) were used to compute and analyse backward trajectories. The maximum geographic area covered by the clusters was calculated using a convex hull model by means of the 'convHull' functions from the 'dismo' R package (Hijmans et al., 2017).

2.4. Study of the influence of dust intrusions in pollen concentrations

First, the random matching of dust intrusion events and the main pollen concentrations was described by analysing the occurrence of both simultaneously. This was done by calculating and comparing the monthly frequency of intrusion episodes and monthly accumulated pollen values. This study focused on the most important pollen types from the ecological and allergological point of view and the most abundant pollen types in the air (Figure S4), so only the monthly values of Cupressaceae, *Platanus*, *Quercus*, *Olea*, Poaceae and Amaranthaceae were compared with the monthly incidence of dust episodes. Amaranthaceae pollen was only considered from August to year end, as two different pollen seasons were evidenced for this pollen type (Elvira-Rendueles et al., 2017). Total pollen amounts were also analysed.

Next, the likelihood of pollen peaks occurring concurrently with a dust intrusion was measured by the percentage of events when both circumstances occurred simultaneously (±1 day of lag time) during the main pollen seasons in the study period (2009–2019). The maximum pollen peak each year was considered. The percentage of days with Saharan-Sahel dust intrusions was calculated compared to the length of the pollen seasons in the study period to determine the frequency of dust episodes for each pollen station. The pollen season for total pollen was calculated using 70% of the pollen collected for each year, i.e. the start date was defined when 15% of the pollen was recorded and the end date when 85% of the pollen was recorded. This strict pollen definition ensured sufficient amounts of pollen for comparison, and avoided days with unrepresentative pollen levels. In the case of specific pollen types, the criterion for establishing the pollen season was increased to 90% of the pollen collected for each year in order to ensure a sufficient number of days for analysis and make it possible to evaluate the probability of both pollen peaks and dust intrusions coinciding.

Secondly, more specific analyses were carried out to assess the influence of the dust intrusion events on the airborne pollen concentrations and meteorological conditions. In these analyses, the average value of pollen concentrations during the dust episodes were compared with the averages for the days before (t-3, t-2 and t-1) and after (t+1, t+2 and t+3) the episodes. It is worth noting that dust episodes may last more than one day; hence if the episode lasted two days, t-1 corresponds to the average for the two previous days, and if the episode lasted three days, t-1 corresponds to the average for the three previous days, and so on. Figure S5 in Supplementary Material clarifies this procedure by means of a diagram. The results of this analysis are displayed in boxplots, which show the differences in pollen concentrations in the dust episodes occurring in the pollen seasons compared to the days before and after. Statistically paired comparisons were carried out after to check the variance of each time parameters with the other (ANOVA). These results were analysed considering all dust events in conjunction, or groups of dust events based on different prevailing wind patterns (cluster analysis of the air mass trajectories). The mean, maximum and minimum values were calculated and added to the boxplot (median and interquartile range). In addition, five random simulations were computed to ensure the clarity of the effect of dust episodes on pollen concentrations. In these random simulations, the same number of days characterized by dust events were randomly selected in the pollen seasons, and the mean pollen concentrations were calculated for these days and for the days before and after the episodes. This allowed the pattern observed to be compared with the random pattern as a control analysis. The same approach was applied to analyse the influence of dust episodes on temperature and atmospheric pressure, and to assess the effect on PM_{10} concentrations (Figure S6) by way of a control analysis to validate the method, since there is known to be a strong positive effect on PM_{10} levels (Pey et al., 2013; Querol et al., 2019). Daily PM_{10} concentrations registered in the station of San Pablo de los Montes (39° 32′N, 4° 21′W) were used in Toledo and the concentrations registered in the station of Viznar (37° 14′N, 3° 32′W) were used in Cartagena (more details in Table S2). In addition, the rate of change in pollen concentrations between episodes and days without intrusions (before and after) was related with the rate of change in meteorological conditions (temperature and atmospheric pressure).

2.5. Study of specific dust episodes

Several specific dust episodes were analysed in detail as study cases to gain a better understanding of the effect of the dust intrusion on pollen concentrations. Three study cases were analysed: the episode of 23rd-24th May 2010 for *Olea* pollen in Talavera, the episode of May 26, 2011 for Poaceae pollen in Toledo, and the episode of May 18, 2012 for *Quercus* pollen in Albacete. We analysed the variations in pollen concentrations and meteorological conditions (temperature, humidity and directions of the air masses) and the distribution of the pollen sources. The study of the changes in pollen concentrations and meteorological conditions follows the same procedure described above, based on the backward trajectory analysis for dust episodes and the days before and after. The distribution of sources was provided by: 1) Corine Land Cover 2018 for the distribution of olive groves (Copernicus Land Monitoring Service, 2020a); 2) Grassland 2018 for the distribution of grasslands (Copernicus Land Monitoring Service, 2020b); and 3) European Atlas of Forest Tree Species for the distribution of *Quercus* forests (De Rigo et al., 2016).

3. Results

The south-eastern area of the Iberian Peninsula showed a higher incidence of Saharan-Sahel dust intrusions (125 ± 20 days/year [average ± standard deviation]) compared to the eastern and central areas (85 ± 16 days/year and 76 ± 23 days/year, respectively) during the period 2009–2019. However, the seasonal pattern throughout the year was similar for all the areas studied (Fig. 1). In general, summer had the highest frequency of dust intrusions, winter had the lowest and spring and autumn showed intermediate values. Specifically, July and August had the highest incidence of these episodes for all areas.

In the case of the central and eastern Iberian Peninsula, April, May, June, July, September and October had at least five episodes per month; and less than five episodes per month occurred only in January, November and December in the southeast, frequently exceeding the value of ten episodes per month (April, May, June, July and August) (Fig. 1).

An intense gradient of total pollen amounts was observed from the central (Talavera, Toledo, Albacete) to the south-eastern (Lorca, Murcia, Cartagena) Iberian Peninsula (Fig. 2). While Talavera and Toledo in the central region had an average annual pollen amount (Annual Pollen Integral, APIn) of 85449 ± 26372 pollen grains/m^3 and 66884 ± 18487 pollen grains/m^3 respectively, Murcia and Cartagena in the south-eastern region had an APIn of 23806 ± 10088 pollen grains/m^3 and 26583 ± 4565 pollen grains/m^3 respectively. The pollen seasonality of the pollen stations was different, but the highest pollen concentrations for all stations were recorded from February to June (Fig. 2). Murcia and Cartagena had a second period in autumn (September–November) which was characterized by pollen concentrations with a daily level of as high as 500 pollen grains/m^3. This representative second pollen season was associated with the pollen emission of Amaranthaceae species, and *Casuarina* in the case of Murcia.

The main pollen types whose season coincided with the Saharan-Sahel dust intrusions were allergenic types such as *Olea* and Poaceae, which flower from May to June in the centre, and from April to June in the southeast of the Iberian Peninsula. Another abundant pollen type with ecological interest mainly in the centre is *Quercus*, which flowers from April to June. During the summer and early autumn in the

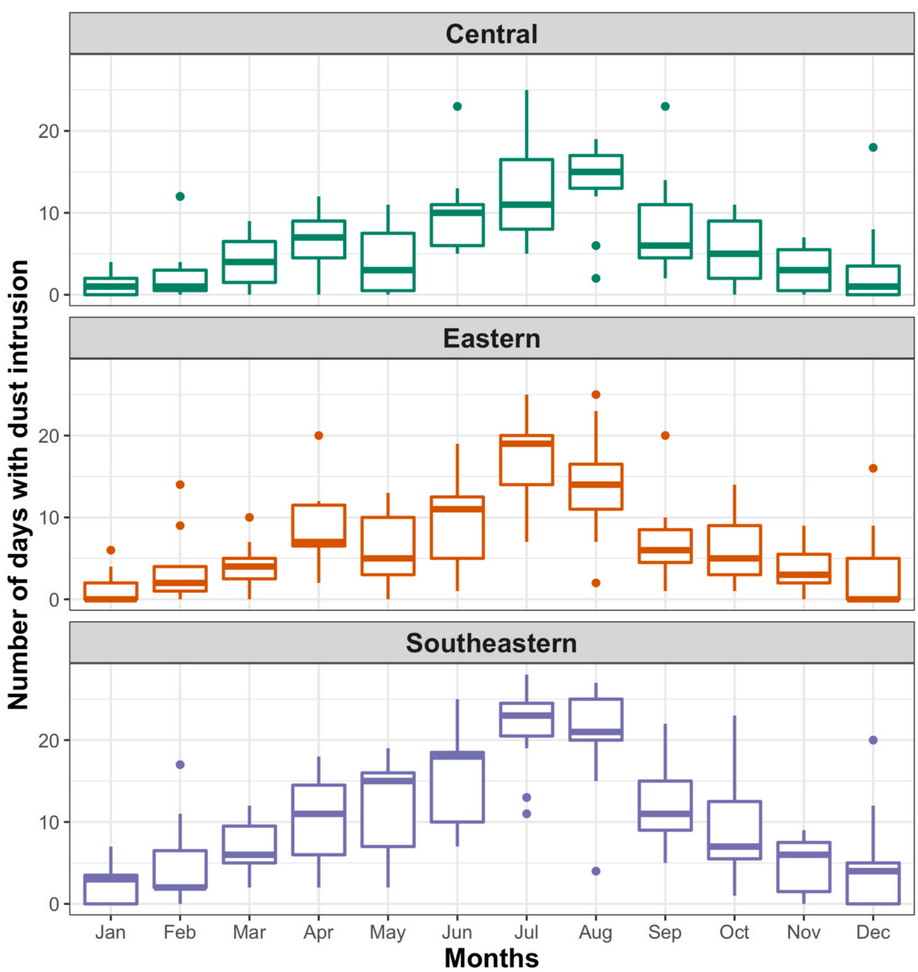

Fig. 1. Frequency of dust intrusion episodes (number of days per month) in areas of the centre, east and southeast of the Iberian Peninsula during the period 2009–2019.

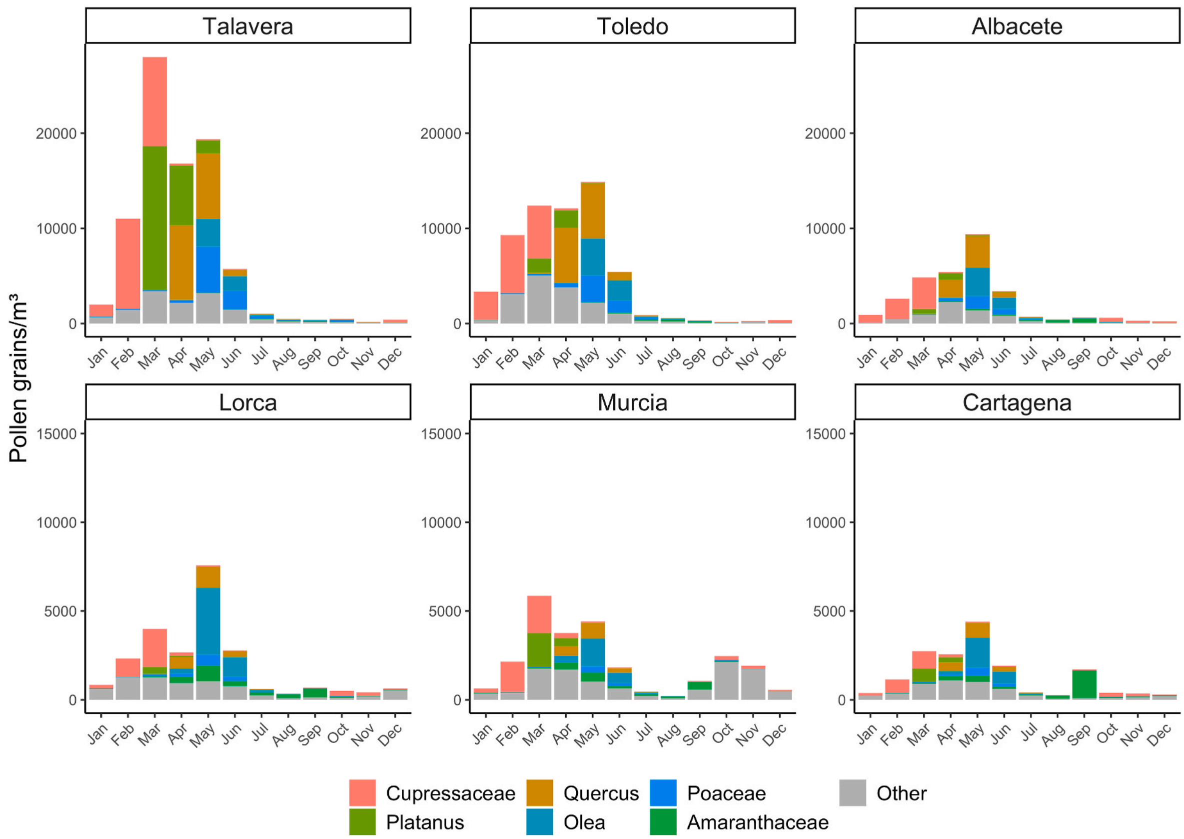

Fig. 2. Average monthly pollen amounts during the period 2009–2019 in Talavera, Toledo, Albacete (central Iberian Peninsula) and Lorca, Murcia, Cartagena (south-eastern Iberian Peninsula). It should be noted that the scale of the y-axis is different for the stations in both central and south-eastern regions (x2 in central areas).

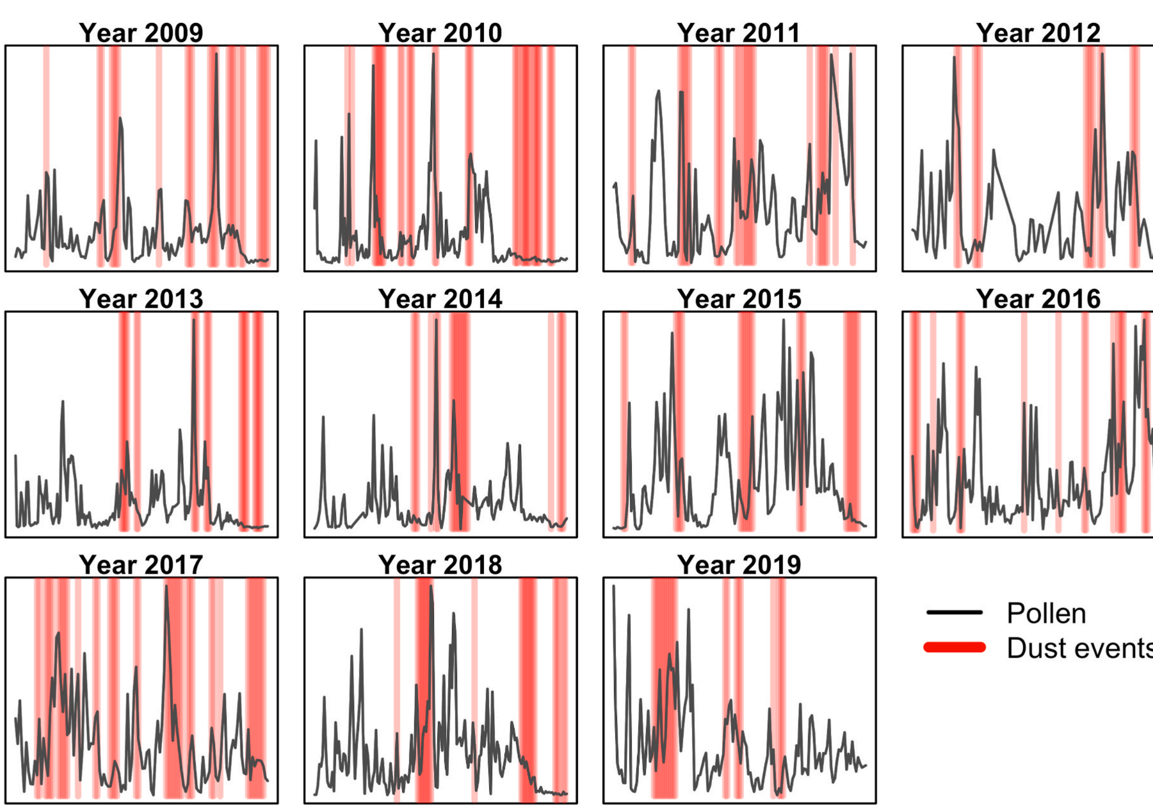

Fig. 3. Match between total pollen peaks and dust episodes in the pollen seasons in Toledo during the period 2009–2019.

southeast, Amaranthaceae pollen attained significant levels which coincided with dust intrusions in August and September (Fig. 2). Cupressaceae and *Platanus* pollen types from ornamental plants in cities were present in the atmosphere mainly during the period from January to March, coinciding with the lowest incidence of dust intrusions, except in Talavera where *Platanus* also reached high pollen amounts in April. Fig. 3 shows an analysis of the likelihood of the maximum total pollen peak and the dust episodes matching in time, as evidence of this phenomenon was observed for several pollen types in specific locations (Supplementary Material, Figures S7-S8).

Fig. 4 shows the degree of matching between maximum pollen peaks and dust episodes for several pollen types (Fig. 4A), and the incidence of dust episodes during their pollen seasons (Fig. 4B). In the centre, the maximum total pollen peak in the year with high probability occurred during a dust intrusion episode (mainly in Toledo, in 82% of the years), although the incidence of intrusions in this area during the total pollen season is very low (17% of the days of the season in the central Iberian Peninsula) (Fig. 4). Conversely, dust intrusions occurred in the south-eastern Iberian Peninsula on around 45% of the days in the total pollen season, while in Murcia and Cartagena the peak date matched the dust episodes in only 27% and 45% of the years respectively for the period 2009–2019.

A detailed study was carried out of the air mass movements during all dust episodes from February to October for the period 2009–2019. Fig. 5 shows the results of the cluster analysis of all wind trajectories for the cities of Talavera and Toledo (central area) and Cartagena and Murcia (south-eastern area) (the analysis for all stations studied may be consulted in Supplementary Material, Figure S9). Most of the air movements in the central area came from the east, west and southwest during dust episodes (26–28%, 34–36% and 24–26% of the trajectories respectively). In the southeast, the easterly wind direction was predominant (44%), while winds from the west and northeast represented 26% and 18–22% respectively. Another minority group was characterized by lower turbulent movements from the east.

Winds from different directions (represented by the clusters) had a different degree of influence on the dust intrusions in terms of total pollen concentrations (Fig. 6). In Toledo (central Iberian Peninsula), a clear increase in total pollen concentrations was observed during the periods of dust intrusion characterized by prevailing winds from the west, southwest and south (C2, C3 and C4) compared to the days before

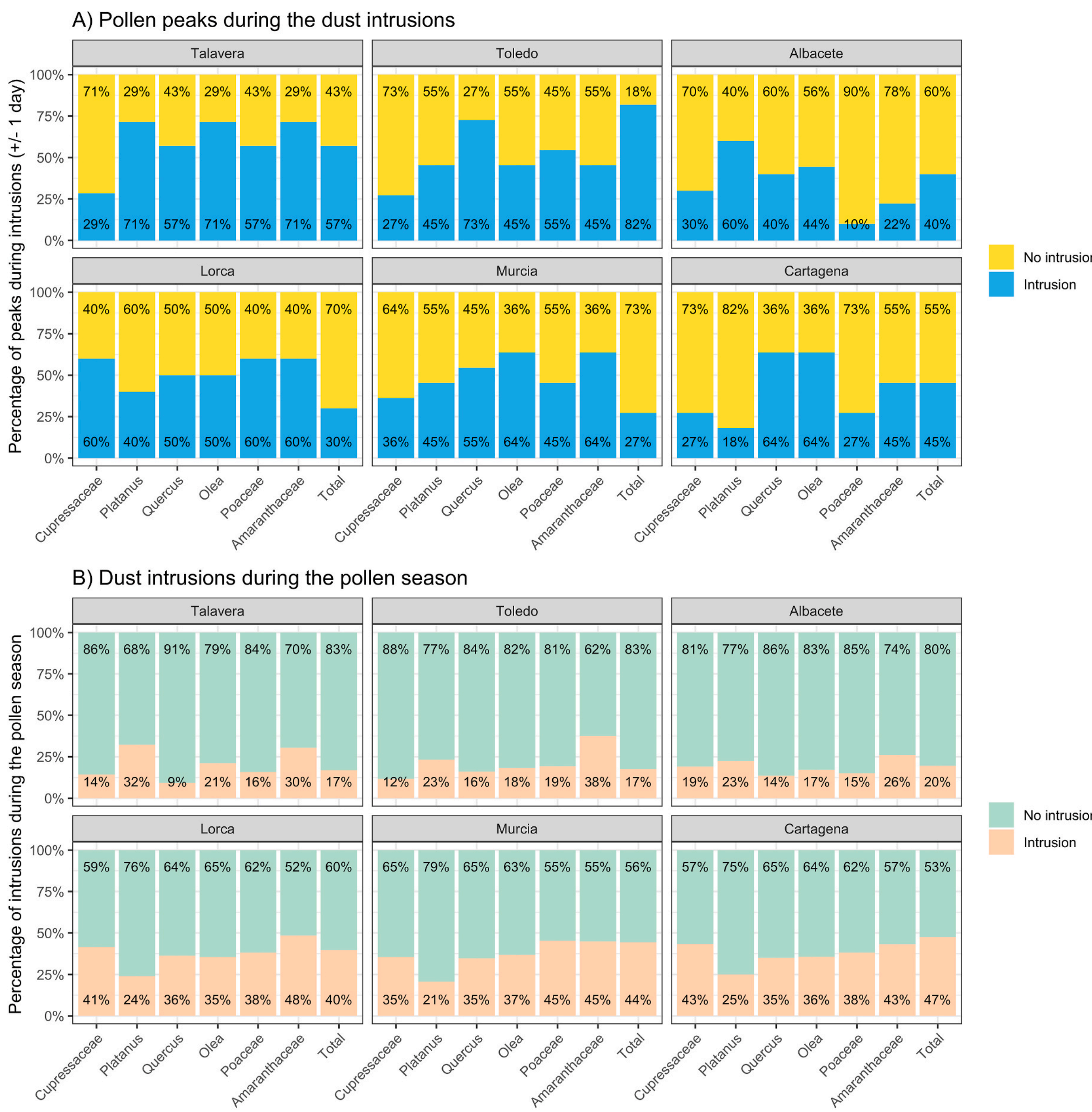

Fig. 4. Numerical comparison of the match between pollen peaks and dust episodes (A), and proportion of days with dust episodes during pollen seasons (B).

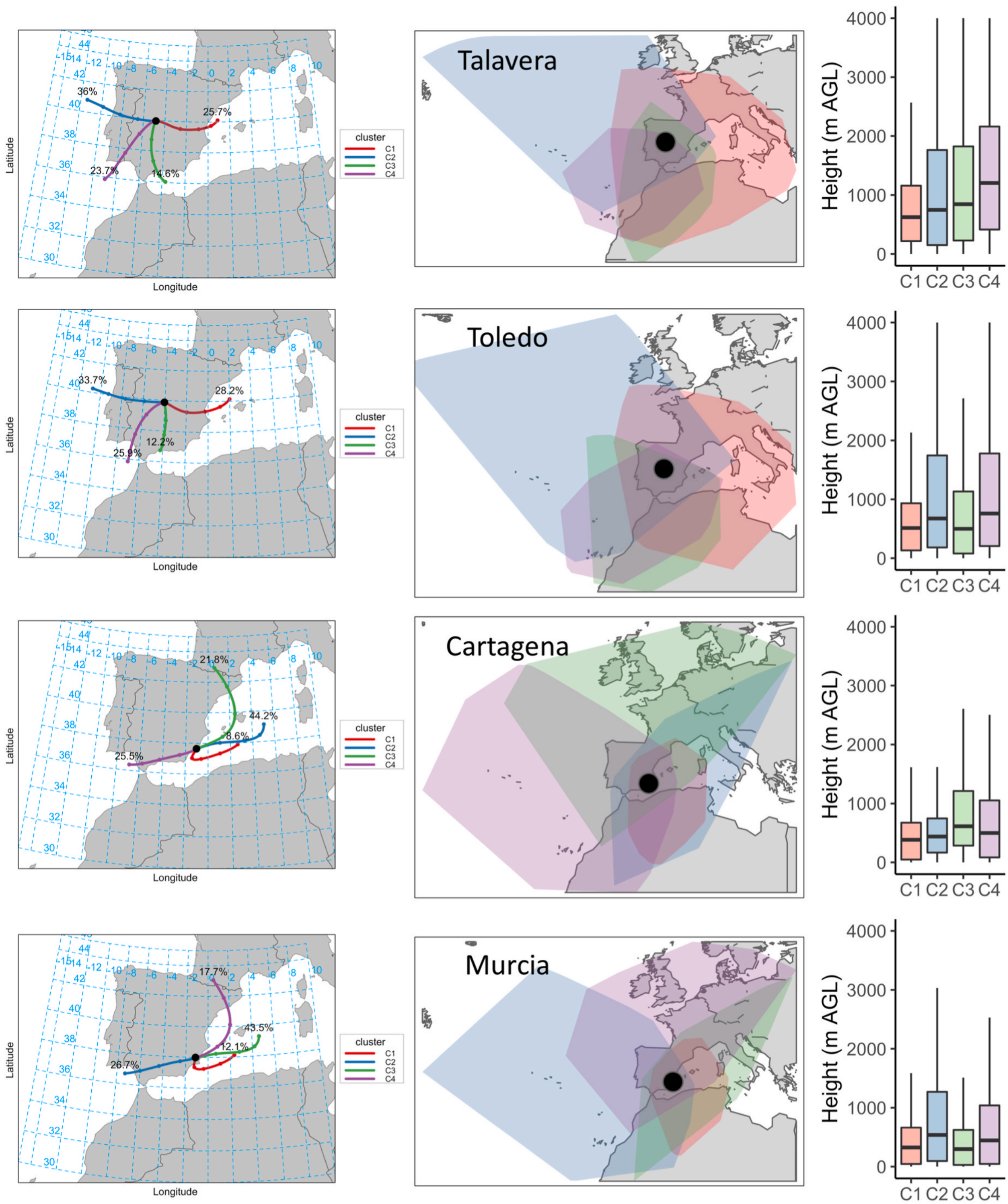

Fig. 5. Cluster analysis of the 3 h-backward trajectories towards the central (Toledo and Talavera) and south-eastern (Cartagena and Murcia) areas of the Iberian Peninsula during the dust intrusion events for the period 2009–2019 (only episodes from February to October were considered). Frequency of the trajectories (right), maximum geographic area covered (middle) and height of the trajectories (left) for each cluster.

and after. However, no significant effects were observed on pollen concentrations in dust episodes with prevailing easterly winds (C1). In contrast, westerly or northerly winds (C3 and C4) had no significant effects on total pollen concentration in Cartagena (south-eastern Iberian Peninsula), where dust episodes had even significantly negative effects on pollen concentrations when the prevailing winds came from the sea, i.e. prevailing easterly winds (C1 and C2) (Fig. 6). When several pollen types are analysed in detail, a significant effect of dust episodes was observed in *Olea*, Poaceae and *Quercus* pollen in the central Iberian Peninsula, although this influence was not evident in south-eastern areas (e.g. no changes in Amaranthaceae pollen are shown for dust episodes and for the days before and after episodes in Cartagena, Fig. 7). Therefore, dust intrusions were observed to have a significant effect on pollen concentrations when all episodes were considered together; however, there are interesting discrepancies when the results are analysed in terms of different prevailing wind patterns. In central Iberian Peninsula, *Olea* and *Quercus* pollen showed a greater increase when dust intrusions coincided with westerly and south-westerly winds (C2, C3 and C4). Although the effect is less apparent, Poaceae pollen increased when dust intrusions came from western areas (C2). Easterly prevailing

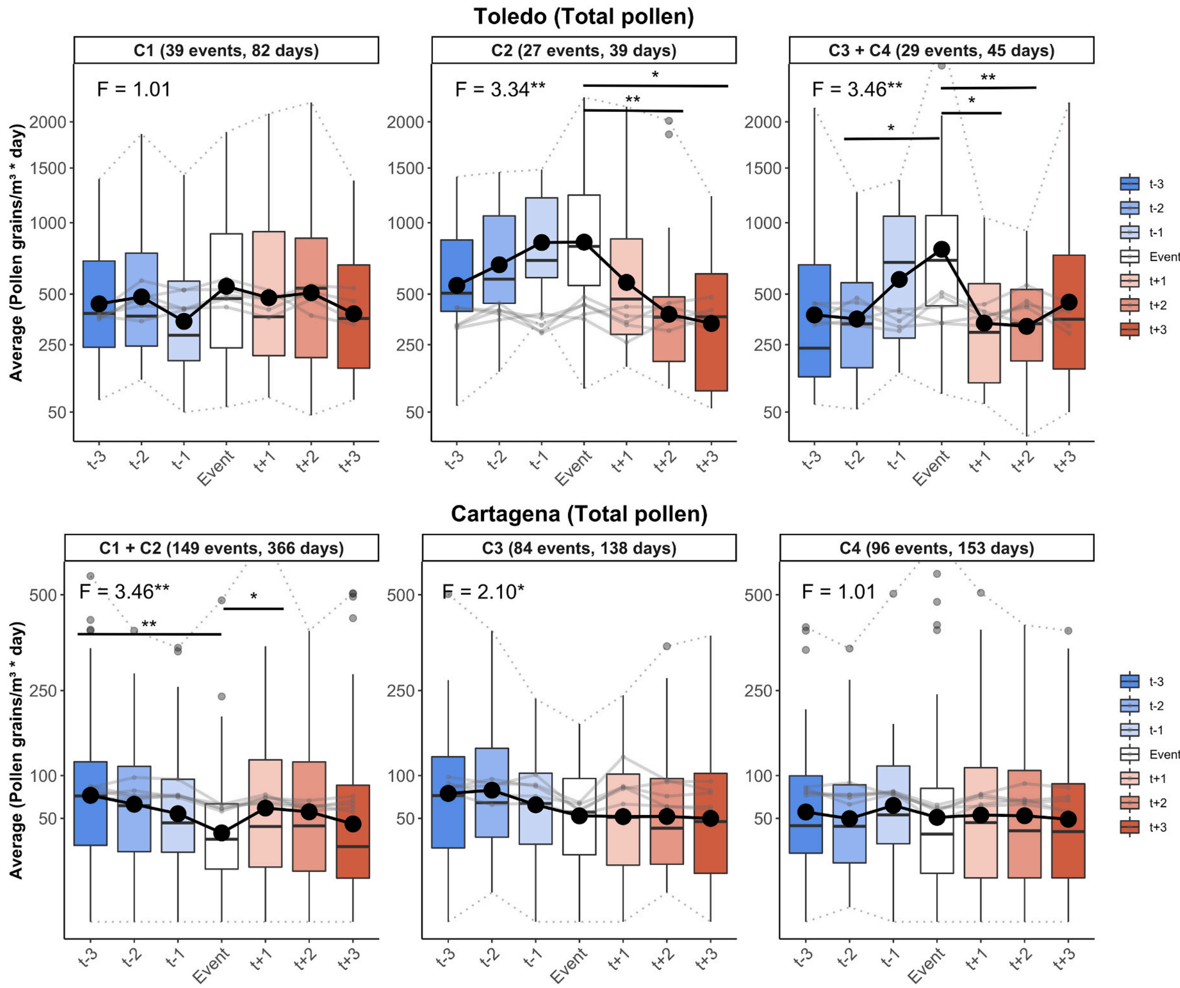

Fig. 6. Influence of dust episodes on pollen concentrations out of total pollen. Legend of figure components. Boxplot, median and interquartile range for the observed values: black dots and lines, mean for the observed values; dashed grey lines, maximum and minimum for the observed values; grey dots and lines, mean for random simulations (5 times). F: Statistic of the ANOVA test (level of significance: *p < 0.05; **p < 0.01; ***p < 0.001).

winds during dust episodes (C1) had the least influence on pollen concentrations for all pollen types, in accordance with the results for total pollen (Fig. 7).

Not only changes in wind directions were observed during dust episodes. These events also triggered significant changes in other meteorological variables such as temperature, humidity and atmospheric pressure (Figs. 8 and 9). Specifically, dust episodes coincided with a rise in temperature compared to the days before and after. Atmospheric pressure had the opposite effect, and a drop in pressure was observed during and after the occurrence of a dust intrusion. A significant relationship was also found between these meteorological changes and variations in total pollen concentrations, with a positive relationship in the case of temperature and negative in the case of atmospheric pressure (Fig. 8) (the analysis for Toledo and Cartagena can be seen in Supplementary Material, Figure S10).

Finally, several specific examples are analysed in detail to gain a better understanding of how dust episodes affect pollen concentrations for several pollen types (episode of 23rd-24th May 2010 for *Olea* pollen in Talavera, episode May 26, 2011 in Poaceae pollen in Toledo and episode May 18, 2012 in *Quercus* pollen in Albacete) (Fig. 9). In the first event (Talavera 23rd-24th May 2010), an increase in pollen concentrations of 321 and 564 pollen grains/m^3 was observed during the days of dust intrusion on 23rd and 24th May respectively compared to the preceding days. During this episode, the prevailing wind patterns underwent a profound change to a south-westerly direction, and the air mass temperature rose compared to the days before and after the intrusions. It was also notable that the pollen concentrations and air mass temperature declined sharply during the two days after the dust intrusion, despite the similar prevailing wind directions (Fig. 9). *Quercus* pollen concentrations revealed a similar behaviour during the second event analysed (Albacete May 18, 2012), when pollen levels increased in 254 pollen grains/m^3, the wind direction changed to prevailing south-westerly winds, and the temperature began to rise. In the case of Poaceae pollen (episode of May 26, 2011 in Toledo), an increase of 90 pollen grains/m^3 was registered during this episode compared to the previous day, and a sharp decline of 197 pollen grains/m^3 occurred when the intrusion ended. In this case, the meteorological variable that changed most significantly was the humidity of the air masses, which increased in the days after the dust intrusions. During the dust episode the prevailing wind direction changed to south-westerly, from areas with more extensive grassland cover (Fig. 9).

4. Discussion

In this study two very different areas of the Iberian Mediterranean region were analysed from the point of view of the airborne pollen load. A strong gradient in pollen amounts can be seen on an axis from the centre to the southeast of the Iberian Peninsula: from central Spain, with an average annual total pollen count of around 65000-85000 pollen grains/m^3 in the station of Talavera and Toledo, to south-eastern Spain where an average annual total pollen amount of some 25000 pollen grains/m^3 was recorded in Murcia and Cartagena. There were highly

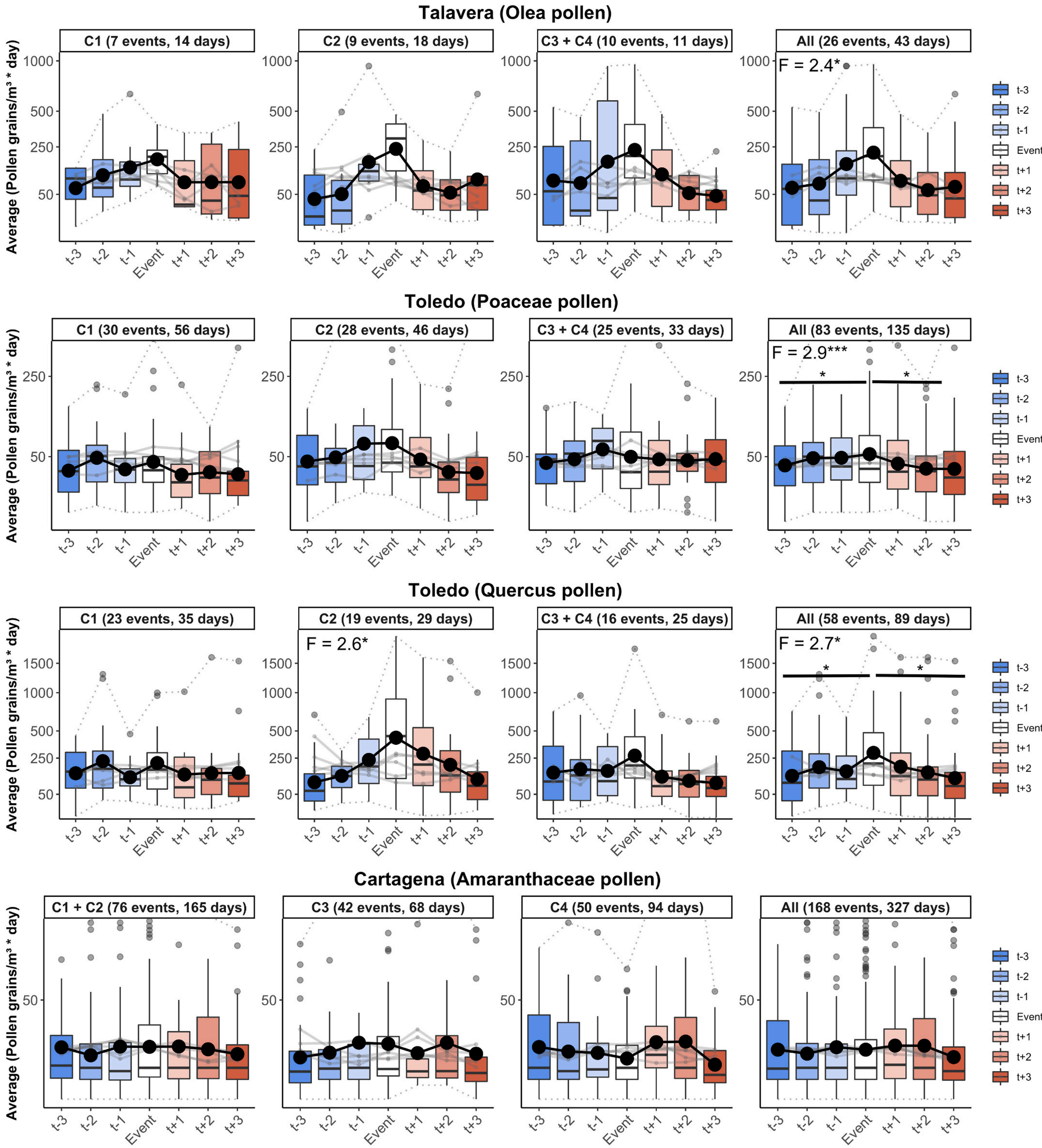

Fig. 7. Influence of dust episodes on pollen concentrations for the various pollen types (*Olea*, Poaceae, *Quercus* and Amaranthaceae). Legend of figure components. Boxplot, median and interquartile range for the observed values; black dots and lines, mean for the observed values; dashed grey lines, maximum and minimum for the observed values; grey dots and lines, mean for random simulations (5 times). F: Statistic of the ANOVA test (level of significance: *p < 0.05; **p < 0.01; ***p < 0.001).

significant differences in the most prevalent pollen types in the atmosphere and in the dynamic of the pollen seasons for specific pollen types (Elvira-Rendueles et al., 2019; Pérez-Badia et al., 2010). These dissimilar pollen patterns are explained by clear and important bioclimatic and biogeographic differences which provoke a distinct spatial configuration of the vegetation in the surroundings, as well as different land-use distribution and dominant patterns of ornamental plants in human-managed environments (Alcaraz, 2017; Fernández-González et al., 2017).

However, it was not only the local contribution that differed widely

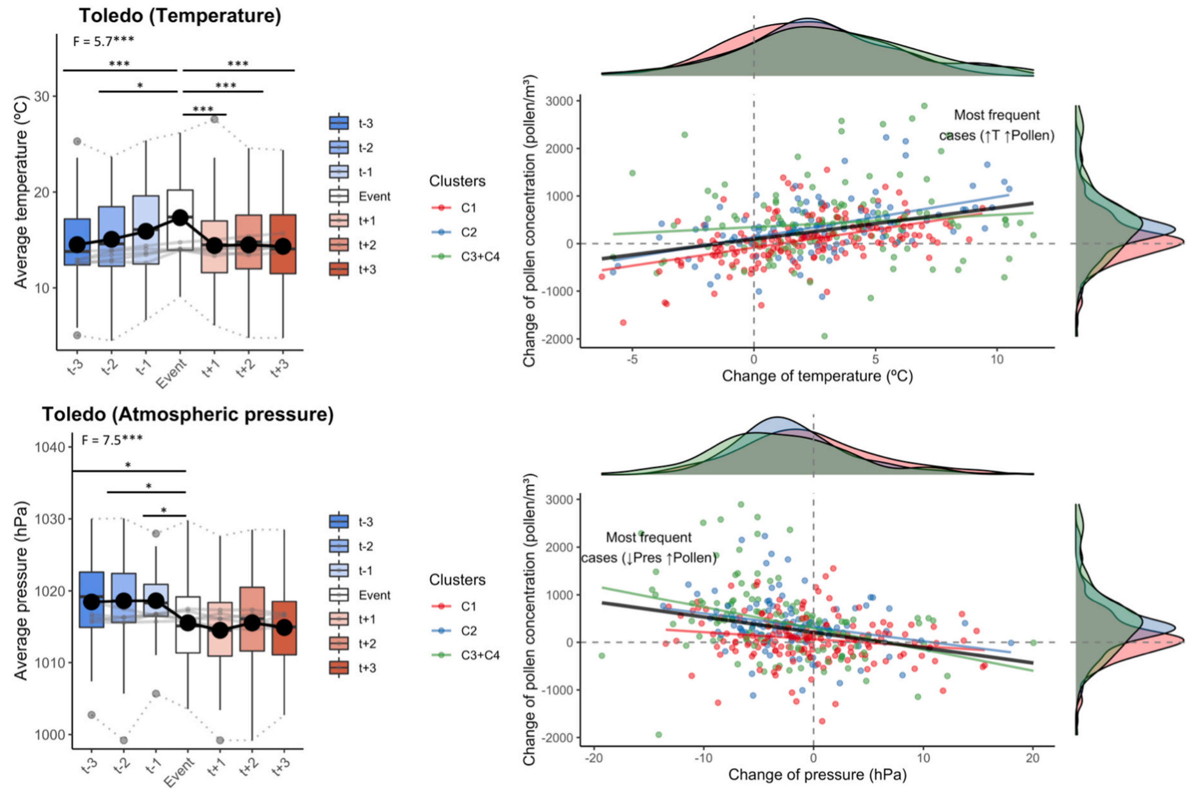

Fig. 8. Influence of dust episodes on temperature and atmospheric pressure (boxplot) and effects of changes in meteorological conditions on pollen concentrations (scatterplot). Legend of boxplot graph components. Boxplot, median and interquartile range for the observed values; black dots and lines, mean for the observed values; dashed grey lines, maximum and minimum for the observed values; grey dots and lines, mean for random simulations (5 times). Density plots in the margins represent well the frequency of the values in the three categories to compare them based on the factors in the axes (temperature, pressure or pollen concentration). F: Statistic of the ANOVA test (level of significance: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$).

in both areas; the patterns of medium and long-range pollen transport also show diverse sources of pollen contribution during specific atmospheric events. Specifically, this work analysed the potential pollen transport triggered by dust intrusion episodes from the desertic Saharan-Sahel regions, which frequently affect the Iberian Peninsula (Russo et al., 2020). There was also a very different incidence of dust intrusion episodes over central and south-eastern areas due to their geographic location (Querol et al., 2019). While Cartagena, on the south-eastern coast of Spain, is about 200 km from the African coast and separated only by the Mediterranean Sea, the central Iberian Peninsula is hundreds of kilometres inside the continental territory. As a result, the frequency of Saharan-Sahel dust intrusions in the southeast was much higher than in the central Iberian Peninsula (on average 125 days/year of intrusion in south-eastern and 76 days/year in central areas).

The pattern of prevailing air mass movements during the dust intrusion episodes in the southeast showed mainly low easterly and south-easterly winds coming from the Mediterranean Sea (about 55% of the 3-hourly trajectories calculated during episodes). According to our results, the wind directions in the central areas are almost evenly distributed between the west, east and south.

This work contains an analysis of the potential effects of dust intrusions on increased pollen exposure. Dust episodes were found to have a significant influence on airborne pollen concentrations in the central Iberian Peninsula, although they had an unclear or even the opposite effect in south-eastern areas. We studied the coincidence between high pollen concentrations in the air and Saharan-Sahel dust episodes. Previous studies have highlighted the concomitant occurrence of bioaerosols in the atmosphere during long-range air mass movements from the African deserts (Grewling et al., 2019; Oduber et al., 2019).

Dust episodes obviously occur the whole year round, so it is difficult to obtain a direct correspondence between pollen levels and dust intrusions. Also, it is difficult to find a positive correlation between PM_{10} and airborne pollen concentrations due to the very different nature (size of particles and sources) and strongly different magnitudes of presence in the air. However, pollen peaks often coincide with dust episodes during the pollen season in the central Iberian Peninsula. In fact, the maximum peaks of total pollen, or of pollen from specific taxa such as *Olea*, *Quercus*, Amaranthaceae and *Platanus*, had a high probability of coinciding with dust intrusions (>70% of years), and even more so when the number of days with dust intrusion accounted for only about 20% of the whole pollen season in this area. It is particularly worth noting the case of total pollen in Toledo, when the maximum peaks coincided with dust intrusions in 82% of the years, although these intrusions only occurred on average during 17% of the days in the whole pollen season. This pattern was not as evident in the southeast, where a higher incidence of episodes makes this phenomenon difficult to observe. In this area, although pollen peaks for Cupressaceae, *Olea*, *Quercus* and Amaranthaceae matched dust episodes in about 60% of the years, the probability of a random coincidence is higher, as dust episodes occurred in most cases on 40–50% of the days in the pollen season.

The direct effect of dust episodes on pollen concentrations is clear in inland Iberian areas, although this was not the case in coastal areas in the southeast, where pollen concentrations could even be seen to decrease when easterly winds from the sea prevailed during dust intrusions. In addition to the proximity to the sea instead of the pollen sources in these coastal areas, the settling rate of pollen grains could be favoured by the effect of hydration during the maritime path (Bunderson and Levetin, 2015). According to our results, there may be several causes for the high pollen contribution in continental areas: air masses could transport pollen during dust intrusions, and synoptic atmospheric conditions could favour the optimal meteorological conditions that allow large quantities of pollen to be emitted into the atmosphere. Both

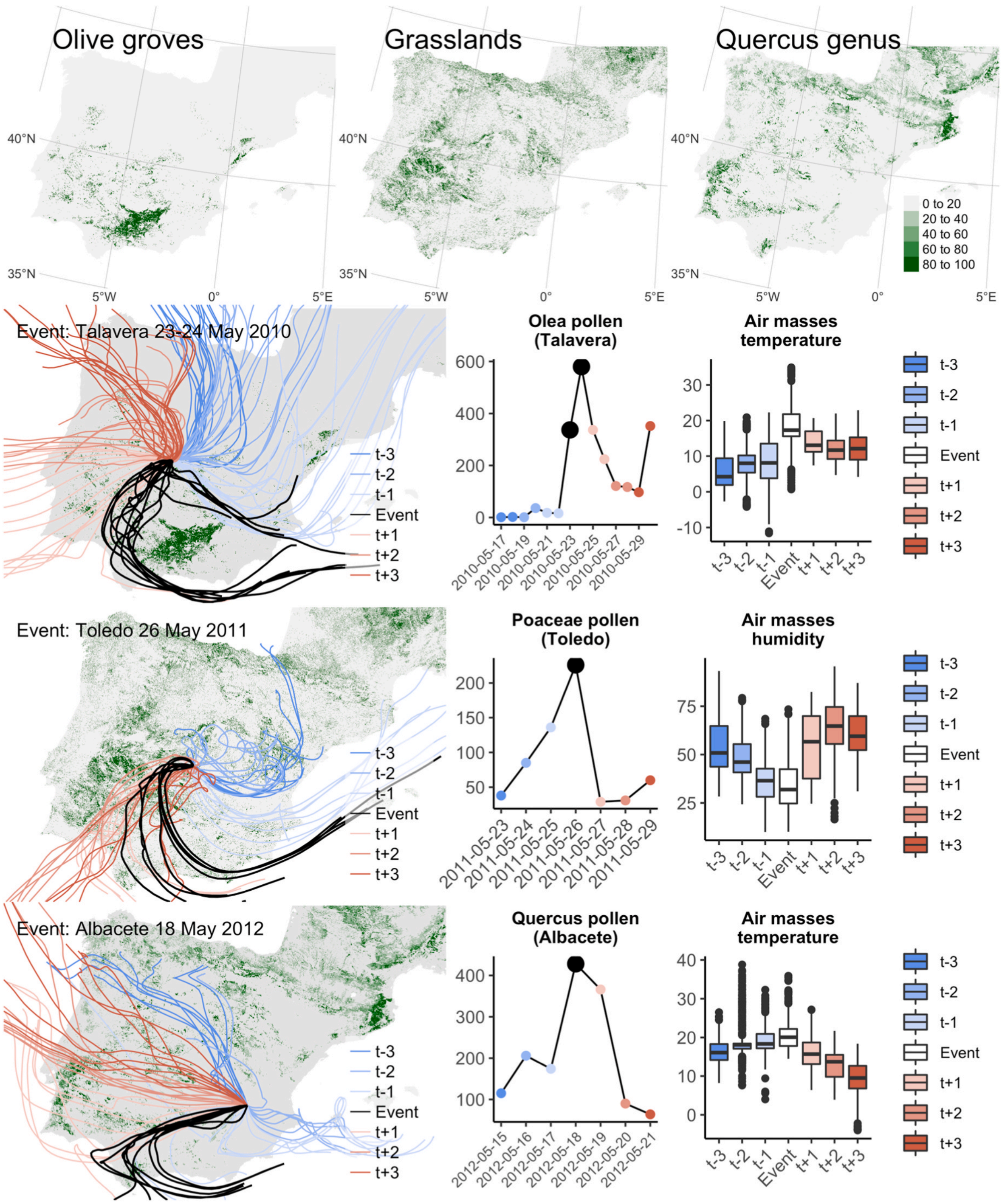

Fig. 9. Specific dust episodes as study cases. Three study cases are analysed: episode on 23rd-24th May 2010 for *Olea* pollen in Talavera; episode on May 26, 2011 for Poaceae pollen in Toledo; and episode on May 18, 2012 for *Quercus* pollen in Albacete. The figure shows the air mass trajectories (left), change in pollen concentrations (middle) and change in temperature and humidity of the air masses (right) during the episode and on the days before and after.

hypotheses will be discussed below in view of the results of this study.

Total pollen concentrations and specific pollen types such as *Olea*, Poaceae and *Quercus* showed an increase in the central Iberian Peninsula during dust episodes compared to the days before and after these events. However, this positive relationship was not observed with the same intensity for all prevailing wind directions. Westerly and south-westerly winds triggered higher pollen contributions, since air masses crossed areas of the Iberian Peninsula with extensive vegetation cover, comprising the main wind-pollinated species such as olive, forests of *Quercus* species and grasslands (Copernicus Land Monitoring Service, 2020b; De Rigo et al., 2016; Fernández-Rodríguez et al., 2014; Rojo and Pérez-Badia, 2015). Although air mass movements during dust episodes transported pollen over a medium or short distance when prevailing winds crossed large source areas, no long-range transport of significant pollen was found to be responsible for the higher amounts of pollen during these events. In fact, this long-range transport of large amounts of pollen seems unlikely, as no positive effects on pollen concentrations were detected in the southeast during dust episodes. In addition, there was a decline in pollen concentrations when prevailing winds came from the Mediterranean Sea, supporting the hypothesis that air masses become loaded with pollen during their passage across inland areas of the Iberian Peninsula.

We do not totally reject the idea of long-range transport of pollen by dust intrusions; in fact, previous research reported transport at the intercontinental scale (García-Mozo et al., 2017; Izquierdo et al., 2011; Šikoparija, 2020), and long-range transport may be significant for specific bioaerosols (Grewling et al., 2019; Makra et al., 2010; Moreno-Grau et al., 2016). However, based on the results, we believe that the proportion of long-range transport is lower than transport over medium and short distances in the central Iberian Peninsula (Rojo et al., 2016). Also, inorganic pollutants were regionally and locally more abundant during dust episodes on the Peninsula (Querol et al., 2019). Nevertheless, small amounts of pollen could be transported over long distances during dust intrusions into southern European areas (Cariñanos et al., 2004; Oduber et al., 2019). Only long-range transport could be efficiently evaluated using the sporadic occurrence of pollen indicators from vegetation types that are abundant in remote areas (Cabezudo et al., 1997; Mohanty et al., 2017), or from outside their typical flowering period in the local area (Oduber et al., 2019). In this manner, a more attention towards the source regions and the concomitant transport with mineral dust produced in the source areas should be paid in future researches.

However, wind direction is not the only factor affecting pollen contributions during dust episodes, as in some cases, pollen concentrations decreased dramatically after the termination of the event, even when the wind remained in the same direction days later. Saharan-Sahel dust events were related to a rise in temperature, and hence to lower humidity and a drop in atmospheric pressure. These meteorological variations can be explained by specific synoptic conditions associated with Saharan-Sahel dust intrusions and are linearly correlated with an increase in airborne pollen concentrations. The same relationship was documented for inorganic and for biological pollutants in central areas of Spain (Salvador et al., 2019), revealing a co-occurrence of biological and chemical pollutants during dust intrusions (Grewling et al., 2019). The analysis of specific dust episodes demonstrated that air masses arriving in the central region were warmer and drier during the Saharan-Sahel dust intrusions, since North African air masses cause warm air advection in higher latitudes of the Mediterranean region (Varga, 2020). At the global scale, the high volume of particulate matter in the atmosphere associated with dust episodes has the opposite effect, due to the direct albedo of solar radiation, i.e. a net negative radiative forcing that could only partially offset the long-term warming of the planet (Bellouin et al., 2020). However, although the temperature balance produced by dust intrusions is highly uncertain (Yoshioka et al., 2019), an increase in temperature on the regional scale was associated with Saharan-Sahel dust intrusions in areas of the Iberian Peninsula (Salvador et al., 2019).

Our results therefore support the hypothesis that not only dust intrusions favour pollen transport over medium and short distances, since the prevailing wind pathways are from southern areas, but also the prevalent synoptic conditions during dust episodes also trigger weather shifts to warmer and drier conditions (Russo et al., 2020; Salvador et al., 2019) which allow more pollen release and dispersal in the area when the plants are primed for anther dehiscence (Cresti and Linskens, 2000; Rojo et al., 2015). All these meteorological phenomena in combination (prevailing winds from pollen sources and warmer and drier conditions) represent an optimal environment for promoting pollen emission into the atmosphere, causing airborne pollen concentrations to increase in the central Iberian Peninsula. Temperature and atmospheric pressure also vary during dust episodes in south-eastern areas, although no changes were evident in pollen concentrations, perhaps due to the large number of episodes during the pollen season. A more detailed analysis of Saharan dust episodes in the southeast is required to determine the effects of various synoptic atmospheric conditions on the pollen spectrum in this Iberian region (Negral et al., 2012).

5. Conclusions

This study offers a comprehensive analysis of the causes triggering an increase in pollen concentrations during Saharan-Sahel dust intrusions in inland areas of the Iberian Peninsula. Certain phenomena of high pollen exposure were observed in previous works, but no research had been done on this topic in central and south-eastern areas of the Iberian Peninsula. Our study therefore fills an important gap in the knowledge of the effects of dust intrusions on airborne pollen concentrations in the Iberian Mediterranean region. We found an increase in concentrations of total pollen and of several specific pollen types in the atmosphere during dust episodes when the prevailing winds came from large areas of the main wind-pollinated pollen sources at the medium or short scale, and in the optimal meteorological conditions that favour pollen release and dispersal into the atmosphere. Both these conditions often occur during Saharan-Sahel dust intrusions in the centre of the Iberian Peninsula, although this behaviour was not found for pollen levels in the southeast. Actually, other specific analyses could be conducted in the southeast, since this area has a very different pattern of incidence of dust intrusions, and the air mass movements also follow very different pathways during these episodes. According to our findings, the long-range transport would not be the main cause of increased pollen exposure in the Iberian Peninsula during Saharan-Sahel dust intrusions. The negative effects of mineral dust on public health are well known, and even more so when the allergenic biological agents are co-transported by air mass movements from desert areas. The findings of this study have very important implications for defining health-emergency alerts for severe Saharan-Sahel dust episodes.

Credit author statement

Jesús Rojo: Conceptualization; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing – original draft; Writing – review & editing. José María Moreno: Funding acquisition; Investigation; Resources; Supervision; Writing – review & editing. Jorge Romero-Morte: Data curation; Formal analysis; Methodology; Resources. Beatriz Lara: Data curation; Formal analysis; Methodology; Resources; Visualization. Belén Elvira-Rendueles: Data curation; Investigation; Methodology; Resources; Validation. Luis Negral: Data curation; Methodology. Federico Fernández-González: Formal analysis; Funding acquisition; Project administration; Resources. Stella Moreno-Grau: Funding acquisition; Project administration; Resources; Supervision; Writing – review & editing. Rosa Pérez-Badia: Conceptualization; Funding acquisition; Project administration; Resources; Supervision; Writing – review & editing.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2021.117441.

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