ASSESSING POLLEN EXTREME EVENTS OVER A MEDITERRANEAN SITE: ROLE OF LOCAL SURFACE METEOROLOGY

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Abstract

The presence of very high pollen levels in the atmosphere is associated with a strong impact on health and a worsening of symptoms in people who already have a respiratory disease. However, there is no specification on the aerobiological, environmental and meteorological factors that allow for characterizing a pollen event as of great magnitude due to the significant impact it can cause on the population and the environment. This work proposes criteria to typify the levels of atmospheric pollen as an extreme pollen event (EPE), and aims to determine the meteorological variables that can affect the presence and permanence of high pollen concentrations over a period of time. To address this goal, the quasi-climatological pollen dataset recorded in Granada (Southeastern Spain) during the period 1992-2019, has been used. On the daily accumulated pollen concentrations, the 95th, 97th and 99th percentiles were calculated. Spearman's correlation between the pollen concentration exceeding the proposed thresholds ($C_{\geq P95}$, $C_{\geq P97}$, $C_{\geq P99}$) and surface meteorological variables recorded during up to five days before the event were established in order to identify the meteorological conditions that might affect the EPEs. As for the number of days with values higher than the established percentiles, it has been seen that in the case of total pollen and *Olea*, Cupressaceae and *Pinus*, there is a robust monotonically ascending trend throughout the study period. Regarding meteorological variables, relative humidity and 24-h accumulated precipitation are shown as the two most influential variables up to three days before the event, although temperatures, visibility and wind direction also show a correlation with some pollen types. The criteria proposed in this work allow us for classifying high levels of pollen as an EPE, and lay the foundations of these extreme events in a context of climate change in which they will become more frequent.

Keywords: pollen, extreme pollen events (EPE), climate change, surface meteorology

1. INTRODUCTION

Atmospheric pollen is associated with the development of adverse respiratory reactions in the population (Gaig et al., 2014; Zhang et al., 2015). These reactions occur when a certain concentration of pollen grains are suspended in the fraction of breathable air, enough for sensitized patients to have symptoms (de Werger et al., 2013). However, the lack of a standardized criterion when defining the pollen levels from which respiratory symptoms develop has generated disparity in the establishment of an allergic response threshold. On some occasions, this threshold value is established according to the group of patients who initiate symptoms, considering those who are more sensitive (Viander and Koivikko, 1978), or when the percentage of symptomatic patients is the majority (Jäger, 1998). In many cases, risk categories according to the presence of pollen in the air of certain place have been established from the pollen concentrations recorded with a Hirst-type volumetric sampler for a long time enough to assess the impact on local people (Thibaudon, 2003, Rapiejko et al., 2007, Camacho et al., 2008). Where there seems to be a greater consensus is that under high or very high pollen concentrations in the air, the allergic response in sensitive patients is very intense. This reaction is further exacerbated by the presence of particular meteorological conditions or atmospheric pollutants, with which adjuvant reactions can be established (Sénechal et al., 2015; Oduber et al., 2019; Sauliene et al., 2019; Cariñanos et al., 2021). This is even more relevant given the evidence of rising trends of annual sums of daily concentrations of pollen observed in many places in relation to increasing temperatures and high CO_2 concentrations (Levetin, 2001; Ziska and Caulfield, 2000; Teranishi et al., 2000; Ziska et al., 2019). In particular, the Iberian Peninsula is likely to undergo an increase in maximum temperature throughout the year as forecasted by the climate-change projections at the end of this century (e.g. García-Valdecasas et al., 2020). Recent data also confirm a greater intensity of the allergic response in people already sensitized and an increase in the coming years in the percentage of people affected by respiratory diseases related to the presence of allergenic pollen in the atmosphere (Pawankar, 2014; Schmidth, 2016; Lake et al., 2017).

One of the main health impacts that the presence in the atmosphere of very high levels of pollen can have is the worsening of the symptoms of people who already have a previous respiratory pathology (Goodman et al., 2017; D´Amato et al., 2020). Some studies show that exposure to extreme pollen values, such as those that usually occur during olive tree flowering in southern Europe, can cause minor allergens in pollen exine to become major allergens, generating an even more severe reaction in the population (Barber et al., 2007). For asthma sufferers, periods of very high pollen concentrations become critical periods, considerably increasing the number of visits to hospital emergencies (Hansik et al., 2001). Sometimes, the mere presence in the atmosphere of high concentrations of one or more allergens, is enough for epidemic days of asthma to be recorded (Galán et al., 2010). But asthma outbreaks in which high concentrations of atmospheric pollen have occurred with specific meteorological episodes of heavy rains, storms or winds of a certain intensity are more frequent (de Weger et al. 2013; D´Amato et al., 2013; Galveias et al., 2021). Grass pollen is one of the pollen types that usually causes the most impact since, in addition to being the main pollen allergen worldwide (García-Mozo, 2017), at times of thunderstorms it usually releases starch granules that contain the main allergens (D´Amato et al., 2007). This has been the cause of extreme asthma episodes in numerous locations, such as those that occurred in Melbourne (Australia) in November 2016, which caused the death of 8 people (Lee et al., 2017; Thien et al., 2018), or the massive pollen clouds that have covered various cities in the United States in recent years, in which high temperatures, increased rainfall, and winds associated with severe thunderstorms created a dramatic scenario for allergy sufferers (Scott, 2018). High concentrations of Poaceae pollen have also been associated with daily deaths due to chronic obstructive pulmonary disease and pneumonia in the Netherlands (Brunekreef et al., 2000).

Airborne pollen in the atmosphere is the result of the pollination process carried out by vascular plants, which in turn is the phenological phase most closely related to the meteorological conditions in which the species growth (Weber, 2003; Stepalska et al., 2016). Generally, flowering takes place in the season most favorable to the requirements of the plants in terms of meteorological and climatic conditions. Depending on the species, meteorological conditions can have an effect in the months before the flowering period in the case of trees, or immediately before or during the flowering period in the case of herbaceous species (Cariñanos et al., 2004; Grossiord et al., 2017). The presence of pollen of a given taxa in the air of a location during the pollination period, regardless of its origin or morphotype, usually adjusts to a sigmoid curve with two bends, one at the beginning of the considered Main Pollen Season (MPS), and another at the end of it (Jato et al., 2006; Galán et al., 2017). The maximum value in this curve constitutes the peak, defined as the maximum pollen record in a flowering season for a species, indicating that most specimens in a given population are in full bloom (García-Mozo et al., 2010; Bastl et al., 2017). The date of the peak value is the annual date in which this maximum value is registered (García-Mozo et al., 2010). In phenological studies, this peak also marks the downward beginning of the pollen curve, dividing the pollen season into pre-peak and post-peak periods (Smith and Emberlin, 2005). Numerous studies have considered the peak recording date as a variable when establishing pollen concentration forecast models (Jato et al., 2006; Zhang et al., 2015). The main factors driving this peak value have also been analyzed, especially when the figure reached is very high in relation to the average range of peak values of the historical data series. Thus, Prtenjak et al. (2012) identified periods of high ragweed pollen concentrations (above 600 grains/m^3) in Zagreb (Croatia), when an anticyclonic situation lasting more than 10 days led to high temperatures, absence of rain and moderate intensity winds. For the same taxon, Csépe et al. (2012) found an association between extreme daily pollen concentrations and meteorological variables such as temperature, global solar radiation, relative humidity, air pressure and wind speed. Kasprzyk (2008) found a relationship between days with high pollen counts and the presence of a persistent anticyclonic situation over the Southwest of Poland.

Other studies have analyzed the effect of extreme weather events on the presence of pollen in the atmosphere, finding a different response depending on the plant species considered. Thus, during the heat wave that hit Europe in the summer of 2003, in some parts of Switzerland the pollen values of Chenopodiaceae, *Plantago* and Poaceae were extremely high compared to the mean annual records of the historical series (Gehrig, 2006). On the contrary, very hot periods accompanied by drought can affect the pollination of *Ambrosia*, a group of ruderal plants well adapted to sub-desert habitats, which due to the scarcity of water, decreases the production of pollen, considered as a main allergen in the center and east of Europe and North America (Makra et al., 2012). Cariñanos et al. (2004) analyzed the responses of the different components of flora from a high-mountain area with a sub-desert climate to changeable meteorological conditions, finding a better response to water stress situations in the best adapted species to arid conditions, such as Amaranthaceae and *Artemisia*. Some of the most severe episodes of pollen-related asthma in Melbourne (Australia) have been recorded during gusts fronts in which there was a rapid drop in temperature, above 10ºC, and a significant increase in relative humidity, up to 70-80 % (Thien et al., 2018).

Given the need to generate a risk alert service for the allergic population, different scales to warn of the presence of risk levels of atmospheric pollen have been developed. Some of these scales usually consider the morphotype of the emitting plant (tree, shrub, weed and herb), and the different concentrations of pollen that generate a symptomatic response (nil, low, moderate, high and very high) (Thibaudon, 2003; Galán et al., 2007; Rapiejko et al., 2007; Cariñanos et al., 2016; Pfarr et al., 2017). However, in the category of very high values, the cofactors that can increase this risk to the maximum are not specified, that is, when due to phenological, meteorological and environmental circumstances, the atmospheric pollen load can have an exceptional impact on health. In meteorology, an extreme event is defined as an episode or event that is rare or infrequent, according to its statistical distribution, for a given place (IPCC, 2014). Similarly, extreme pollen events (EPEs) could be considered as all those episodes or events of atmospheric pollen, which due to their magnitudes, low frequency and effects, can have a significant impact on the population and the environment. In order to advance in the knowledge of these EPEs, this work proposes criteria to typify the levels of atmospheric pollen as an extreme pollen event, and aims to determine the meteorological variables that can affect the presence and permanence of these high concentrations over a period of time, thus increasing the risk for people suffering from pollen allergy and other respiratory diseases. This work will lay the foundations for the recognition of these extreme events in a context of climate change in which they may become more frequent.

2. EXPERIMENTAL SITE AND INSTRUMENTATION

For the determination and classification of extreme pollen events, the dataset of pollen recorded at the Aerobiological Monitoring Unit of the University of Granada, during the period 1992-2019, has been used. Aerobiological records were obtained from a volumetric suction Hirst-type sampler (Hirst, 1952) Lanzoni VPPS 2000 (Lanzoni, s.r.l., Bologna, Italy). The instrument is a suction trap in which the pollen grains enter through a narrow orifice that is directed into the wind by a weather vane, and finally are impacted on a silicon-coated microscope slide moved across the orifice at a rate of 2 mm/hr. The unit is installed at the building roof of the Faculty of Sciences in Granada (Spain, 37.18°N, 3.61°W, 680 m a.s.l.) (Figure 1). The pollen spectrum of the atmosphere is representative of a city with a Mediterranean climate (annual average temperature 15.6°C, annual average rainfall 359 mm for the period 1981-2010, AEMET, 2018), surrounded by important natural spaces, among which stands out Sierra Nevada, as well as large areas dedicated to woody and herbaceous crops. In this spectrum, it is possible to find a great diversity of pollen types from the vegetation units of the mountains: grasslands, holm oaks (*Quercus* spp.), Junipers (*Juniperus* spp.), pine forests (*Pinus sylvestris, P. nigra*) (Cariñanos et al., 2019), olive groves, cereal crops from peri-urban agroforestry systems, and urban trees which make up urban forests, among which the genera *Cupressus, Platanus, Populus, Acer, Ulmus* and *Fraxinus* are the most frequents (Díaz de la Guardia et al., 2006; Cariñanos et al., 2014; 2016). In this study, the eight most abundant pollen types in the atmosphere of this region have been selected according to historical aerobiological records, namely Cupressaceae, *Olea, Pinus, Platanus*, Poaceae, *Populus*, *Quercus* and Urticaceae, as well as the amount of total pollen.

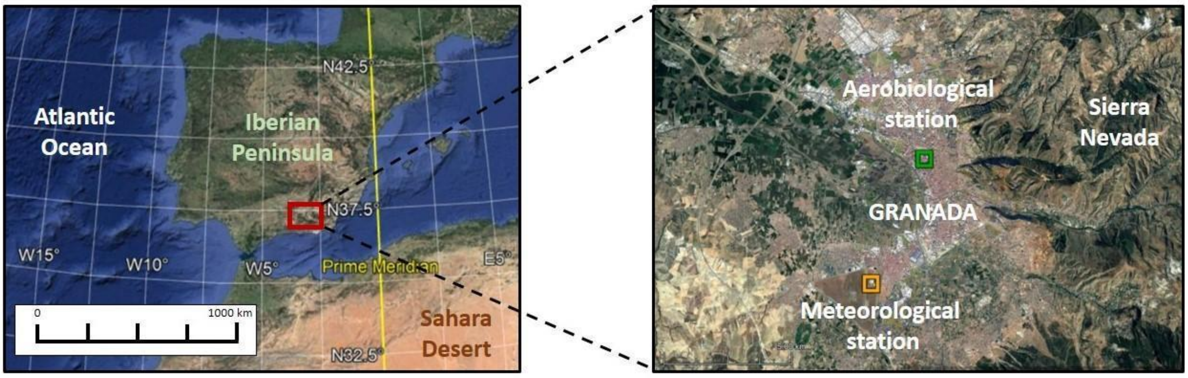

Figure 1. *Location of study area.*

3. METHODOLOGY

3.1. Aerobiological data

The sampling methodology conforms to the standardized protocol of the Spanish Aerobiology Network (REA), which recommends the use of Hirst type suction volumetric samplers with a fixed suction volume of 10 l air / min, uninterrupted operation 24 h per day, 365 days per year. The particles contained in the air are deposited on a Melinex © tape mounted on a drum and impregnated with silicone fluid, which allows the adherence of particles in the range 0.5-100 microns. The presence of a clockwork mechanism allows the movement of the 2 mm drum every hour, so each 48 mm fragment corresponds to 24 hours. The daily samples mounted on slides and stained with basic fucshin (specific for pollen proteins), are analyzed under an optical microscope, generating qualitative and quantitative results expressed in pollen*day/m^3. From these results, the values of Annual Pollen Integral (APIn) of each year, obtained by summing the daily concentrations of all pollen types from 1st January to 31st December of every year, and the Seasonal Pollen Integral (SPIn) of each pollen type, obtained by summing the daily concentrations of the specific pollen type from 1st January to 31st December of every year, were calculated for the period between 1992-2019 (Galán et al., 2007, 2017; EN 16868, 2019). Once the SPIn of each pollen type had been calculated, the Main Pollen Season (MPI) was established, i. e., the period of time in which the concentrations of pollen in the atmosphere are significant. For this work, the 95% method was used, i. e., the period from the time the sum of daily mean pollen concentrations reaches 2.5% until the time when the sum reaches 97.5% (Andersen, 1991).

3.2. Meteorological data

The meteorological data were acquired for the same data period as the pollen dataset by standard meteorological instruments installed at the station located at Armilla Air Base (37.81°N, 3.38°W, 687 m asl), located 7 km southwest of the location of the aerobiological sampler (Figure 1), and managed by the State Meteorological Agency (AEMET). The meteorological dataset is composed by the standard surface meteorological variables, namely daily maximum temperature (T_{max}), daily minimum temperature (T_{min}), daily mean temperature (T_{mean}), daily thermal amplitude (ΔT), relative humidity at 00, 07, 13 and 18 UTC (RH_{00}, RH_{07}, RH_{13} and RH_{18}, respectively), daily maximum pressure (p_{max}), daily minimum pressure (p_{min}), daily accumulated precipitation ($Prec_{24}$), visibility at 07, 13 and 18 UTC (VIS_{07}, VIS_{13} and VIS_{18}, respectively), insolation (SunDur), daily global solar radiation (Rad_{gl}), daily diffuse solar radiation (Rad_{d}), wind speed at 00, 07, 13 and 18 UTC ($W\text{-}vel_{00}$, $W\text{-}vel_{07}$, $W\text{-}vel_{13}$ and $W\text{-}vel_{18}$, respectively) and wind direction at 00, 07, 13 and 18 UTC ($W\text{-}dir_{00}$, $W\text{-}dir_{07}$, $W\text{-}dirl_{13}$ and $W\text{-}dir_{18}$, respectively). The effect of the surface meteorological variables on the extreme pollen events has been analyzed both on the day of occurrence of the pollen event and five days before.

3.3. Extreme pollen events

To identify an extreme event one of the key approaches involves calculation of the number of days in a year exceeding specific thresholds, which can be absolute or percentile thresholds. Here, to identify the extreme pollen events (EPEs), statistical criteria on the accumulated pollen concentrations during 24 hours have been considered. After computing the 95th percentile over the Main Pollen Season (MPS) for the eight most predominant types (and for the total pollen), a certain value is considered as EPE if its daily pollen concentration value equals or exceeds this threshold (represented as $C_{\geq P95}$). In order to propose a scale of warning for the presence of risky atmospheric pollen conditions, similar criteria based on more strict percentiles, i.e. based on 97th and 99th percentiles ($C_{\geq P97}$ and $C_{\geq P99}$, respectively), has also been considered. Once the thresholds $C_{\geq P95}$, $C_{\geq P97}$ and $C_{\geq P99}$ were established for the main pollen types of the aerobiological spectrum of Granada, the significance of the trend for number of days with extreme events throughout the series was analyzed with the Mann-Kendall test, and non-parametric Spearman correlations were computed between the extreme values of each pollen type at different percentiles and the surface meteorological variables of up to 5 days before these events were recorded, in order to identify the meteorological conditions that might influence the occurrence of EPE and its persistence.

The reason for choosing mostly percentile thresholds rather than absolute thresholds is that the number of days exceeding percentile thresholds is more evenly distributed in space and is meaningful in every region. Indices based on percentile thresholds, computed during a base period (in our case almost a 30-year period), are expressions of anomalies relative to the local climate, orography and environmental conditions, and therefore, the values of the thresholds are site-specific. Thus, such indices based on thresholds allow for spatial comparisons because they sample the same part of the probability distribution of the investigated variables at each location, and are preferred against absolute thresholds, which are less suitable for spatial comparisons extreme events. Following WMO (2009), by using the same definitions of extremes and analyzing the data in a standardized way, it is possible to compare results from different places and to obtain coherent pictures of change around the world.

Previous studies have applied percentile thresholds to identify a variety of extreme events. Clark et al. (2006) and Meehl and Tebaldi (2004) used 99th percentile for determining the threshold of extreme heat waves. Comparing the results obtained from three procedures (Peak Over Threshold (POT), 95th and 99th percentiles of the data), Kuswanto et al. (2015) observed that the POT thresholds lie between percentile values, which is a good choice for rainfall studies. Moreover, because using 95th percentile as the threshold may lead to misspecification of the result as it consists of too many small values and using 99th percentile as the threshold, it yields on very high values and may reduce the number of extreme events too much, we propose to explore 95th, 97th and 99th percentiles in our work.

4. RESULTS

Figure 2 presents the daily averaged values for the accumulated total pollen concentrations during 24 hours over the period 1992-2019 in Granada. It can be observed that from early February to early July, the aerobiological load in the atmosphere of Granada is greater than

100 pollen*day/m^3 due to the successive flowering of the different plant species of the urban and peri-urban environment.

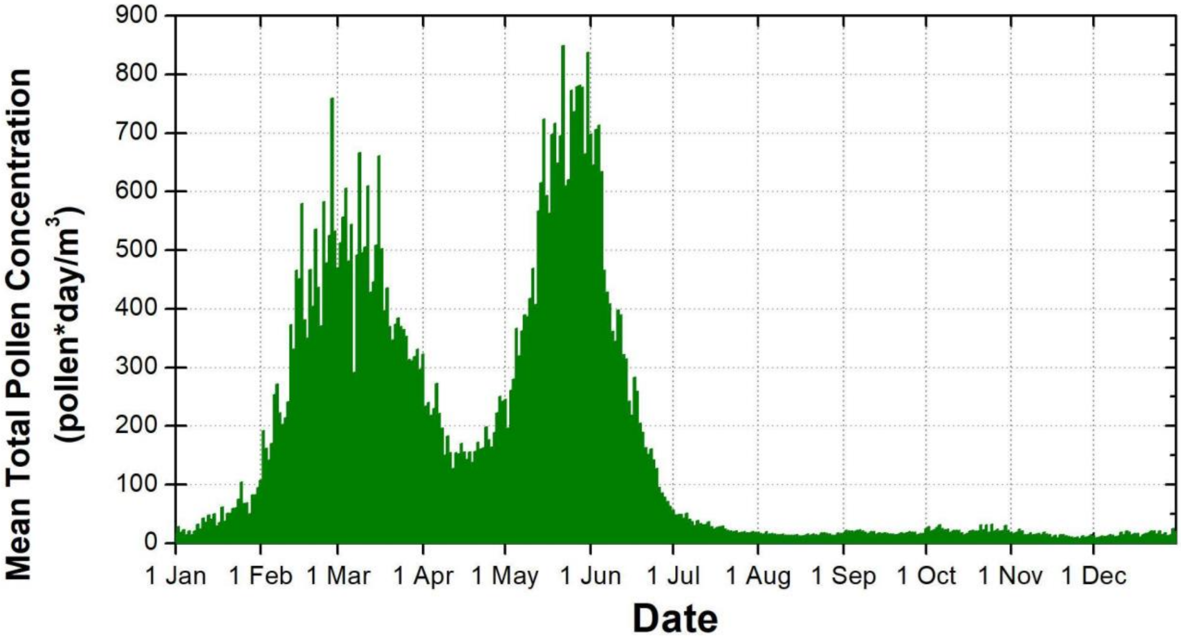

Figure 2. *Daily averaged values for the accumulated total pollen concentrations during 24 hours at Granada during the period 1992-2019.*

Table 1 reports the accumulated values for the pollen and the eight most contributing taxa to the aerobiological spectrum during the period 1992-2019. Although the percentage of these eight taxa is 92.4% of the total pollen, only *Olea* and Cupressaceae represent 67.5% of this total, while *Populus* only contributes 1.9%. For total pollen, percentile values range from 849 pollen*day/m^3 (95th percentile) to 1813 pollen*day/m^3 (99th percentile). Urticaceae and *Olea* are the two taxa presenting the extreme values for all the three percentiles (minima and maxima, respectively), being 44, 58 and 96 pollen*day/m^3 for 95th, 97th and 99th percentiles, respectively, in the case of Urticaceae, and 764, 1071 and 1597 pollen*day/m^3 for the corresponding percentiles of *Olea*. Cupressaceae is the taxon that registers the largest increment between percentiles, being the 99th percentile 3.6 times higher than the 95th percentile. The lowest variation between percentiles is found for *Populus*, with a 99th percentile 1.8 times higher than the 95th percentile.

<table>
<tr><th colspan="7">Total</th></tr>
<tr><th></th><th>Max value (date)</th><th>Ac-APIn (Pollen*day/m^3)</th><th>Percentage (%)</th><th>95th percentile (Pollen*day/m^3)</th><th>97th percentile (Pollen*day/m^3)</th><th>99th percentile (Pollen*day/m^3)</th></tr>
<tr><td></td><td>5310
(15/05/2015)</td><td>1 704 230</td><td>100.00</td><td>849</td><td>1154</td><td>1813</td></tr>
<tr><th colspan="7">Predominant taxa</th></tr>
<tr><th>Taxon</th><th>Max value (date)</th><th>Ac-SPIn (Pollen*day/m^3)</th><th>Percentage (%)</th><th>95th percentile (Pollen*day/m^3)</th><th>97th percentile (Pollen*day/m^3)</th><th>99th percentile (Pollen*day/m^3)</th></tr>
<tr><td><i>Olea</i></td><td>4933
(15/05/2015)</td><td>602 896</td><td>35.4</td><td>764</td><td>1017</td><td>1597</td></tr>
<tr><td>Cupressaceae</td><td>4274
(27/02/2019)</td><td>546 985</td><td>32.1</td><td>418</td><td>707</td><td>1512</td></tr>
<tr><td><i>Quercus</i></td><td>1029
(29/03/2009)</td><td>114 236</td><td>6.7</td><td>151</td><td>190</td><td>305</td></tr>
<tr><td>Urticaceae</td><td>305
(15/02/1998)</td><td>103 690</td><td>6.1</td><td>44</td><td>58</td><td>96</td></tr>
<tr><td><i>Platanus</i></td><td>1534
(06/04/2018)</td><td>81 279</td><td>4.8</td><td>291</td><td>369</td><td>614</td></tr>
<tr><td>Poaceae</td><td>309
(02/06/1996)</td><td>55 085</td><td>3.2</td><td>49</td><td>67</td><td>115</td></tr>
<tr><td><i>Pinus</i></td><td>470
(16/03/2019)</td><td>39 489</td><td>2.3</td><td>44</td><td>61</td><td>120</td></tr>
<tr><td><i>Populus</i></td><td>480
(14/03/2006)</td><td>31 668</td><td>1.9</td><td>111</td><td>149</td><td>202</td></tr>
</table>

Table 1. *General context over the period 1992-2019 at Granada discriminating by the total and the eight predominant taxa: yearly accumulated annual pollen integral (Ac-APIn) over the complete period, yearly accumulated seasonal pollen integral (Ac-SPIn) over the complete period, percentage over the total and thresholds for EPE definition based on the 95th, 97th and 99th percentiles ($C_{\geq P95}$, $C_{\geq P97}$ and $C_{\geq P99}$). Date for the maximum (and its pollen concentration) registered over the period 1992-2019 is also included.*

Regarding the maximum values reached throughout the series, it is noteworthy that for four of the pollen types and for total pollen, the maximum values have been recorded in the last 5 years: total pollen and *Olea* in 2015, *Platanus* in 2018, and Cupressaceae and *Pinus* in 2019. All values are between 2.5-3.9 times higher than the threshold $C_{\geq P99}$. At the opposite extreme, both Poaceae and Urticaceae registered the maximum value in the years 1996 and 1998 respectively, very early in the series.

Figure 3 shows the quasi-climatological temporal series of the number of days labeled as EPE per year (N_{EPE}) identified by the criteria $C_{\geq P95}$, $C_{\geq P97}$ and $C_{\geq P99}$ during the period 1992-2019. The visual inspection allows for highlighting some features for the eight predominant taxa at Granada.

In general, all the predominant pollen types and total pollen have presented the highest N_{EPE} for all percentiles in the second half of the analyzed time series. In particular, there is an increasing trend in the number of EPEs days from 2015 and onwards, except for Urticaceae with a prominent reduction after 2009 and Poaceae with a slight reduction after 2005. Also in general terms, the first decade (1992-2002) was the one in which fewer events were registered, as well as in the years of severe drought in the region (2005, 2008, 2010 and 2015) (Páscoa et al., 2017). The pollen types of tree species show a clear upward trend towards a greater number of EPEs at the end of the series, very noticeable in the case of Cupressaceae, *Quercus*, *Platanus* and *Pinus*. The herbaceous plants of the Urticaceae and Poaceae group have strong oscillations throughout the series, with an irregular distribution in the number of events. In contrast to most, the number of extreme pollen events in Urticaceae has drastically decreased from 2010 onwards.

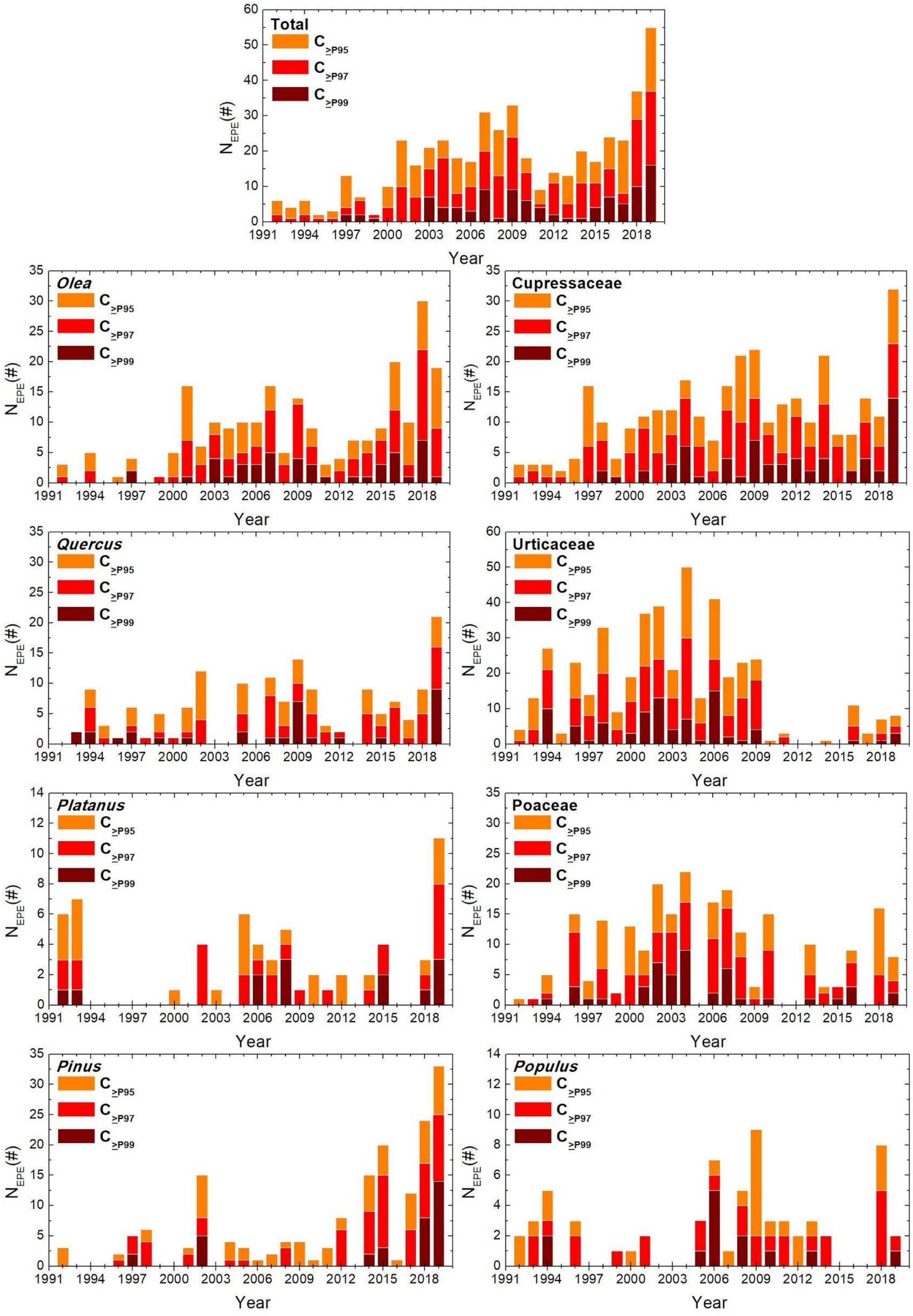

Figure 3. *Quasi-climatological temporal series of number of extreme days (N_{EPE}) per year identified*

by the criteria ($C_{\geq P95}$, $C_{\geq P97}$, $C_{\geq P99}$) for the total and the eight predominant taxa at Granada during the period 1992-2019. Note the different Y-axis scales. Bars are superimposed for each criteria.

Table 2 presents the trend analysis for the number of days with values higher than the percentiles P95, P97,P99 per year during the period 1992-2019, through the Mann-Kendall test at the significance level of 95%. In the case of total pollen, a robust monotonically ascending trend (95% significance level) is shown for the three percentiles. Out of the eight predominant taxa at Granada, only three of them, namely *Olea* and Cupressaceae, and *Pinus*, showed trends statistically significant and positive over the quasi-climatological period analyzed and with different features depending on the applied criteria. On one hand, *Olea* and Cupressaceae taxa presented the most robust monotonically ascending trends with significance at 95% independent of the threshold defining the EPEs. On the other hand, *Pinus* taxon also presented a monotonically ascending trend with significance at 95% for $C_{\geq P95}$ and $C_{\geq P97}$, but not for the criteria $C_{\geq P99}$. For the remaining taxa, no trend was found for N_{EPE} throughout the series, considering any EPE definition.

Moreover, Table 2 shows total pollen shows the positive Sen's slopes for total pollen, *Olea*, Cupressaceae and *Pinus*, for all the criteria (except *Pinus* under the criteria $C_{\geq P99}$ where no trend is found). For total pollen, N_{EPE} roughly increases by 1 day each 1, 1.6 and 4 years under the criteria $C_{\geq P95}$, $C_{\geq P97}$ and $C_{\geq P99}$, respectively. For *Olea*, N_{EPE} increases about 1 day each 2, 3.2 and 16 years under the criteria $C_{\geq P95}$, $C_{\geq P97}$ and $C_{\geq P99}$, respectively. For Cupressaceae, N_{EPE} approximately increases by 1 day each 2.3, 3 and 8 years under the criteria $C_{\geq P95}$, $C_{\geq P97}$ and $C_{\geq P99}$, respectively. Finally, for *Pinus*, N_{EPE} roughly increases by 1 day each 3, and 11 years under the criteria $C_{\geq P95}$ and $C_{\geq P97}$, respectively.

Taxon	**$C_{\geq P95}$**		**$C_{\geq P97}$**		**$C_{\geq P99}$**	
	Trend	**Slope (N_{EPE}/year)**	**Trend**	**Slope (N_{EPE}/year)**	**Trend**	**Slope (N_{EPE}/year)**
Total	Trend	0.946	Trend	0.625	Trend	0.250
Olea	Trend	0.500	Trend	0.308	Trend	0.061
Cupressaceae	Trend	0.429	Trend	0.333	Trend	0.125
Quercus	No trend	NC	No trend	NC	No trend	NC
Urticaceae	No trend	NC	No trend	NC	No trend	NC
Platanus	No trend	NC	No trend	NC	No trend	NC
Poaceae	No trend	NC	No trend	NC	No trend	NC
Pinus	Trend	0.333	Trend	0.091	No Trend	NC
Populus	No trend	NC	No trend	NC	No trend	NC

Table 2. *Trend analysis using the Mann-Kendall test (significance level of 95%) for the number of days with extreme events per year during the period 1992-2019. Sen's slope is computed when a significant trend is found. Days with extreme events were defined according to the criteria established in terms of the thresholds based on 95th, 97th and 99th percentiles ($C_{\geq P95}$, $C_{\geq P97}$ and $C_{\geq P99}$, respectively). Non calculated (NC) slopes are due to not enough significance level.*

Figures 4, 5 and 6 show the correlation, based on Spearman's analysis, of pollen concentrations during the EPEs identified by the criterion $C_{\geq P95}$, $C_{\geq P97}$ and $C_{\geq P99}$, respectively, with different daily meteorological variables, analyzing both the effect of meteorological variables on the day when the EPE occur and the effect of meteorological variables occurring in previous days (up to 5 days before).

In general, Urticaceae is the taxon that has shown the highest correlation, both positive and negative, with meteorological variables, especially when the criterion $C_{\geq P95}$ is used for the EPE definition. The RH_{00}, RH_{07} RH_{18}, p_{max}, p_{min} and W-vel_{07} up to five days before the extreme value recording are the most influential variables with a positive Spearman's correlation coefficient of up to 0.30. T_{max}, T_{min}, T_{mean}, Rad_{gl}, Rad_{d} and insolation are, on the contrary, the variables with the greatest negative influence when the criterion $C_{\geq P95}$ is used, with correlation coefficients up to -0.30. Under the criterion $C_{\geq P97}$, Urticaceae concentrations during EPEs correlate positively with relative humidities mainly between 3 and 5 days before registering the EPEs, and with atmospheric pressure and wind speed at early morning up to three days before the EPE, all of them with a positive Spearman's correlation coefficient of up to 0.30. Under the criterion $C_{\geq P97}$, wind speed and direction during the second half of the day are also correlated negatively during the EPE and the previous day, with Spearman's correlation coefficient up to -0.30. Also, radiative variables such as Rad_{d} and insolation exhibit a negative correlation during the EPE and the previous day for the former, and between 3 and 5 days for the latter. Under the criterion $C_{\geq P99}$, it is remarkable that the thermal amplitude and insolation are negatively correlated during the 4-5 days before the EPE, with correlation coefficients up to -0.40, and visibility after noon is positively correlated during the 2-3 days prior the event, with correlation coefficients up to 0.40 at high significance level ($p<0.01$). Positive correlation coefficients up to 0.30 also occur with precipitations in the 4-5 days prior to the event.

At the other extreme *Populus* is found that barely shows correlation with the meteorological variables on the day of the EPE when the criterion $C_{\geq P95}$ is used, and, occasionally, with the p_{min} and wind speed at late evening (18 UTC) on the day labelled as EPE, and with wind speed and direction at several hours of the previous 2-4 days. When the criteria applied for EPE definition are more strict, i.e. when the thresholds $C_{\geq P97}$ and $C_{\geq P99}$ are applied, the number of correlations between pairs sharply decreases but the correlation coefficients strengthen. Thus, under the criterion $C_{\geq P97}$ *Populus* concentrations during EPEs correlate positively with relative humidity at midnight, insolation and wind properties at early morning (7 UTC) occurring 5 days before the event with correlation coefficient up to 0.40, and correlate negatively with p_{min} on the day occurring the EPE, with a correlation coefficients up to -0.50, all of them at the significance level of $p<0.05$. Under the criterion $C_{\geq P99}$ *Populus* concentrations during EPEs correlate positively with relative humidity at midnight at the fourth day before registering the EPE, characterized by a correlation coefficient up to 0.70 and even more strongly (correlation coefficient larger than 0.70) with wind direction late evening at the second day before registering the EPE, and correlate negatively with p_{max} on the same day when the EPE is detected.

Olea shows a medium and positive correlation (up to 0.30) with temperature-related variables in the 2-3 days prior to the EPE, while relative humidity along the day between 1 and 3 days before occurring the EPE and 24-h accumulated precipitation during 4-5 days before the event have a negative effect, with Spearman's correlation coefficient up to -0.30. Under the criterion $C_{\geq P97}$, temperature variables no longer have an influence on the *Olea* concentrations during EPEs or the previous days and atmospheric pressure plays a role 5 days before the EPE, with positive correlation up to 0.30. Under the criterion $C_{\geq P99}$, only the wind direction at late evening has a significant negative correlation, with Spearman's correlation coefficient up to -0.50. No correlation between EPE concentrations and visibility is observed for *Olea* under any of the criteria defined.

When defining the EPEs under the criterion $C_{\geq P95}$, Cupressaceae concentrations correlate positively with all the temperature-related variables (except T_{min}) during the day of the EPE's detection and one day before, with correlation coefficients up to 0.30. The 24-h accumulated precipitation occurring during the EPE also shows a negative effect on the Cupressaceae concentrations during EPEs, with Spearman's correlation coefficients up to -0.20. The wind speed at midnight and early morning positively influences the Cupressaceae concentrations between 3 and 5 days before the EPE, sometimes at 99% significance level. Conversely, they correlate negatively with relative humidity at noon during the EPE and one day before, with Spearman's correlation coefficients up to -0.20. Interestingly, relative humidity at midnight exhibits a negative effect on the day labeled as EPE and a positive effect on the previous day, both of them with a correlation coefficient of 0.20 (in absolute terms). Under the criterion $C_{\geq P97}$, it is worthy to mention that visibility during the whole day influences positively mainly during the day occurring the EPE and 5 days before its detection, and wind speed at midnight also correlates positively with the Cupressaceae concentrations from the day occurring EPE up to 3 days before, with correlation coefficients up to 0.20. Under the criteria $C_{\geq P99}$, some of the previous correlations mentioned strengthen such as wind speed at midnight (with positive correlation coefficients up to 0.50) between 1 and 4 days before the EPE, and the visibility during the morning and noon up to 3 days before occurring the EPE (with positive correlation coefficients up to 0.40). The relative humidity at midnight and early morning, on the other hand, present a negative correlation coefficient on the day of the event and on the 2 previous days. Interestingly, the wind speed and direction during late evening positively influence the Cupressaceae concentrations during the day of the event detection.

Quercus shows a marked different behavior depending on the criterion adopted for EPE definition. Thus, under the criterion $C_{\geq P95}$, the concentrations are negatively correlated with the atmospheric pressure up to 2 days before occurring the EPE and with insolation one day before the EPE, with Spearman's correlation coefficients up to -0.30 and high significance level ($p<0.01$) in both cases. Besides, thermal amplitude at the same day when EPE occurs negatively correlates, with a high significance level ($p<0.01$). Under the criterion $C_{\geq P99}$, the high correlation ($p<0.01$) with the visibility is striking, not only during the EPE at noon and late evening but also between 2 and 4 days prior to the EPE during daytime, with correlation coefficients up to 0.50. Under this criterion, the *Quercus* concentrations during EPEs show a strong and negative correlation with the diffuse radiation and wind direction early morning but only 3 days prior to the event.

Under the criterion $C_{\geq P95}$, Poaceae concentrations during EPEs positively correlate with wind speed and direction during the second half of the day mainly during the day when the EPE occurs, with Spearman's correlation coefficients up to 0.30. On the contrary, the maximum temperature and thermal amplitude show a negative effect on the EPE concentrations for Poaceae, just during the day of occurrence. Under the criterion $C_{\geq P97}$, Poaceae concentrations during EPEs show correlations with wind-related variables mainly along the day of EPE occurrence. Interestingly, under the criterion $C_{\geq P99}$, all the temperature-related variables considered in this study (except the thermal amplitude) exhibited a strong effect on the EPE concentrations for Poaceae during the previous days, from 1 to 5, with positive Spearman's correlation coefficients up to 0.50 (and significance level $p<0.01$ for some pairs of datasets). Also, the EPE concentrations are positively correlated atmospheric pressure observed between 2 and 3 days before the EPEs and negatively correlated with both RH_{07} and precipitation 5-day prior to the event.

Pinus shows a marked different behavior depending on the criterion adopted for EPE definition. For criterion $C_{\geq P99}$, only thermal amplitude 5 days before the EPE and wind speed at noon and midnight during the previous 2 or 3 days have an effect on the EPE concentration for *Pinus*, with positive correlation coefficients up to 0.60 under a high significance level ($p<0.01$). Under the criteria $C_{\geq P95}$ and $C_{\geq P97}$, EPEs for *Pinus* seem to have a positive correlation with atmospheric pressure and visibility during most of the days previous to the EPE detection, with Spearman's correlation coefficients up to 0.40 and 0.30, respectively. Additionally, EPEs for *Pinus* have a negative correlation with the wind-related variables during the second half of the day and especially with the diffuse radiation, being the correlation coefficients up to -0.40.

Under the criterion $C_{\geq P95}$, *Platanus* has shown an intense positive correlation with all the temperature-related variables (except the minimum temperature) of the day in which the EPE is registered, with Spearman's correlation coefficients up to 0.50 and a high significance level (p<0.01). During 1 and 2 days immediately preceding the EPE, *Platanus* concentrations are positively correlated with insolation and negatively correlated with the diffuse radiation, with correlation coefficients up to 0.40 and up to - 0.30, respectively, and with a high significance level. Under the criterion $C_{\geq P97}$, the wind directions occurring during the second half of the day have an effect on the EPE concentrations for *Platanus*, with positive correlation coefficients up to 0.50 between 3 and 5 days prior to the EPE. Interestingly, *Platanus* is the taxa with the strongest correlations observed under the criterion $C_{\geq P95}$. Thus, EPE concentrations for *Platanus* are positively correlated with Spearman's coefficient above 0.70 for minimum temperature 4 days prior to the EPE and wind direction at noon on the day immediately preceding it. Conversely, EPE concentrations for *Platanus* are negatively correlated with Spearman's coefficient above -0.70 for wind speed at noon 4 days prior to the EPE, and for wind direction at late evening and midnight 1 day before the EPE with correlation coefficient up to -0.70.

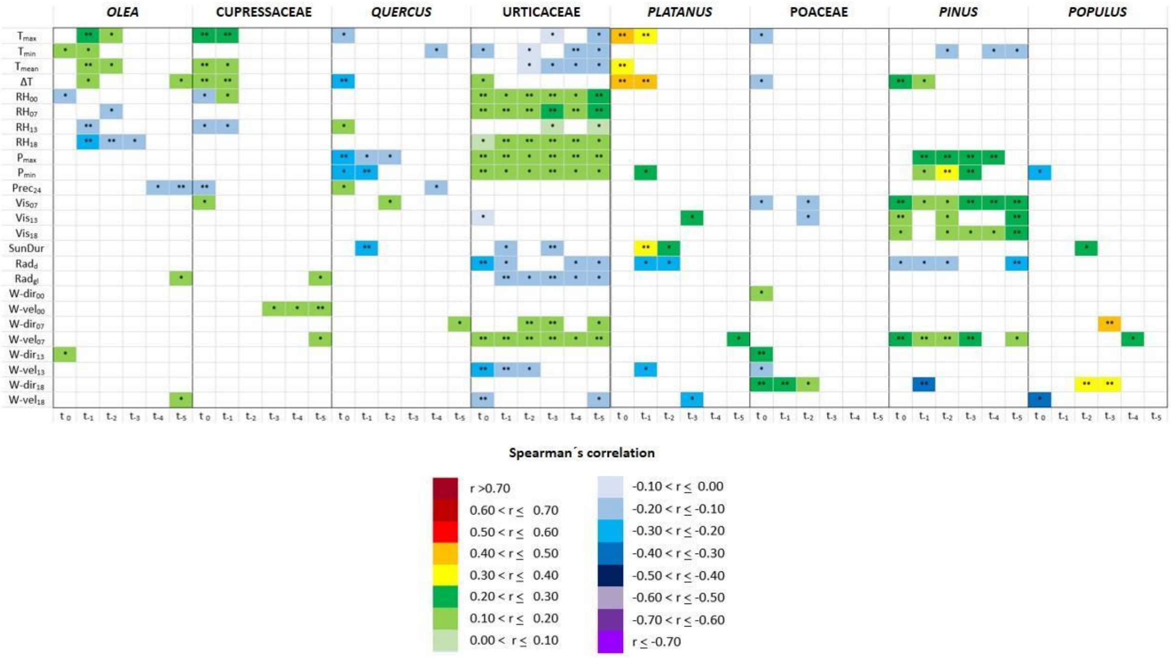

Figure 4. *Quasi-climatological analysis of the Spearman´s correlation (r) for daily concentrations for the eight predominant taxa during extreme events in Granada, identified by the criterion $C_{\geq P95}$, with respect to the daily mean values of different meteorological variables monitored during the day of pollen sampling (t_0) and during 1-5 previous days (t_1, t_2, t_3, t_4 and t_5, respectively). The surface meteorological variables daily maximum temperature (T_{max}), daily minimum temperature (T_{min}), daily mean temperature (T_{mean}), daily thermal amplitude (ΔT), relative humidity at 00, 07, 13 and 18 UTC (RH_{00}, RH_{07}, RH_{13} and RH_{18}, respectively), daily maximum pressure (p_{max}), daily minimum pressure (p_{min}), daily accumulated precipitation ($Prec_{24}$), visibility at 07, 13 and 18 UTC (VIS_{07}, VIS_{13} and VIS_{18}, respectively), insolation (SunDur), daily global solar radiation (Rad_{gl}), daily diffuse solar radiation (Rad_d), wind speed at 00, 07, 13 and 18 UTC ($W\text{-}vel_{00}$, $W\text{-}vel_{07}$, $W\text{-}vel_{13}$ and $W\text{-}vel_{18}$, respectively) and wind direction at 00, 07, 13 and 18 UTC ($W\text{-}dir_{00}$, $W\text{-}dir_{07}$, $W\text{-}dirl_{13}$ and $W\text{-}dir_{18}$, respectively). Significance level is identified by one asterisk ($p<0.05$) and two asterisks ($p<0.01$).*

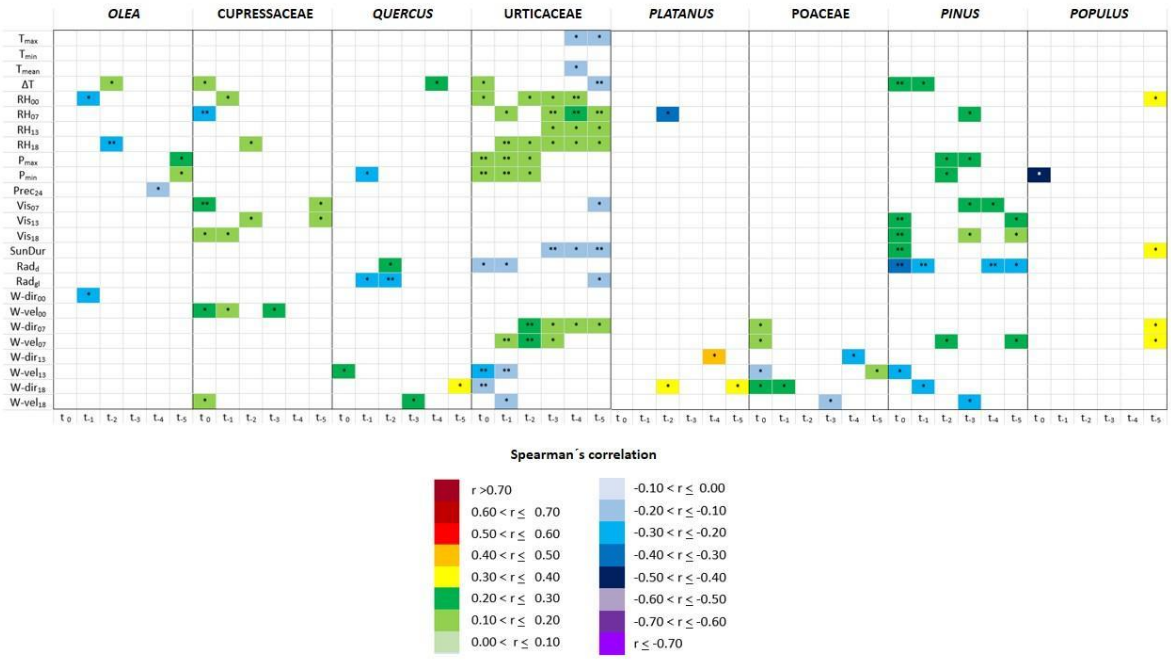

Figure 5. *Same as Figure 4 but identified by the criteria $C_{\geq P97}$.*

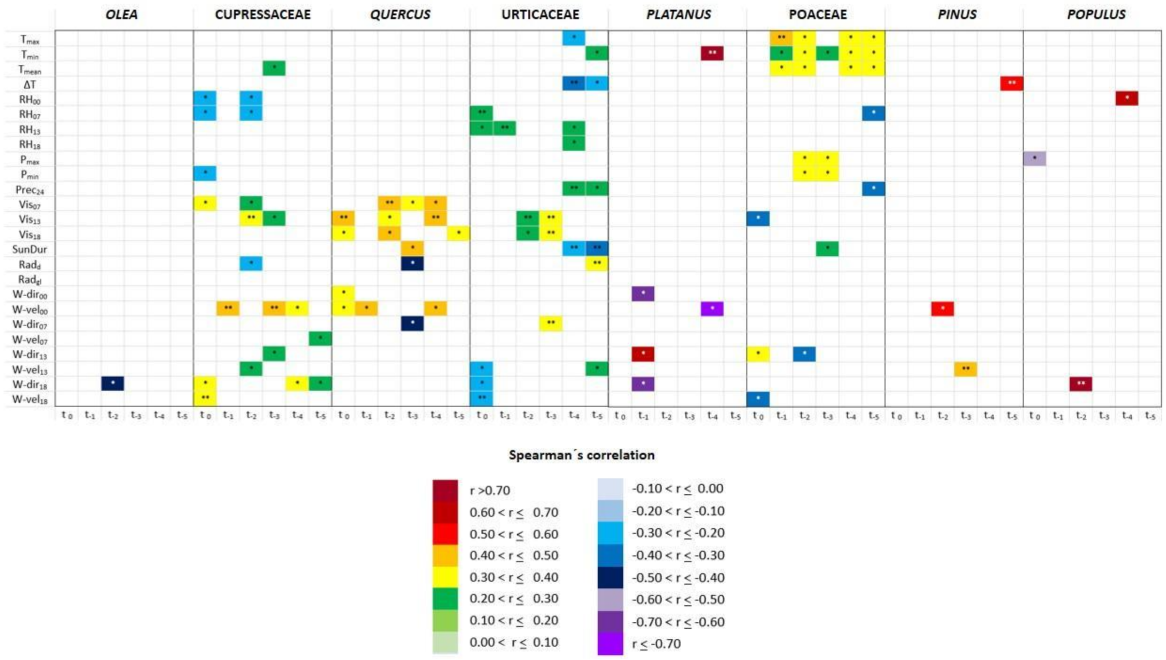

Figure 6. *Same as Figure 4 but identified by the criteria* $C_{\geq P99}$.

5. DISCUSSION

The results have shown that pollen concentrations in the atmosphere of Granada can be very high during a long period of the year due to the existence of numerous sources of pollen emission, both inside the city and in the peri-urban environment (Cariñanos et al., 2016). Although with unequal contribution, the eight selected pollen types constitute 92.4% of the total bioaerosol pollen-type in this atmosphere, so they are also the main causative agents of allergic symptoms in the local population (Díaz de la Guardia et al., 2006; De Linares, 2007). The EPEs identified under the percentile criteria, i.e. $C_{\geq P95}$, $C_{\geq P97}$ and $C_{\geq P99}$, have shown clear differences between herbaceous (Poaceae, Urticaceae) and woody species (Cupressaceae, *Olea*, *Platanus*, *Pinus*, *Populus*, *Quercus*), and between their urban origin or the peri-urban environment, forming part of the natural or cultivated vegetation (Cariñanos et al., 2021).

The application of the criterion $C_{\geq P95}$ (Table 1) has established a value high enough for each taxon so that the response of allergic people, once the symptoms have started, is of great magnitude. At this threshold, the values of several of the pollen types considered are higher than the thresholds for the high (or very high) pollen concentration categories established by some allergy academies and aerobiological associations in Europe and North America, which in turn have established their values according to the levels of atmospheric pollen sufficient to generate an exacerbated symptomatic response in the population (Table S1, Supplementary Material). Thus, the threshold established in this work of 44 pollen*day/m^3 of Urticaceae under the criterion $C_{\geq P95}$ is already higher than the 30 pollen*day/m^3 suggested as very high by the Spanish Aerobiology Network (REA) (Galán et al., 2007). The almost 300 pollen*day/m^3 of the London plane (*Platanus* x *hispanica*) exceeds the maximum threshold established by the REA, the RNSA-France (Thibaudon, 2003) or, in general, for the whole of Europe (de Werger et al., 2013). The thresholds concentrations under the criterion $C_{\geq P95}$ for *Olea* and Cupressaceae far exceed the 500 pollen*day/m^3 established as a very high category threshold by the American Academy of Allergy, Asthma and Immunology (AAAAI, 2014). In the case of Poaceae, the threshold of 50 pollen grains*day/m^3 established in our study under the criterion $C_{\geq P95}$ is similar to that of REA, Europe and AAAAI (Galán et al., 2007; AAAAI, 2014; de Werger et al., 2013). In relation to this value, it must be taken into account that some authors previously indicated the threshold of 10 pollen*day/m^3 of grasses as a sufficient value to increase adverse allergic effects (DellaValle et al., 2012), and 30 pollen*day/m^3 is designated as a pollen warning threshold for the development of symptoms in the nose, eyes and lungs in the city of Malmö (Sweden) (Kiotseridis et al., 2013), so a daily record of 50 pollen*day/m^3 can already be considered as an extreme value for this taxon. The threshold of grasses established here by the criterion $C_{\geq P99,}$ 115 pollen*day/m^3, is close to the threshold of 150 pollen*day/m^3 considered by MeteoSwiss as a very high pollen load. The thresholds defined by the criterion $C_{\geq P99}$ of the remaining pollen types is also much higher than the very high category thresholds considered by the main aerobiological networks and the EAAACI (Table 1 Supplementary Material). In the case of *Olea* pollen, the 400 pollen*day/m^3 considered as a critical threshold to cause severe allergic symptoms and bronchial asthma in patients over the Mediterranean region are widely exceeded (Bonofiglio et al., 2012). It should be mentioned that, throughout the quasi-climatological series (i.e. over a period of almost 30 years), this value has been exceeded in almost all of the years (Table 1 and Figure 3), with a maximum value of almost 5000 pollen*day/m^3 on May 15, 2015 (Table 1).

The slope analysis for the number of days with pollen concentrations exceeding the criteria $C_{\geq P95}$, $C_{\geq P97}$, and $C_{\geq P99}$ has shown significant upward trends for two of the predominant pollen types in Granada, i.e. *Olea* and Cupressaceae (Table 2). In the case of *Olea*, this trend towards a greater number of days with pollen concentrations considered as EPE agrees with the increase in the Annual Pollen Integral (APIn) experienced both in Granada (Cariñanos et al., 2021) as in the rest of the Iberian Peninsula (Galán et al., 2016) and other areas of the Mediterranean basin (Sicard et al., 2012; Bonofiglio et al., 2013), in which daily pollen counts of more than 5000 pollen*day/m^3 are frequently recorded (Bonofiglio et al., 2013; Aguilera and Ruiz-Valenzuela, 2009). To the good adaptability that the olive tree presents to changing climatic conditions in the Mediterranean region, it must be added that in the province of Granada the irrigated olive cultivation area has increased greatly in the last decade, and the high percentage of trees (46.6%) over 50 years old, which in the case of the olive tree is considered the age of greatest production (ESYRCE, 2016). Cupressaceae pollen has also increased its presence in the atmosphere of several European countries in recent years due to its use as an element of urban green infrastructure due to its good adaptability to urban environment and climatic conditions (Galán et al., 2016; Charpin et al, 2013; Cariñanos et al., 2021). The maximum values recorded in some years in Granada throughout the series 1992-2019 are among the highest in the Mediterranean region due to the high number of *Cupressus* specimens existing in the city and the *Juniperus* plant formations in Sierra Nevada (Cariñanos et al., 2019; Díaz de la Guardia et al., 2006). The upward trend presented by *Pinus* for the criteria $C_{\geq P95}$ and $C_{\geq P97}$ is in line with the increasing trend that the Monthly Pollen Index (MPI) presents in several Spanish localities, which results in higher concentrations of pollen*day/m^3, and a greater frequency of exceeding these threshold values (De Linares et al., 2017).

Meteorological variables have an effect on pollen concentrations in the air, with surface temperatures and precipitation being the most influential properties (Galán et al., 2016; Matyasovszky et al., 2018). Our results have shown the correlation between the extreme pollen values registered using different criteria established in terms of several percentiles and these surface meteorological variables, with a different effect according to the pollen type and the delay between the atmospheric scenario and EPE occurrency. In general, T_{max}, T_{min}, and T_{mean} have a significant correlation with the presence of most of the predominant atmospheric pollen several days before the EPE is recorded. This could be related to the adjustment of the temperature requirements necessary for the dehydration of the anther and of the pollen grain itself in the moments prior to anthesis and dispersion (Pacini, 2000), which in most cases is accompanied by a decrease in relative humidity, However, in taxa such as *Parietaria*, of the Urticaceae family, in which pollen grains can have up to more than 30% water content at maturation, their greater presence in the atmosphere is favored with high relative humidity (Franchi et al., 2007). In addition to the fact that its presence in urban areas is highly conditioned to the actions of green area management, with intense manual extraction techniques of the considered weeds (Cariñanos and Casares-Porcel, 2011; Moretto and Di Domenico, 2017), the significant interannual variation experienced by the relative humidity throughout the series it may also be the cause of the progressive decrease in its atmospheric presence (Cariñanos et al., 2021), and of the high correlation of the concentrations identified by the different percentile criteria.

Neither has a significant correlation between temperature and pollen concentrations of Poaceae and *Populus* have been obtained. In the case of Poaceae, it has already been commented previously that the maximum values of the series and the N_{EPE} for all percentiles were recorded in the first half of the series, with a reduction from 2005. A previous analysis on this pollen type in the area in the last 25 years it has shown large interannual fluctuations due to its great dependence on hydrometeorological variables, in particular on the snow cover in Sierra Nevada, where the main extensions of grassland are located (Algarra et al., 2019). The lack of correlation of *Populus* pollen not only with temperature but with most variables could be caused by the regression of biocultures in the area, where the traditional poplar groves of La Vega are being replaced by other crops with lower water requirements (Gallego, 2019).

Olea, Cupressaceae and *Platanus* are the pollen types that have shown the highest correlation with temperatures and thermal amplitude in the two days prior to the record of pollen concentrations identified as EPE under the criterion $C_{\geq P95}$. In the case of *Platanus*, a stronger correlation (r<0.40) was obtained with the T_{max}. This close correlation has already been observed in other locations, with T_{max} being one of the variables with the greatest influence on the construction of pollen prediction models (Iglesias et al., 2007) and for the establishment of urban allergen risk maps (Lara et al., 2019; Cariñanos et al., 2020; Pérez-Casimiro et al., 2019).

Another meteorological variable presenting a significant correlation with pollen concentrations during EPEs under the different criteria is the visibility. Because it is inversely proportional to the extinction coefficient (Middleton, 1952), visibility is a horizontal measure of the aerosol load in the atmosphere, leading to identify clean/turbid atmospheres. Although several studies include bioaerosols from natural biomass (pollen, spores, fibers) as participants in the haze process and the presence of high concentrations of pollen may be related to a loss of visibility in urban areas (Kim, 2007), visibility may be more affected by the presence of other atmospheric pollutants, which have a greater participation in light attenuation (Titos et al., 2012). Our work has demonstrated significant positive correlation of visibility with concentrations during EPEs for several taxa, being particularly relevant with *Pinus* under the criteria $C_{\geq P95}$, and *Quercus* and Cupressaceae under the criteria $C_{\geq P99}$. *Pinus* and *Quercus* are linked to important forest masses existing in the surroundings of the city, both in the Sierra Nevada (western part) and in other mountain ranges to the Northeast (Sierra de Huétor, Sierra de Baza). Its positive correlation with visibility is explained by the combination of two facts. On one hand, during the dates on which the maximum annual events for these taxa are usually recorded in our region are usually in March and April (spring) (De Linares et al., 2017), the atmospheric flow favors East-Northeastern winds through the intrabetic corridor (Viedma Muñoz, 1998), increasing the concentration of these taxa at our station. On the other hand, late winter also implies a considerable reduction in the use of domestic heating, which is an important source of pollution in the atmosphere of Granada during winter (Titos et al., 2017; Casquero-Vera et al., 2021). Thus, despite having large concentrations of these taxa, the air is cleaner in a net sense and visibility is increased.

Differently, Cupressaceae is linked to important urban vegetation masses. The positive correlation of visibility with Cupressaceae concentrations during EPEs is due to Cupressaceae grains are relatively transparent to visible radiation. The Cupressaceae exin with a lower content of sporopollenin than other pollen grains of Gymnosperms, degrades rapidly as a result of the atmospheric hydration and dehydration processes, leaving a homogeneous smooth surface intine composed of cellulose (Pacini and Hesse, 2012) and increasing its transparency. Moreover, many of the EPEs for Cupressaceae occur in February when Northern flows clean the atmosphere in Granada. Therefore, despite having large Cupressaceae pollen concentrations visibility is not reduced.

The Mediterranean region has been identified as one of the most vulnerable areas in the world to the effects of climate change, where a worsening in the frequency and magnitude of extreme weather events can be expected (IPPC, 2014), together with a greater occurrence of phenomena such as heat/cold waves, floods, severe droughts and the spread of pests and diseases (Giorgi and Lionello, 2008; Lionello et al., 2014). Although strong impacts on biodiversity are also expected, the opportunity also opens up for those plant species that have shown a better response to recent changes and greater resilience to future changes. This work has shown that for several taxa the number of EPEs has increased in recent years. Several studies have highlighted the correlation between higher pollen production and an increase in greenhouse gases such as CO_2 (Albertine et al., 2014; Ziska and Caulfield, 2000). Other studies have shown an association between O_3 and atmospheric pollen concentrations

(Sousa et al., 2008; Cariñanos et al., 2021). It has also been possible to show that some plant groups have a better adaptive response to environmental conditions of increasing aridity, highlighting highly allergenic species with cosmopolitan and/or invasive behavior such as ragweed, mugwort or those of the Amaranthaceae family (Cariñanos et al., 2004; Déak et al., 2013; Sikoparija et al., 2017). In the agricultural field, a change is also being detected towards a selection of species and varieties that are more resistant to both pests and stressful environmental conditions, which guarantee the highest productivity through an intensification of pollination (Mazzeo et al., 2014).

In the case of maintaining the current trend towards a greater number of EPEs per year, we could expect important consequences in different areas. For Public Health, this greater number of EPEs can generate an exacerbation of the symptoms of allergic persons and the number of associated pollen-related asthma episodes (Damialis et al., 2019; D´Amato et al., 2020). Subsequently, there will be an increase in social and economic costs, due to the detriment of the quality of life of the affected people and the increase in spending on preventive drugs and the hours of school and work absenteeism (Zuberbier et al. al., 2014; Lake et al., 2017). In turn, the impacts in areas such as atmospheric processes may be important, and there is increasing certainty about the participation of bioaerosols as cloud condensation nuclei and ice nuclei (Wozniak et al., 2018; Mikhailkov et al., 2019). In these processes, the sub-pollen particles formed by the rupture of pollen grains during the atmospheric transport, either by mechanical impact with other particulate material (Laakso et al., 2003) or by the successive processes of hydration and dehydration experienced by the pollen cover as a function of environmental humidity (Hughes et al., 2020; Galveias et al., 2021). Then, in the face of an increase in the periods in which the pollen load of the atmosphere is very high, a greater participation of pollen in these atmospheric processes could be expected, and, ultimately, a more relevant and active role of bioaerosol in atmospheric physics and chemistry (Ariya and Amyot, 2004).

The different climate scenarios also project an effect on plant biodiversity, with unequal impact depending on the ecological and geographical characteristics of the ecosystem in which they are found (Valladares et al., 2005). Thus, in general, a better adaptive response can be expected in drought-tolerant *Pinus* species than in *Quercus* species elusive of drought and more dependent on the rainfall regime (Ferrio et al., 2003). The intrinsic survival strategy of the latter may lead them to intensify pollen production as a response mechanism to stress (Recio et al., 2018). But it is in urban ecosystems where the most intense impacts can occur due to urban microclimate conditions. In addition to the direct effects that temperatures and relative humidity can have on the phenology and reproductive biology of urban plant species (Neil and Wu, 2006), the presence of certain atmospheric pollutants such as CO_2 can increase the pollen production of certain species (Albertine et al., 2014; Ziska and Caulfield, 2000). Some of the pollen types considered in this work come from trees widely used in Mediterranean urban forests such as *Platanus* x *hispanica* and *Cupressus* spp, both having shown a significant tendency to increase SPIn values in the coming years and a tolerance to the presence of atmospheric pollutants (Cariñanos et al., 2021). In the case of *Cupressus*, the significant upward trend towards a greater number of days labeled as EPE is noteworthy, even under the criterion $C_{\geq P99}$.

6. CONCLUSIONS

The criteria used in this work allow for characterizing the presence of high concentrations of pollen in the atmosphere as an extreme pollen event (EPE). In this way, episodes of atmospheric pollen can be identified, which due to their magnitude and frequency can have a great impact on the health of the population. The percentile criteria applied to the main pollen types causing allergic response in the Mediterranean region have highlighted, on the one hand, the very high concentrations of pollen that can be registered on certain occasions, and on the other hand, the increasing trend that the number of EPEs for pollen types such as *Olea* and Cupressaceae have been registered in recent years.

Regarding the effect of the local surface meteorology, our results have shown that temperature is one of the most influential variables both on the day on which the EPE is registered and in the days prior to it. As a variable linked to temperature, a decrease in ambient relative humidity has also been shown to be an influencing variable in the occurrence of EPEs. Surprisingly, visibility is another of the meteorological variables that has presented a significant correlation with some pollen types, in particular with those that come from forest masses in the peri-urban environment, such as *Quercus* and *Pinus*. Due to visibility is a complex meteorological variable, where all the other local and advected particle types from different sources (such as black carbon, sulfates, nitrates and mineral dust, among other) affect its behavior, specific studies examining the role of pollen grains in the horizontal visibility and vertical extinction coefficient profiles are encouraged. Finally, it would be expected that given the perspective of the climate scenario projected for the area, with increasing temperatures and decreasing rainfall, EPEs may increase both in magnitude and frequency, which will have significant impacts on atmospheric processes and socio-economical areas such as public health.

ACKNOWLEDGEMENTS

The authors thank the Spanish Ministry of Economy and Competitiveness (MINECO) for support through project BIOCLOUD (RTI2018-101154-A-100) and INTEGRATYON3 (PID2020.117825GB.C21), the Regional Government of Andalusia through project AEROPRE (P18-RT-3820) and ADAPNE (P20-00136), and the University of Granada, Programa Operativo FEDER Andalucia 2014-2020 through project INPARK (B-RNM-474-UGR18), DEM3TRIOS (A-RNM-430-UGR20) and the Earth System Excellence Units Program. The authors acknowledge AEMET (Spanish Meteorological Agency) for the historical meteorological surface data used in this work and the Aerobiological Sampling Unit of the University of Granada for the aerobiological data.

Credit Author Statement

P. Cariñanos: Conceptualization, Methodology, Formal analysis, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing; **J.L. Guerrero-Rascado**: Conceptualization, Methodology, Software, Formal analysis Data, Curation, Writing - Original Draft, Writing - Review & Editing; **A. M. Valle**: Data Curation; **A. Cazorla**: Writing - Review & Editing; **G. Titos**: Writing - Review & Editing; **I. Foyo-Moreno**: Writing - Review & Editing; **L. Alados-Arboledas**: Writing - Review & Editing; **C. Díaz de la Guardia**: Methodology, Resources, Data Curation, Writing - Review & Editing, Supervision.

Declaration of interests

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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SUPPLEMENTARY MATERIAL

Table S1. *Pollen thresholds for the high/very high class for some of the main allergy-causing pollen types worldwide, reported by the Aerobiological Network or Association that has established it. Values expressed in pollen*day/m*^{3}.

	METEO-SWISS [1]	**REA [2]**	**AAAAI´s NBA [3]**	**RNSA-FRANCE [4]**	**POLAND [5]**	**FINLAND [6]**	**EUROPE [7]**
Alnus	>250	>50	>500		>85	>100	>150
Ambrosia	>40		>50				
Artemisia	>50	>50	>50	>69		>30	
Betula	>300	>50	>500	>99	>75	>100	>100
Corylus	>250	>50	>500	>227			>100
Cupressus		>200	>500	>141			>150
Fagus	>400	>200					>200
Olea		>200	>500	>227			>250
Platanus	>400	>200	>500	>227			>200
Quercus	>400	>200	>500	>227			>200
Grasses	>150	>50	>50	>35	>37	>30	>50
Urticaceae		>30	>200	>69			

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