

The importance of interactions between meteorological conditions when interpreting their effect on the dispersal of pollen from homogeneously distributed sources

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Received: 26 September 2005 / Accepted: 21 July 2006
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Abstract The interaction between different meteorological conditions recorded in Badajoz (SW Spain) over a 13-year period has been studied. The results were used for analysis of the effect of these conditions on atmospheric concentrations of *Plantago* and Brassicaceae pollen grain. For both types of pollen there was a positive effect of NE winds and a negative effect of SW winds which could not be explained by the location of the sources, because these species are very abundant all around the sampling station. The two effects were interpreted on the basis of the action of these winds on temperatures and relative humidity, because these conditions physically and biologically directly determine the

concentrations of these types of pollen. Wind from the west is associated with an increase of wind speed and a decline in calm periods; wind from the south is associated with increased rainfall and humidity; wind from the opposite directions is associated with a decrease in these meteorological conditions. These main associations can explain the variation in pollen concentration, although there are also variations in seasons and years. These types of pollen also behave differently, so wind speed reduces the concentration of pollen from *Plantago* but increases it from Brassicaceae. Beyond the immediate application of the analysis to this specific case, there is a clear interest in observing the interaction between meteorological factors to gain a broader perspective for interpretation of the results of aerobiological studies aimed at determining the effect of these factors on the release and transport of particles into the air.

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Keywords Aerobiology · Pollen dispersion ·
Plantago · Brassicaceae · Meteorological
interaction

1 Introduction

In aerobiological studies, as in many other types of physical and biological study, meteorological conditions are used to explain the different kinds

of behaviour they may affect. Meteorological conditions may act in several ways on the dynamics of dispersion of particles of biological origin. As well as directly affecting the dispersion itself, they may have an indirect effect by previously influencing the status of the sources. For example, levels of pollination of many spring-flowering plants may be affected by autumn and winter rainfall. These direct effects are usually studied by determining the correlations between the daily values of the atmospheric concentrations of biological particles and the daily values of selected meteorological conditions, among which those most often used are the mean, maximum, and minimum temperatures, relative humidity, dew-point, hours of insolation, calm periods, and wind speed and direction. These analyses are performed using only the principal pollination periods, which may be calculated by a variety of methods, a good review can be found in Jato et al. (2006), who proposed the term “atmospheric pollen season” for this concept. The objective is always to use only the period when variations in concentrations depend more on the environmental conditions of release and transport than on the phenological variations of the sources. The results must always be interpreted by taking into account both how the meteorological condition affects the physiology of the organism releasing the particles (which may determine whether or not any release actually occurs), and how it affects the phenomenon of transport. Thus, the effects of temperature and humidity are usually associated with the first group of effects, considering, for instance, that humidity has a negative effect on pollen release from the anthers because they do not open when environmental humidity is high. Rainfall, however, is generally recognized to act against transport, because it precipitates grains suspended in the air and thus reduces their concentrations.

The effect of calm periods and wind speed may be explained in a variety of ways. Thus, for example, the proximity of the sampling site to the sources is usually positively related to the first of these conditions but negatively to the second, because wind tends to dilute the concentrations whereas they build up near the source in calm periods. This would be true of the behaviour of

the pollen from the families *Amaranthaceae* and *Chenopodiaceae* in different localities of Extremadura that are situated near suitable zones for the growth of the species of these families (Muñoz, Silva, Tormo, Moreno, & Tavira, 2000). In other instances, however, there may be a direct relationship between wind speed and particle release. This is true for *Plantago* species, for which there is clear inverse relationship between these factors, explained on the basis of the effect of the wind on the pollen-release process (Tormo, Silva, Muñoz, Tavira, & Moreno et al., 2001).

Most studies interpret the relationship between particle concentrations and the different wind directions according to the relative position of the sources relative to the trap. Thus, Badajoz, Silva, Tormo, & Muñoz (2000a) explain variations in the concentrations of different types of pollen with localized sources in terms of wind direction. For example, concentrations from ornamental species grown within the city limits increased when the wind was from the quadrant in which the city centre is situated whereas for species growing in zones of irrigation farming, situated to the east of the trap, concentrations increased when the wind was from that direction and decreased when it was from the west. It was shown in the same work that for some plants with major distribution all around the trap site the effect of wind direction was not very important. One can, occasionally, even use the correlation with wind direction to establish the location of the particle source when this was previously unknown. One example was the study of *Artemisia* pollen in the Extremadura region (Silva et al., 2000b) in which the known sources were insufficient to explain the amount of this pollen in the atmosphere. It was found the most probable sources were located in distant zones of SW Spain, on the basis of the effect of winds from that direction increasing the concentrations. It is, however, sometimes observed that concentrations of particles from homogeneously distributed sources vary in a way that is statistically related to variations in wind direction. This could be explained by the existence of a close relationship between this condition and another meteorological condition which also affects pollen levels.

The purpose of this study was to analyse the relationship between different meteorological conditions over an thirteen-year period in the city of Badajoz and then to use the results to attempt to explain correlations between wind direction and levels of two types of pollen with homogeneously distributed sources, and thereby demonstrate the importance of taking interactions between meteorological factors into account when interpreting the results of this type of study.

2 Material and methods

The study was conducted in the city of Badajoz from 1993 to 2005, using meteorological data acquired by the Territorial Meteorological Centre of Extremadura (Talavera station: 38°53' N; 6°49' W; 185 m over sea) and pollen-concentration data obtained in the aerobiological monitoring station located in the Escuela de Ingenierías Agrarias of the University of Extremadura (pollen station: 38°53' N; 6°58' W; 186 m above sea level; 17.4 km from the meteorological station). The study site is in the Mesomediterranean bioclimatic zone and the Luso-Extremadurensis biogeographical province; its immediate environment is strongly affected by farming activity, the percentage of land area devoted to crops is 66.4%; irrigation predominates, the town is located on the River Guadiana; the remaining vegetation cover is mainly riparian, pasture, and *Quercus rotundifolia* “dehesas” (parkland grazing systems). The meteorological conditions analysed were: mean, maximum, and minimum temperatures (°C), relative humidity (%), rainfall (mm), wind speed (km h⁻¹) and calm periods (hours) of winds from the quadrants 1 (NE), 2 (SE), 3 (SW), and 4 (NW).

The Spearman correlation coefficients were calculated for these conditions, and differences were considered significant when $p < 0.05$, previously the Kolmogorov–Smirnov test was used to test normality; the results obtained led to rejection of this hypothesis. Three groups of statistical calculations were performed—using the values for the entire study period (4,748 days, because for three days the data were unsuitable); using values separated into whole seasons (1,195 days

for spring, 1,197 days for summer, 1,184 days for autumn, and 1,084 days for winter); and using values for each year separately. The seasons were taken to be: spring, 21 March–20 June; summer, 21 June–20 September; autumn, 21 September–20 December; and winter, 21 December–20 March.

Concentration data were obtained by using a Burkard volumetric trap (Hirst, 1952). Samples were analysed by counting pollen grains in four longitudinal scans; this enables determination of the daily concentration of the different types of particles analysed.

The particles used in the analysis were *Plantago* and Brassicaceae-type pollen grains. These both consist of a large number of species widely distributed around the city and the trap (Devesa, Tormo, Ruiz, Viera, & Fernández, 1991; Gonzalo, Tormo, Muñoz, & Silva, 2006; Ortega, 1995a, 1995b), so the sources for both are scattered over all directions. The first type are spring-flowering anemophiles which are wind-pollinated. The species in the second group are entomophiles, so for these transport of pollen by the wind is incidental. For these flowering occurs mainly from autumn to spring. These types were chosen because significant correlations have been shown between their concentrations and periods of wind from a specific direction, without any explanation on the basis of their distribution (Tormo et al., 2001).

For each of the years studied we calculated the principal pollination period of the two types, by the method described by Nilsson and Persson (1981). The period calculated as that of 90% of pollination, discarding the two 5% tails at the beginning and end. For *Plantago*, we calculated this period by calendar years. For Brassicaceae, however, we used 12-month periods from September to August, because of the winter flowering. For the 1993–1994 period, therefore, we used data corresponding to 1993. We calculated the Spearman correlation coefficients for the daily concentrations in this period, again taking $p < 0.05$ as the significance level.

3 Results

Table 1 gives the mean values obtained for the entire study period, for each season, and for each

Table 1 Mean data for the different meteorological conditions for the entire study period and for each season (meanT, maxT, and minT are mean, maximum, and minimum temperatures in °C); relative humidity (RH,%); accumulated rainfall (rain, mm); wind speed (wind, km h⁻¹); calm periods (calm, h); q1, q2, q3, q4: periods of winds (h) from the quadrants 1 (NE), 2 (SE), 3 (SW), and 4 (NW)

	meanT	maxT	minT	RH	rain	wind	calm	q1	q2	q3	q4
Period 1993–2005	17.08	23.74	10.51	65.93	435.6	25.61	1.29	3.87	3.47	8.74	6.64
Spring	18.17	25.09	11.28	60.64	101.8	22.61	0.86	3.63	2.75	9.27	7.50
Summer	27.9	33.1	16.7	51.26	19.23	27.32	0.58	2.38	1.62	9.66	9.76
Autumn	14.55	20.16	9.05	74.74	182.5	22.37	2.16	4.57	4.44	8.34	4.49
Winter	10.70	16.44	5.14	77.38	126.2	25.76	1.70	4.73	4.95	7.99	4.63

of the meteorological conditions analysed, and Fig. 1 shows the monthly variations. The temperatures, relative humidity, and rainfall are typical of the evolution of a Mediterranean climate, i.e. autumns and winters that are cold, rainy, and with high relative humidity, and spring, and even more so summer, that are hot, dry, and with little rainfall. With regard to wind conditions, the geographical location of the city determines that wind speeds are greater in spring and summer and that most of the winds are from the west (Fig. 2). One sees in the figure that the winds in summer are predominantly from the south-west and north-west quadrants, and that in autumn there are fewer winds from the north-west and more from the east. The latter are most intense in winter, in which season there is approximate equality of winds from each of the four quadrants. Finally, during spring the winds with an eastern component again decline and there is an increase of winds from the west. One also sees in the figure that winds from the north-east and south-east quadrants have very similar seasonal variations, whereas those from the south-west and north-west quadrants are more independent, the latter with greater variations over the course of the year.

Table 2 gives a summary of results from analysis of correlations between meteorological conditions, showing which were significant, and their sign, in the overall analysis, in seasonal analysis, and in study of the separate years.

Temperatures and relative humidity: As was to be expected, the three temperature conditions are always positively correlated with each other and they are negatively correlated with the relative humidity. The only exception was the appearance of a positive correlation between the minimum temperatures and the relative humidity in winter.

Rainfall and temperature: At a general level, there was always a negative correlation between rainfall and maximum temperatures. This was so for all the seasons and all the years of the study. For mean temperatures, however, this relationship was observed in spring and summer only. The action of rainfall on minimum temperatures was not significant either at the general level or for any of the separate years of the study. There were, however, a significant positive correlation in autumn and winter.

Rainfall and relative humidity: As was expected, all the analyses revealed the positive effect of rainfall on relative humidity.

Wind speed and calm periods: In this case also the antagonism between these two conditions is seen in all the analyses.

Wind speed and calm periods versus temperature: The calm periods, at the overall level and with some exceptions during the separate years of the study, were negatively related to the temperatures. In analysis by season, however, in spring and summer the relationship was generally positive. For the mean and minimum temperatures the effect of wind speed was opposite to that of the calm periods, but of the same sign for the maximum temperatures. The annual correlations were, however, highly variable. Seasonal analysis showed wind to be negatively related to temperatures during spring and summer, and its effect was completely the opposite to that of the calm periods.

Wind speed and calm periods versus relative humidity and rainfall: The overall analysis showed rainfall to be positively related to wind speed whereas calm periods were positively related to relative humidity. Nevertheless, although the former relationship was present in

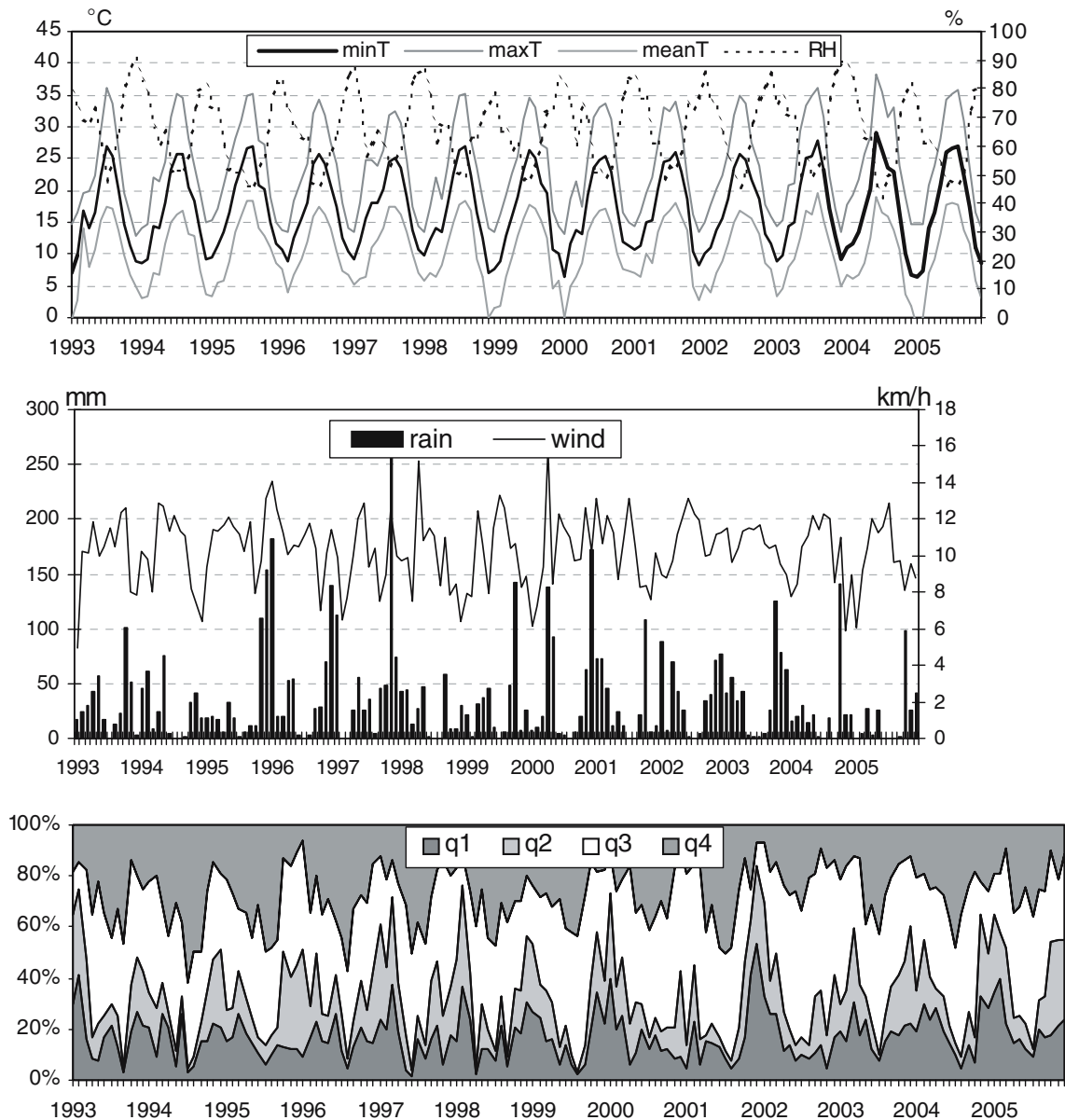


Fig. 1 Monthly variation of meteorological conditions for the period studied

most of the years of the study and in summer, autumn, and winter, annual variations in significance and sign occurred in the latter and it was, moreover, only observed in summer.

Different wind directions: In all three analyses there was a positive relationship between winds from quadrants 1 and 2 (i.e. winds from the east), negative relationships between each of these and winds from quadrants 3 and 4 (from the west),

and no constant relationship between the last two quadrants.

Wind directions and temperatures: Winds from quadrant 1 (NE) tended to decline with temperature in the overall analysis. This was true for minimum temperatures in all the separate years of the study. The correlation was not uniform over all the seasons, however, because the relationship tended to be positive in spring and

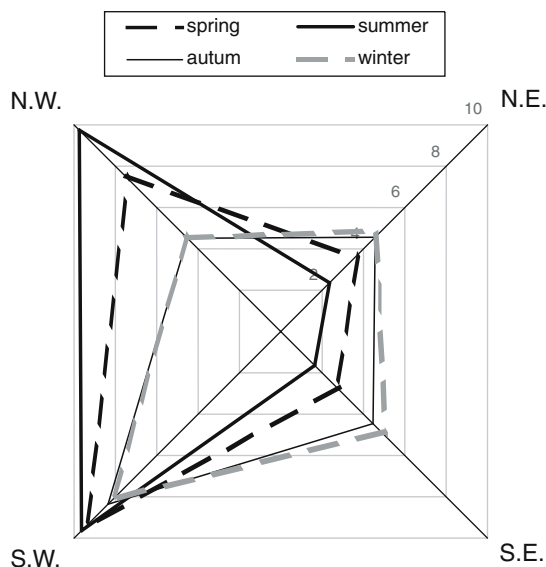


Fig. 2 Mean number of hours of the entire period of the study (1993–2005) in which the wind was from the different quadrants in each of the four seasons

summer, but negative in autumn and winter. The winds from quadrant 2 (SE) had an overall negative relationship which was repeated in most of the years analysed. At the seasonal level, however, there was a positive relationship in summer and a negative one in autumn, with this same pattern seen for the three temperature conditions. In the overall study the winds from quadrant 3 (SW) were positively related to minimum temperatures; this was also true for the years and seasons analysed separately. For the mean temperatures, however, there was a positive relationship in the overall analysis which was not present in most of the years studied separately, and only present in autumn and winter, with the relationship being negative in the other two seasons. For the relationship between winds from quadrant 3 and maximum temperatures there were no significant correlations either at the overall level or in most of the years, and at the seasonal level there was only a negative relationship during spring and summer. It is curious that, although winds from quadrant 4 (NW) were positively associated with the three temperature conditions, and this was also true for the separate years, in the seasonal study negative correlations were obtained.

Wind directions versus relative humidity and rainfall: Winds from quadrants 1 and 4 (i.e. those from the north) tended to be negatively related to both relative humidity and rainfall. This relationship was also present for most of the seasons and most of the years. Winds from quadrant 3 (SW) tended to be positively related to these two conditions, with the same effect being seen for the four seasons. Winds from quadrant 2 (SE) had an positive effect overall on relative humidity and rainfall, which was maintained to a great extent in the separate years studied. The effect, however, was not clear in the different seasons, except for winter for which the positive relationship was confirmed for both conditions.

Wind directions versus wind speed and calm periods: Winds from quadrants 3 and 4 (from the east) were positively related overall and, in almost all the years and seasons, were positively related to wind speed and negatively related to calm periods. The relationship of the winds from quadrants 1 and 2 (from the west) with these conditions was the opposite, although for their relationship with the calm periods this was only so in summer, and only in some years for quadrant 2.

Results from analysis of correlations between daily concentrations of *Plantago* and Brassicaceae pollen and meteorological conditions in the principal pollination periods for the two types of pollen in the study are given in Table 3. The spring character of *Plantago* pollination is clear, as also is the prolonged period of pollination for the Brassicaceae, which includes winter and spring.

Table 4 gives the correlations between the daily concentrations of these two types of pollen and meteorological conditions. In both types, there is a definite positive relationship with mean temperatures and, above all, with maximum temperatures. The opposite effect observed for relative humidity. The wind speed acts in most years to reduce the *Plantago* pollen concentrations.

For both types of pollen there were frequent positive correlations with winds from quadrant 1 (NE) and negative correlations with those from quadrant 3 (SW). Neither relationship was significant in 1996 or 2000 for *Plantago*, or in the 12-month periods 1995–1996 and 1998–1999 for Brassicaceae.

(A) Global analysis (1993–2005)

(C) Year analysis (1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005)

Table 2 continued

	meanT	maxT	minT	RH	rain	wind	calm	q1	q2	q3	q4
q1									+++++	-----	--00--
q2									+++++++	-----	-----
q3										-----	-----
q4										-----	000+++ ++Ho+

(A) Using all the days of the study period ($n = 4,380$); (B) using the days of spring ($n = 1,195$), summer ($n = 1,197$), autumn ($n = 1,084$), and winter ($n = 1,084$) independently; (C) using the days of each year independently (for 1999, $n = 364$; for 1993, 1994, 1995, 1997, 1998, 1999, 2001, 2002, 2003, 2005, $n = 365$; for 1996, 2000, 2004, $n = 366$). The result of each correlation is indicated as: (+) significant positive correlation; (-) significant negative correlation; (o) non-significant correlation. The significance level is taken as $p < 0.05$

4 Discussion

First, we observed the presence of very many significant interactions between the different meteorological conditions. Some of these could have a simple interpretation, such as those between the different temperatures, relative humidity, and rainfall. The relationships involving wind conditions, however, reflect the geographical situation of the locality of the study and its surroundings.

The objective of this study was not to analyse the interactions between the meteorological conditions in themselves but to use these to interpret correlations that arise when one analyses the effect of these conditions on variations in atmospheric pollen concentrations. The partial correlations calculated are only significant for two meteorological conditions—wind speed (*Plantago*: $r = -0.194$, $p = 0.000$; Brassicaceae: $r = 0.128$, $p = 0.000$) and rainfall (*Plantago*: $r = -0.115$, $p = 0.003$).

In Badajoz during the years of the study, when the direction of the winds was from the west this resulted in an increase in wind speed and a decline in calm periods. Likewise, winds from the north seem to be dry, resulting in a decline in relative humidity and rainfall, in contrast with the effects of winds from the south. Each of the three temperature conditions was distinctly influenced, with variation between seasons. Only SE winds had the same type of effect on each temperature condition, increasing them in summer and reducing them in autumn. Curiously, unlike the other wind directions, the effect of SE winds on relative humidity and rainfall was not at all constant.

There were negative relationships between winds from different directions, except for those from quadrants 1 and 2 which were positively related, because both tended to increase in parallel in winter and decline in parallel in summer.

With regard to analysis of correlations between the meteorological factors and daily concentrations of *Plantago* and Brassicaceae pollen, similar results were obtained. Both types were negatively affected by relative humidity, and positively affected by temperature. Such findings are very common in aerobiological studies, because these

Table 3 Beginning and end of the principal pollination periods calculated for *Plantago* and Brassicaceae

Plantago			Brassicaceae		
Year	Beginning	End	Period	Beginning	End
1994	31/3	23/6	1993–1994	6/12	14/6
1995	26/3	18/6	1994–1995	30/11	25/4
1996	11/4	16/6	1995–1996	15/2	12/6
1997	26/3	10/7	1996–1997	31/10	26/6
1998	26/3	4/7	1997–1998	18/10	20/5
1999	2/4	14/6	1998–1999	8/11	29/5
2000	17/3	14/6	1999–2000	8/11	8/5
2001	9/4	27/6	2000–2001	28/10	30/5
2002	27/3	30/5	2001–2002	7/3	1/5
2003	7/4	24/6	2002–2003	23/1	1/5
2004	9/4	11/6	2003–2004	7/12	27/5
2005	6/4	21/6	2004–2005	19/2	7/5

two conditions are related to the release and transport of pollen (Norris-Hill, 1997).

More notable is the negative relationship between wind speed and concentrations of *Platanago* pollen. This is interpreted as an effect on pollen release rather than on its transport (Tormo et al., 2001).

The relationships which motivated inclusion of these two types of pollen in this study were, however, that both are positively affected by winds from the east, especially those from quadrant 1, and negatively by winds from the SW. The species in the two types are widely distributed over all the habitats around the trap, and concentrations should not therefore be directly related to wind direction. Indeed, such independence of wind direction was found to be true for other types of pollen of similar distribution in an earlier study at the same observatory (Silva et al., 2000a). For *Plantago*, Tormo et al. (2001) found similar correlations at three sampling stations which they studied in Extremadura: Badajoz, Mérida, and Cáceres. For this type of pollen the correlations indicated above with temperature, relative humidity, and wind-path were observed, and there were negative correlations with winds from quadrant 3. There were also some positive correlations with winds from quadrant 1. These three sites have quite different surroundings, which led the authors to postulate that the reason must be the interaction between meteorological factors. This has been borne out in this study. It is

Table 4 Results from analysis of correlations between daily *Plantago* and Brassicaceae pollen concentrations and meteorological conditions

[illegible]

The results from each year of the study are given consecutively: (+) significant positive correlation; (-) significant negative correlation; (o) non-significant correlation. The significance level is taken as $p < 0.05$

also supported by the fact that, for the Brassicaceae type, the relationships with the winds observed during 1997 and 1998 were similar to those found at Badajoz (Moreno, 2001).

The effect of these winds could be because of their effect on temperatures or on relative humidity. Thus, NE winds are negatively related to both temperature and humidity, which would imply that their effect on the latter is the cause of the correlations found with pollen levels. Nevertheless, during winter and spring these winds have a positive effect on maximum temperatures, so that their action must be interpreted as a conjoint effect on both conditions.

The negative effect of SW winds (quadrant 3) on *Plantago* pollen concentrations must be interpreted on the basis of their positive effect on relative humidity in all seasons and on mean and maximum temperatures during spring. For Brassicaceae pollen, the only possible explanation is their effect on relative humidity, because a major part of the principal pollination period of Brassicaceae is in winter, and these winds have no negative effect on temperature in that season.

To summarise, correlations between the daily biological particle concentrations in the atmosphere and the different meteorological conditions may usually be analysed on the basis of the effect on the biological and physical factors that directly determine pollen release and transport (Mäkinen, 1977; McDonald, 1980). Occasionally, however, such simple explanations may lead to mistaken interpretations, and the interaction between the factors must be taken into account. It would thus always be advisable in these studies to conduct prior analysis of these interactions, to enable viewing of the results from a wider perspective.

Acknowledgement This study was financed by the project grants IPR00A032 granted by the Consejería de Educación y Juventud of the Junta de Extremadura.

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