STUDY OF THE METEOROLOGICAL MECHANISMS CONTROLLING LEVELS AND TRANSPORT PROCESSES OF AIRBORNE POLLEN IN THE ATMOSPHERE

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Abstract

Aerobiology is the science that focuses on the study of the airborne living organisms (bacteria, fungal spores, pollen, small insects, etc.). Aerobiology includes a number of specialties such as aerosol physics, biometeorology, respiratory physiology, and many others. The influence of meteorology, climate and climate change on ecosystems has been largely recognized in the literature in the recent years. Some effects of climate variability on plant phenology include shifts in the timing of the pollination seasons or an increase of the pollen production of different plants. Moreover, atmospheric pollen can be considered a very sensitive indicator of climate variability. In this sense, aerobiological databases provide useful information for understanding the trends induced by climate change.

The present study explores the role of meteorological and climatological variability in the pollen dynamics. The main standardized airborne pollen parameters (Annual Pollen Integral (APIn), Start, End and Length of the main pollen season) of 22 taxa collected by the Xarxa Aerobiològica de Catalunya (XAC) at 6 localities in Catalonia (Barcelona (BCN), Bellaterra (BTU), Girona (GIC), Lleida (LLE), Manresa (MAN) and Tarragona (TAU)) during the 18-year period from 1994 to 2011, have been considered.

Correlations between precipitation, insolation and temperature and the main pollen parameters have been investigated. Considering that the main pollen season of most of the taxa in Catalonia lasts from spring to summer or autumn, correlations between the pollen parameters and winter (from December to March) values of meteorological variables were also calculated. The results obtained report the synchronism registered in the variations of pollen concentration with precipitation (negative), insolation (positive) and temperature (positive). Temperature was the meteorological variable that showed a greater influence in the pollen production and the timing of the pollen season, being insolation the least one. The Start of the Main Pollen Season was the pollen parameter more correlated with the meteorological variables, especially with winter temperatures.

The influence of the climate variability associated with Northern Hemisphere teleconnection patterns (North Atlantic Oscillation, Arctic Oscillation and Western Mediterranean Oscillation) over the main pollen parameters has been also investigated. For most of the taxa, positive phases of the 3 climatic indices were related to a decrease in the APIn and an advance and enlargement of the main pollen season. Furthermore, negative phases of the climatic indices were linked to higher pollen production via an increase in rainfall. A clear relationship between climatic indices and the End of the main pollen season was not observed.

In order to study the effect of local winds, 12 pollen types with sources are situated near the aerobiological stations were considered. It was found that a positive correlation, thus an increase of pollen concentration, exists when the wind blows towards the station from the direction of the source location, and negative correlation, meaning dispersion and cleaning processes, results when the wind blows in a direction from the station towards the source of pollen or coming from the sea. This study could also be useful not only to identify and locate airborne pollen sources but to detect changes in the geographical distribution of vegetation near the sampling stations. The cleaning and dispersion effect over the pollen concentrations has been observed on the coastal stations (BCN, BTU and TAU) mainly due to the wind induced by the sea breeze effect (SW and SE) and on the inland stations (LLE and MAN) when westerly frontal synoptic situations are produced.

Two forecasting models were used to predict the Start of the main pollen season. Taking into account that temperature is one of the primary factors affecting blossoming, the first method consists on the cumulative sum of the daily average temperatures from a statistically determined initial date and above a thermal threshold. The second method consists on a multiple regression using rainfall and temperatures. These two models were tested by computing the discrepancy between the predicted and the observed values by means of different quantitative metrics commonly used to test the behaviour of models. The Root Mean Square Error (RMSE) ranged from 0.7 days for *Pistacia* in Manresa by the multiple regression model, up to 10 days for other taxa and stations. *Platanus* was the taxon showing the best results for all the stations.

Long-range atmospheric transport of pollen over Catalonia has been also investigated. A source-receptor model has been applied to the study of the source areas of pollen that arrive to the northeast of the Iberian Peninsula transported by the wind. Specifically, this work presents the results of applying the model to estimate the source areas of 6 pollen taxa that, not being very abundant in the territory, episodically present high values and hence are susceptible to come from distant sources: *Ambrosia, Betula*, *Corylus*, *Fagus*, *Fraxinus*, and *Olea.* Apart from the great scientific interest that lies in the modelling of the source areas to understand the life cycles of the species, the use of these models can be useful to biologists, allergists, and environmental quality managers in the study and treatment of problems such as respiratory allergies.

Resum

L'aerobiologia és la ciència que estudia els organismes vius aerovagants (bacteris, espores, pol·len, petits insectes, etc.). L'aerobiologia inclou una sèrie d'especialitats com ara la física d'aerosols, la biometeorologia, la fisiologia respiratòria i molts d'altres. La influència de la meteorologia, el clima i el canvi climàtic en els ecosistemes ha estat àmpliament reconeguda en la literatura en els últims anys. Alguns efectes de la variabilitat climàtica en la fenologia vegetal inclouen canvis en els períodes de pol·linització o un augment de la producció de pol·len de diferents plantes. A més, el pol·len atmosfèric pot considerar-se un indicador molt sensible de la variabilitat climàtica. En aquest sentit, les bases de dades aerobiològiques proporcionen informació útil per comprendre les tendències induïdes pel canvi climàtic.

El present estudi explora el paper de la variabilitat climàtica i meteorològica en la dinàmica del pol·len. El principals paràmetres de pol·len (Annual Pollen Integral (APIn), i l'inici, el final i la durada del període de pol·linització) per a 22 tàxons recollits per la Xarxa Aerobiològica de Catalunya (XAC) a 6 estacions de Catalunya (Barcelona (BCN), Bellaterra (BTU), Girona (GIC), Lleida (LLE), Manresa (MAN) i Tarragona (TAU) durant els anys 1994 – 2011, han estat l'objecte de l'estudi.

S'ha investigat la correlació entre precipitació, insolació i temperatura i els principals paràmetres de pol·len. Considerant que el període de pol·linització de la majoria dels tàxons a Catalunya comença a la primavera i s'estén fins a l'estiu o la tardor, també es van calcular les correlacions entre els paràmetres de pol·len i els valors hivernals (de desembre a març) de les variables meteorològiques. Els resultats obtinguts mostren el sincronisme registrat entre la concentració de pol·len i la precipitació (negativa), la insolació (positiva) i la temperatura (positiva). La temperatura va ser la variable meteorològica que va mostrar una major influència en la dinàmica del pol·len, sent la més baixa la insolació. L'inici del període de pol·linització va ser el paràmetre més correlacionat amb les variables meteorològiques, especialment amb les temperatures hivernals.

També s'ha investigat la influència de la variabilitat climàtica associada als principals modes de circulació de l'Hemisferi Nord (Oscil·lació de l'Atlàntic Nord, oscil·lació Àrtica i oscil·lació de la Mediterrània Occidental) sobre els principals paràmetres de pol·len. Per a la majoria dels tàxons, les fases positives dels 3 índexs climàtics es van relacionar amb una disminució de l'APIn i una anticipació i extensió del període de pol·linització. A més, les fases negatives dels índexs climàtics es van associar a una major producció de pol·len a causa de l'augment de la pluja. No es va observar una clara relació entre els índexs climàtics i el final del període de pol·linització.

Per estudiar l'efecte dels vents locals, es van considerar 12 tipus de pol·len amb fonts situades a prop de les estacions. Es va trobar que hi ha una correlació positiva, es a dir un augment de la concentració de pol·len, quan el vent bufa cap a l'estació des de la localització de la font, i una correlació negativa, es a dir processos de dispersió i neteja, resultat del vent que bufa de l'estació cap a la font del pol·len o venint del mar. Aquest estudi també podria ser útil no només per identificar i localitzar fonts de pol·len, sinó per detectar canvis en els usos del sòl a prop de les estacions de mostreig. L'efecte de neteja i dispersió de les concentracions de pol·len s'ha observat a les estacions costaneres (BCN, BTU i TAU), principalment a causa del vent induït per l'efecte de la brisa marina i sobre les estacions interiors (LLE i MAN) quan es produeixen situacions sinòptiques frontals de l'oest.

Dos models de pronòstic s'han utilitzat per predir l'inici del període de pol·linització. Tenint en compte que la temperatura és el factor primari que afecta la floració, el primer mètode consisteix en la suma acumulada de la temperatura mitjana diària des de una data inicial calculada estadísticament i per sobre d'un llindar tèrmic. El segon mètode consisteix en una regressió múltiple amb precipitacions i temperatures. Aquests dos models es van provar calculant la discrepància entre els valors previstos i els observats mitjançant diferents mètriques quantitatives que s'utilitzen habitualment per provar el comportament dels models. L'error quadràtic mitjà va oscil·lar entre els 0,7 dies per a *Pistacia* a Manresa, fins a 10 dies per a altres tàxons i estacions. *Platanus* va ser el taxó que va mostrar els millors resultats per a totes les estacions.

També s'ha investigat el transport atmosfèric de pol·len de gran abast a Catalunya. El model de font-receptor es va aplicar per estimar les àrees d'origen de 6 tàxons que no són molt abundants al territori, però presenten episodis puntuals de concentracions elevades i, per tant, són susceptibles de procedir de fonts llunyanes: *Ambrosia, Betula*, *Corylus*, *Fagus*, *Fraxinus* i *Olea.* A part del gran interès científic que resideix en la modelització de les àrees d'origen, l'ús d'aquests models pot ser útil per a biòlegs, al·lergòlegs i responsables de qualitat ambiental en l'estudi i tractament de problemes com les al·lèrgies respiratòries.

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1.2.2. Airborne pollen parameters

1.3. Climate of Catalonia

1.4. Objectives and outline

1.4.1. Publications

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1.1. Introduction

Aerobiology is the branch of biology that studies the transportation of biological particles through the air. Biological particles are present in the atmosphere in form of pollen grains, fungal spores, bacteria, viruses and fragments of plants, fungi and animals. Matthias-Maser et al. (2000) suggested that the proportion by volume of the total airborne particulate matter made up by biological material in remote continental, populated continental and remote maritime environments is respectively 28%, 22% and 10%.

Pollen has a very important role to trigger allergic respiratory diseases. Human health is directly affected by the presence of high concentrations of pollen in the atmosphere (Traidl-Hoffmann et al., 2003), which varies according to climate, geography and vegetation. Data on the presence and prevalence of allergenic airborne pollens obtained from both aerobiological studies and allergological investigations allow the design of pollen calendars with the approximate flowering period of the plants in the sampling area. Europe is a geographically complex continent with a widely diverse climate and a wide spectrum of vegetation. Forecasting of how much pollen will be produced in a given season and when it will become available for release into the atmosphere is of crucial importance. The environmental drivers controlling the dynamics of pollen season must be known to implement pollen production and transport in the simulation models (Duhl et al. 2013). The amount of pollen collected at a sampling station is dependent, first, on the amount of emission sources in the surrounding regions and, second, on the weather, that affects the strength and timing of the emissions as well as the atmospheric transport (Zhang et al. 2013). Different techniques have been used in the modelling of airborne pollen: regression analyses (Stach et al., 2008a), multivariate statistical methods (Makra et al. 2006), Lagrangian modelling (Kuparinen et al., 2007; Izquierdo et al. 2015b), Large Eddy simulation (Chamecki et al., 2009), mesoscale and long-range transport models (Pasken and Pietrowicz, 2005; Siljamo et al., 2008; Sofiev et al., 2006; Belmonte et al., 2008).

Climate changes, both when they occur for a short period of time or when they are long-lasting or permanent lead to changes in the patterns of the climatic elements such as temperature, precipitation, and wind. This can affect the phenology and the concentration of pollen in the atmosphere over a specific location (Cowie, 2007). Phenological data are simple to record, and the scientific community has pointed out the value of historical, phenological databases for the climate change research. A meta-analysis, comprising different species in European countries, has shown that the response of spring phenology to temperature is unquestionable (Menzel et al. 2006). Changes in phenology depend on the season when they take place, and also on climatic trends (Gordo and Sanz 2005). In general, it has been demonstrated that greater phenological changes are recorded in those events that occur earlier in the year, from early spring to summer. However, for phenological events that occur in autumn, it is more difficult to define a pattern since greater interannual oscillations occur (Menzel et al. 2006; Gordo and Sanz 2005).

In Europe, an increase of annual mean temperature in the last 30 years has been associated with an advance of the start of the growing season and an increase of its duration; although the end of the growing season has shown a lower variability in all regions of Europe (Chmielewski and Rötzer 2001). Studies at regional scale have shown that the rate of change is higher in Western Europe and Scandinavia and that different phenological rhythm and trends occur in the Eastern part of Europe (Ahas et al. 2002; Chmielewski and Rötzer 2001). Most of the long-term phenological studies have been focused on Northern Europe, while comparatively few have addressed the Mediterranean region (Peñuelas et al. 2002; Gordo and Sanz 2005). For instance, it is important to consider that in the Mediterranean region other variables related to changes in rainfall and water availability are also important (Peñuelas et al. 2004). However, Gordo and Sanz (2005) suggested that the relationship between water availability and different phenological phases is difficult to quantify. Furthermore, at the regional level in Europe, it is important to consider the role of NAO in governing the temporal variability of the lower atmosphere, and thus phenological dates in Europe (Scheifinger et al. 2002; Chmielewski and Rötzer 2001). The NAO is the dominant mode controlling climate over Europe (especially in winter and spring). It is characterized by the longitudinal oscillation of atmospheric mass between the two dominant pressure systems over the North Atlantic sector, namely the Azores high and the Icelandic low (Hurrell 1995). Its positive state (the high-pressure difference between the Azores high and the Icelandic low) is connected with the increased zonal flow and causes northern Europe to experience wet and mild winters, while over southwestern Europe, winters are anomalously dry (Xoplaki et al. 2004). The NAO accounts for a significant amount of the interannual variation in temperatures in the North Atlantic (Menzel et al. 2006; Post and Stenseth 1999). Plant phenology in this region is therefore influenced by year-to-year variations in the NAO (D'Odorico et al. 2002; Stenseth et al. 2002). The maximum influence of the NAO on phenological dates is found on early phases and decreases with an increasing year-day (Scheifinger et al. 2002). The influence of the NAO is also reduced with increasing distance from the Atlantic coast (Scheifinger et al. 2002; Ahas et al. 2002; Menzel et al. 2006). Climate change may also influence the behaviour of the NAO. This may enhance or mask climate change on a regional level, which may lead to regionally very different implications of climate change on plant phenology. In this context, the influence of the NAO on phenological trends should be mentioned. A recent example is the change of the NAO from predominantly negative to positive states around 1990. This change advanced many phenological dates leading to pronounced trends. Hence recent trends in phenological time series should be interpreted along with changes in the NAO.

One indirect consequence of the airborne pollen transport is the appearance of allergic reactions in humans when the pollen is inhaled and its proteins are released, thereby forming antigens to which the immune system reacts, provoking allergic symptoms (Palacios el al., 2000). The climate changes affect the symptoms of allergy in two opposite significant ways, which are unexpected yet. The first effect, global warming, may boost the length and severity of the pollen season. In contrast, this increase of the Earth's temperature can produce a decline of the symptoms of asthma and rhinitis D'Amato et al., (2015).

The study of pollen grains and spores in the atmosphere helps to predict when the flowering of plants will take place, both those that produce allergenic pollen and those that are important for the agriculture, thus allowing measures to be taken in advance (Spieksma & Nikels, 1998; Frenguelli et al., 1992). One of the most important aspects of aerobiological studies is to explore forecasting models that help to predict the date of the beginning of the pollination season. The forecast of the beginning has a particular importance because this information is very useful for accurate use of medicine for allergies and for the planning of the patient's activities. In the last decades, there have been many studies on aerobiology that have focused on the pollen seasons, especially on allergenic pollen. This leads to a line of research involving the effect of meteorological factors at the start of the pollination period of anemophilous plants (Frenguelli et al., 1991).

Different aerobiological studies, based on long historical databases, have shown earlier pollen seasons during recent years as a result of temperature increase, most of them related to spring flowering trees (Garcia-Mozo et al. 2006; Galán et al. 2005; Emberlin et al. 2007; Damialis et al. 2007; Frei and Gassner 2008; Bonofiglio et al. 2009; Orlandi et al. 2009). The greatest advances observed in earlier rather than later spring pollen seasons are probably due to the high dependency on temperature of early spring tree species, such as hazel, alder and birch.

During transport by wind, pollen grains are influenced by several factors, including prevailing climatic conditions. Small apertures in the exine offer the best protection against desiccating climatic conditions. The atmospheric pathway is the fastest and the simplest way for biological agents to spread over terrestrial ecosystems. Many organisms can significantly increase the efficiency of their movements by taking advantage of air currents (Isard et al. 2005). Biota that is present in the atmosphere ranges in size from very small (viruses, bacteria, pollen, and spores) to quite large (seeds, aphids, butterflies and moths, songbirds, and waterfowl) (Westbrook and Isard 1999). The link between these biological systems and the atmosphere is the key to understanding the population dynamics of and diseases spread by aerobiota. Biologically-relevant dispersion of bioaerosols affects the structure of ecosystems, since pollen is responsible for gene flow (Ellstrand 1992; Ennos 1994; Burczyck et al. 2004; Belmonte et al. 2008), and it contributes in determining the spatial distribution of plant species (Smouse et al. 2001; Schmidt-Lebuhn et al. 2007; Belmonte et al. 2008).

1.2. Pollen observations and modelling

Pollen is a biological structure functioning as a container, in which is housed male gametophyte generation of the angiosperms and gymnosperms (D'Amato et al. 2007). Such a container is an evolutionary adaptation for life out of water because it protects male gametes from adverse atmospheric influence while transferring from anthers (male) to stigma (female) by various means: wind, water, insects, etc.; this process is known as pollination.

Aerobiologists played a key role in the understanding of the relationship between allergic diseases and pollen, especially through the standardization of the procedure for the assessment of pollen concentration in the atmosphere. The pollen concentration has been used for over 50 years for the assessment of allergen exposure both in clinical practice and clinical experimental studies. The method, proposed by Hirst (1952) is based on the identification and count with a microscope of pollen and spores collected with a volumetric trap and provide the standard for the national networks which are currently covering most of the European continent. This method allows a comprehensive evaluation of airborne particles with a wide spectrum of applications; longer time-series are now available, which can be used for pollen calendars and for research purposes. In this regard 20–25 years long datasets provide an extraordinary tool for climate change studies, showing both changes in the past decades and providing the basis for modelization of future scenarios (Cecchi et al. 2010).

The importance of particular pollen grain from the allergological point of view depends both on pollen allergological potency and pollen abundance in the atmosphere. According to these two prerequisites, 12 pollen types originating from anemophilous plants are of particular allergological interest: ragweed (*Ambrosia*), alder (*Alnus*), mugwort (*Artemisia*), birch (*Betula*), goosefoots (Chenopodiaceae), hazel (*Corylus*), cypresses including yews (Cupressaceae), olive (*Olea*), plane tree (*Platanus*), grass (Poaceae), oak (*Quercus*) and wall pellitory, including stinging nettle (Urticaceae).

1.2.1. Pollen records: Aerobiological Network of Catalonia

Airborne pollen data were recorded by the Aerobiological Network of Catalonia (XAC) at six stations located in Barcelona (BCN) and Bellaterra (BTU) over an 18-year period from 1994 to

2011, and in Girona (GIC), Lleida (LLE), Manresa (MAN) and Tarragona (TAU) over a 16-year period from 1996 to 2011 (Figure 1.1).

The six aerobiological stations are located in three different environments:

- Barcelona (large city) and Tarragona (medium sized city) are on the coast and have the highest population.
- Lleida and Manresa (medium sized cities) are on the continental rural plain with a pronounced thermal amplitude and notable dry summer period.
- Bellaterra (University campus, semi-urbanized area) and Girona (medium sized city) are located inland with semi-humid and intermediate climatic conditions.

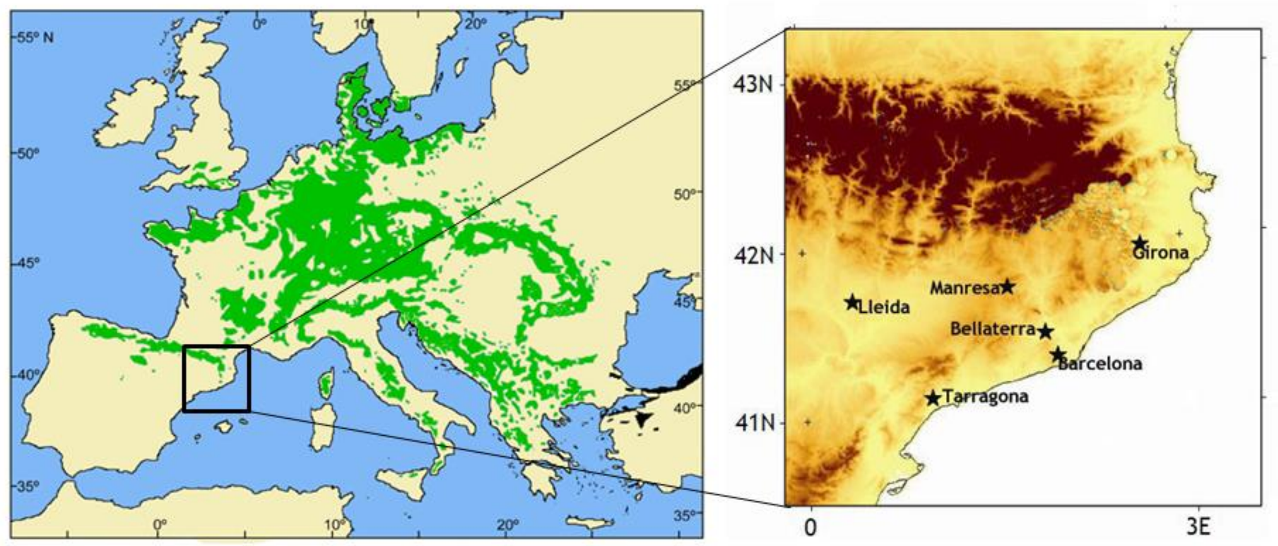

Figure 1.1: Area under study and sampling stations of the Aerobiological Network of Catalonia (XAC).

Samples were obtained daily from Hirst samplers, (Hirst, 1952), the standardized method in European aerobiological networks, and analysed following the standardized Spanish and European method (Galán et al., 2007; Galán et al., 2014). The Annual Pollen Integral (APIn, sum of the mean daily pollen concentrations in a year for the pollen season) has been used as the measure of the pollen, and obtained for 22 pollen taxa considered of high interest due to the abundance, landscape importance and/or allergenic significance (Table 1.1): *Alnus*, *Ambrosia, Artemisia*, *Betula*, *Castanea*, Chenopodiaceae/Amaranthaceae, *Corylus*, Cupressaceae, *Fagus*, *Fraxinus*, *Olea*, *Pinus*, *Pistacia*, *Plantago*, *Platanus*, Poaceae, Polygonaceae, Total *Quercus, Quercus* deciduous type (which includes *Q. canariensis* Willd., *Q. faginea*, Lamk., *Q. humilis* Mill., *Q. petraea* (Matt.) Liebl., *Q. pyrenaica* Willd., *Q. robur* L. and exceptionally the evergreen species *Q. suber* L.), *Quercus* evergreen type (which includes *Q. ilex* L. and *Q. coccifera* L.), *Ulmus* and Urticaceae (de Bolòs & Vigo, 2005).

Table 1.1: Pollen taxa under study.

Pollen taxa	Plant type			Plant biogeography					Plant use			
	T	**B**	**H**	**BA**	**ES**	**SM**	**M**	**Cm**	**S**	**R**	**C**	**O**
Alnus	T				ES				S			(O)
Ambrosia			H				M		S	R		
Artemisia			H					Cm	S	R		
Betula	T			BA	ES				S			O
Castanea	T					SM			S			(O)
Chenop./Amar.			H					Cm	S	R		
Corylus		B			ES				S		C	
Cupressaceae	T	B			ES		M		S		C	O
Fagus	T				ES				S			(O)
Fraxinus	T				ES	SM			S			O
Olea	T						M		S		C	O
Pinus	T			BA	ES	SM	M		S		C	O
Pistacia		B					M		S			
Plantago			H					Cm	S	R		
Platanus	T					SM	M		S		C	O
Poaceae			H					Cm	S		C	(O)
Polygonaceae			H					CM	S			
Quercus Total	T	B			ES	SM	M		S			O
Quercus deciduous t.	T				ES	SM	M		S			O
Quercus evergreen t.	T	B					M		S			O
Ulmus	T				ES				S			O
Urticaceae			H					Cm	S	R		
	T - tree **B** - bush **H** - herb			**BA** - Boreo Alpine region **ES** - Euro-Siberian region **SM** - Sub-Mediterranean province **M** - Mediterranean region **Cm** – Cosmopolitan (all regions)					**S** - Silvestre or wild (not urban) **R** - Ruderal **C** – Cultivated (agriculture &forestry) **O** - Ornamental			

1.2.2. Airborne pollen parameters

The pollen parameters included in this study are: Annual Pollen Integral (**APIn**, sum of the mean daily pollen concentrations in a year), the dates of **Start** and **End** of the Main Pollen Season and the **Length** (number of days between the Start and the End). The Main Pollen Season (**MPS**) has been established as the period beginning the date (Start) in which the sum of the daily mean pollen concentrations reaches 2.5% of the annual sum and ending the date (End) in which the sum reaches 97.5% (Andersen, 1991).

The 22 pollen taxa considered in this paper are the most abundant in the sampling stations of Catalonia and accounted for 83-94% of Total Pollen recorded (Table 1.2). The 22 taxa have different roles in the environments. Most of them (15) are trees/shrubs and the rest (7: *Ambrosia*, *Artemisia*, *Chenop./Amar*., *Plantago*, Poaceae, Polygonaceae and Urticaeae) are herbs. They are taxa especially important in the natural landscape (*Alnus*, *Artemisia*, *Betula*, *Castanea*, *Corylus*, *Fagus*, *Fraxinus*, *Pinus*, *Pistacia*, Poaceae, *Quercus* and *Ulmus*) and or in the urban areas, due to the use as ornamental plants (*Betula*, Cupressaceae, *Fraxinus*, *Olea*, *Platanus*, *Ulmus*) and their capacity to leave in ruderal areas (*Chenop./Amar*., Polygonaceae, Urticaeae).

As shown, Cupressaceae, Total *Quercus*, *Platanus, Pinus* and *Quercus* evergreen type are the main contributors to the pollen spectra. Here they are cited in decreasing order of importance taking into consideration the mean APIn for Catalonia, but at each locality they are also situated in the positions 1 to 5 in order of importance, with the only exception of *Platanus* that in Girona, Lleida and Tarragona is located between positions 6 and 8. Cupressaceae and *Platanus* are planted as ornamental trees in urban and urbanized areas, and this is the main cause of their abundance in the airborne spectra. *Quercus* (evergreen and deciduous type) and *Pinus* are the main trees in the Catalan landscapes; moreover sometimes they are also planted in the cities as ornamental. Regarding pollen taxa from herbaceous plants, the main contributors are from the Urticaceae family, containing ruderal plants usually abundant in urban and urbanized areas, the Poaceae family, present everywhere although specially abundant in grasslands and open landscapes, and *Plantago*, a genus of plants abundant in grasslands. Also important to be cited is the Amaranthaceae family (here cited as Chenopodiaceae/Amaranthaceae pollen type), composed by ruderal plants and plants from dry and salty environments included littoral landscapes.

Girona is the locality showing the highest APIn, followed by Manresa, Barcelona, Bellaterra, Tarragona and Lleida. This means that the localities with higher precipitation (Table 1.3) show higher pollen concentrations and those continental meteorological conditions (Lleida) contributes to lower pollen concentrations.

Table 1.2: Mean values of Annual Pollen Integral (APIn) for each individual pollen taxon and for Total Pollen (expressed in pollen day m^{-3}) collected at the 6 sampling stations for the period 1994-2011 or 1996-2011. See also in the last column the mean values for Catalonia.

	Barcelona **BCN**	Bellaterra **BTU**	Girona **GIC**	Lleida **LLE**	Manresa **MAN**	Tarragona **TAU**	**Catalonia**
Alnus	159	149	703	517	154	85	295
Ambrosia	8	11	8	5	5	3	7
Artemisia	145	166	85	378	182	227	197
Betula	196	183	302	72	141	131	171
Castanea	252	165	551	70	102	179	220
Chenop./Amar.	530	483	426	4133	958	590	1187
Corylus	227	224	531	103	204	982	379
Cupressaceae	6889	6592	6750	8160	7981	9015	7565
Fagus	18	19	74	19	18	14	27
Fraxinus	281	272	1779	266	404	352	559
Olea	1234	1088	869	2153	2375	3081	1800
Pinus	4783	8067	6864	2614	6797	4142	5545
Pistacia	73	120	65	77	181	116	105
Plantago	392	979	703	982	3774	516	1224
Platanus	15915	4108	5186	1710	5367	1337	5604
Poaceae	1119	1496	2096	2304	2389	1233	1773
Polygonaceae	78	77	131	136	73	79	96
Quercus Total	4911	7208	15618	3665	5065	3961	6738
Quercus deciduous t.	1007	2247	5528	749	1228	633	1899
Quercus evergreen t.	3904	4961	10090	2916	3837	3328	4839
Ulmus	128	268	108	67	309	284	194
Urticaceae	2889	2173	3193	1050	3282	3401	2665
Other taxa	2520	5936	9465	3457	3794	3146	4718
Total Pollen	**42747**	**39784**	**55498**	**31938**	**43555**	**32874**	**41066**

1.3. Climate of Catalonia

The climate in Catalonia is governed by processes linked to mid-latitude circulation patterns, but also by phenomena with subtropical characteristics. Its climatic diversity is strongly influenced by the Mediterranean Sea and the orography. The Pyrenees, all along the North border between France and Catalonia, act as a barrier in many parts of the country against the northern and northwestern flows. At the same time, the effects of the Mediterranean perturbations are limited to the coast line and have less effect than expected inland because they are reduced by the Littoral and Pre-littoral chains than run parallel to the coast from north to south in Catalonia. Also, the Iberian Peninsula lessens the intensity of rainfall generated by westerlies that arrive from the Atlantic reaching the Spanish Mediterranean littoral. Consequently, only northwestern Catalonia remains significantly affected by Atlantic perturbations.

The Littoral (where BCN and TAU are) and Pre-littoral areas (with BTU and GIC) are governed mainly by Mediterranean advection, where the effect of frontal passages coming from the Atlantic is less significant. The central basin (with LLE and MAN) is protected against the Mediterranean advection by the Littoral and Pre-littoral chains and also against northern outbreaks by the Pyrenees. Furthermore, fronts coming from the Atlantic are weakened by their trajectory across the Iberian Peninsula. Table 1.3 shows geographical and climatic information about the 6 localities of Catalonia included in this study.

Table 1.3: Information about 6 monitoring sites during the period considered in the study, including geographical location (altitude, latitude and longitude), and climatic characteristics (mean annual temperature and total annual rainfall) during the years included in the study (1994-2011).

	Geographical characteristics			Climatic characteristics	
Station	**Altitude (m.a.s.l)**	**Latitude**	**Longitude**	**Mean annual temperature (ºC)**	**Total annual precipitation (mm)**
Barcelona	93	41º 24' N	02º 11' E	15.8	602
Bellaterra	245	41º 33' N	02º 07' E	15.6	562
Girona	98	41º 59' N	02º 60' E	16.1	702
Lleida	202	41º 37' N	00º 37' E	14.7	319
Manresa	291	41º 44 'N	01º 50' E	14.9	597
Tarragona	44	41º 07' N	01º 15' E	16.4	551

The total annual precipitation over the 6 stations is 3333 mm although spatial distribution of the rainfall varies from each station. The lowest value is registered in Lleida (319 mm) and the highest value is registered in Girona (702 mm). Figures 1.2 show monthly values of precipitation and maximum, mean and minimum temperatures averaged for all the years included in the study for the six stations. The rainfall displays a clear picture of the Mediterranean climate pattern for all the stations: the maximum precipitation occurs in autumn and the minimum in summer. In Barcelona, Bellaterra, Girona, and Manresa the wettest month is October, and for Lleida and Tarragona, the wettest month is September. July is the driest month for all the stations except for Girona that is June.

Figures 1.2: Monthly values of precipitation and maximum, mean and minimum temperatures averaged for all the years included in the study (1994-2011) for the stations of BCN, BTU, GIC, LLE, MAN and TAU.

1.4. Objectives and outline

Chapter 2: Influence of meteorological variables on airborne pollen levels.

In this chapter, we aim to investigate the influence of meteorology on the airborne pollen dynamics through correlation analysis between precipitation, insolation and temperature and the main pollen parameters characterizing the pollination season for 22 taxa collected at 6 localities in Catalonia during the 18-year period 1994-2011. The pollen parameters included in this study are: Annual Pollen Integral (APIn, sum of the mean daily pollen concentrations in a year), Monthly Pollen Integral (MPIn, sum of the mean daily pollen concentrations in a month), the dates of Start and End of the Main Pollen Season (MPS) and the Length (number of days between the Start and the End). Spearman's rank correlation coefficient will be applied to measure the relationship between pollen data (APIn, MPIn, Start, End and Length of the MPS) and the meteorological variables. Considering that the MPS of most of the taxa in Catalonia lasts from spring to summer or autumn, correlations between the pollen parameters and winter (from December to March) values of meteorological variables will be calculated. Correlations between MPIn and monthly values of the meteorological variables will be also calculated.

Chapter 3: Influence of the wind on the daily airborne pollen concentrations.

The aim of this chapter is to analyse the influence of wind speed and wind direction on the daily airborne pollen concentrations for 12 pollen taxa recorded at 6 aerobiological stations in Catalonia during the 11 years-period 2004-2014. We will focus on those pollen types which sources are situated near the station and have a major representation in the atmosphere. The wind direction will be divided into 8 sectors: north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W) and northwest (NW). For each sector, the correlation between the daily pollen concentration and the daily mean wind speed will be computed using Spearman's rank correlation coefficient. We will limit our study to days without precipitation during the Main Pollen Season of each taxon.

Chapter 4: Influence of atmospheric teleconnection patterns on airborne pollen levels.

In this chapter, we aim to investigate the correlation between the atmospheric teleconnection patterns and the main standardized airborne pollen parameters of 22 taxa collected at 6 localities in Catalonia during the 18 years-period 1994-2011, in order to determine the effect of climate variability on their pollen dynamics. Climate indices reduce complex space and time variability of the atmospheric teleconnections patterns and gathering different climatic variables into simple measures. The most influence climatic indices in the western Mediterranean region are the North Atlantic Oscillation (NAO), the Western Mediterranean Oscillation (WeMO) and the Arctic Oscillation (AO). The pollen parameters included in this study are also the Annual Pollen Integral (APIn), the dates of Start and End, and the Length of the Main Pollen Season (MPS). Spearman's rank correlation coefficient will be applied to measure the relationship between pollen data (APIn, Start, End and Length of the MPS) and the climate indices.

Chapter 5: Forecasting the Start of the Main Pollen Season.

The goal of this chapter is to develop a model to forecast the Start of the Main Pollen Season (SPS) using a statistical approach based on meteorological data. Here we will apply and explore two different methods: the first method is based on the sum of daily mean temperatures and the second is based on a multiple regression analysis with maximum and minimum temperatures and precipitation. In order to measure the quality of the models and also their predictability power, root mean squared error (RMSE) will be computed. An analysis of the systematic and random part of the RMSE will be also implemented, in order to identify the sources of the error. The forecast of the SPS has a particular importance because this information is very useful for accurate use of medicine for allergies and for the planning of the patient's activities.

Chapter 6: Long-range transport.

This chapter presents the results of the use of the source-receptor model applied to the study of the source areas of pollen that arrive to the northeast of the Iberian Peninsula transported by the wind. Specifically, this work presents the results of applying the model to estimate the source areas of 6 pollen taxa that are susceptible to reach Catalonia from distant regions: *Ambrosia*, *Betula*, *Corylus*, *Fagus*, *Fraxinus*, and *Olea*. Apart from the great scientific interest that lies in the modelling of the source areas to understand the life cycles of the species, the use of these models can be useful to biologists, allergists, and environmental quality managers in the study and treatment of problems such as respiratory allergies.

1.4.1. Publications

- Majeed, H.T.; Periago, C.; Alarcón, M.; Belmonte, J. (2018). Airborne pollen parameters and their relationship with meteorological variables in NE Iberian Peninsula. *Aerobiologia.* https://doi.org/10.1007/s10453-018-9520-z
- Izquierdo, R.; Alarcón, M.; Majeed, H.T.; Periago, C.; Belmonte, J. (2015). Influence of atmospheric teleconnection patterns on airborne pollen levels in the NE Iberian Peninsula. *Climate Research, 66*(2), 171-183

1.4.2. International meetings

- Periago, M.C.; Majeed, H.T.; Alarcon, M.; Belmonte, J. (2017): *Influence of wind on daily airborne pollen concentrations in Catalonia (NE Iberian Peninsula)*. MedPalyno 2017: Mediterranean Palynology APLE-GPPSBI-APLF Symposium. Barcelona, 4-6 September 2017. Pag: 104. ISBN: 978-84-945378-7-5
- Periago, M.C.; Majeed, H.T.; Alarcon, M.; Belmonte, J. (2017): *Effect of temperature and precipitation on the airborne pollen parameters in Catalonia (NE Iberian Peninsula)*. MedPalyno 2017: Mediterranean Palynology APLE-GPPSBI-APLF Symposium. Barcelona, 4-6 September 2017. Pag: 133. ISBN: 978-84-945378-7-5
- Periago, M.C.; Majeed, H.T.; Alarcon, M.; Belmonte, J. (2017): *The effect of wind on daily airbone pollen concentrations in Catalonia (NE Iberian Peninsula)*. RICTA 2017: 5th Iberian Meeting on Aerosol Science and Technology. Barcelona, 4-6 July 2017.
- Majeed, H.T.; Periago, M.C.; Alarcón, M.; Belmonte, J.; De Linares, C. (2016): *Influence of wind on daily airborne pollen counts in Catalonia (NE Iberian Peninsula)*. EGU 2016: European Geosciences Union General Assembly. Viena (Austria), 17-22 April 2016. Geophysical Research Abstracts Vol. 18.
- Periago, M.C.; Majeed, H.T.; Alarcón, M.; Izquierdo, R.; Belmonte, J. (2015): *Forecasting the start of the pollination period for some taxa in Catalonia (NE Iberian Peninsula)*. RICTA 2015: 3rd Iberian Meeting on Aerosol Science and Technology. Elche (Alicante), 29 June-1 July 2015. Proceedings of RICTA 2015. Pag: 30
- Majeed, H.T.; Alarcón, M.; Periago, M.C.; Izquierdo, R.; Belmonte, J. (2015): *Airborne pollen (API, Start, End and Length) and its relationship with meteorological parameters in Catalonia (NE Iberian Peninsula)*. RICTA 2015: 3rd Iberian Meeting on Aerosol Science and Technology. Elche (Alicante), 29 June-1 July 2015. Proceedings of RICTA 2015. Pag: 55.

- Alarcón, M.; Belmonte, J.; Majeed, H.T.; Periago, M.C.; Izquierdo, R. (2015). *Impact of atmospheric circulation patterns on the airborne pollen dynamics in Catalonia (NE Iberian Peninsula)*. 5th International Conference on Meteorology and Climatology of the Mediterranean. Istanbul (Turkey), 2-4 March 2015. Editorial: ACAM. Año: 2015. Pag: 15.
- Alarcón, M.; Belmonte, J.; Majeed, H.T.; Periago, M.C. (2014): *Sensitivity of the airborne pollen to the climate variability in the North East of the Iberian Peninsula.* RICTA 2014. 2nd Iberian Meeting on Aerosol Science and Technology. Tarragona (Spain), 7-9 July 2014. Editorial: Publicacions de l'ETSE de la URV (2014). Pag: 155. ISBN: 978-84-695-9978-5
- Alarcón, M.; Belmonte, J.; Majeed, H.T.; Periago, M.C.; Izquierdo, R. (2014). *Relationship between climate variability indices and airborne pollination in Catalonia (NE Iberian Peninsula)*. Meeting of the European Aeroallergen Network and the European Aerobiology Society. EAN-EAS 2014. Viena (Austria), 10-11 November 2014.

1.4.3. Participation in R&D and Innovation projects

- Name: New TEChnologies for the study of the diversity and dynamics of aeroBIOlogical components and for their forecast based on METeorology (**TECBIOMET**)
  Code: CTM2017-89565-C2-2-P
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  Principal investigator: Marta Alarcón Jordán (Universitat Politècnica de Catalunya)

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2. INFLUENCE OF METEOROLOGICAL VARIABLES ON AIRBORNE POLLEN LEVELS

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2.1. Introduction

Many studies have been conducted to examine pollen of different species and its relationship with meteorological variables. In these studies maximum, minimum and mean temperature, relative humidity, precipitation, wind speed, wind direction, sea level pressure, sunshine hours and dew point temperature were correlated with daily pollen concentrations (e.g. Galán et al., 2000; Stefanic et al., 2005; Weryszko-Chmielewska et al., 2006). Temperature was the most important factor in the timing of flowering in winter- and spring-blooming temperate tree species, while in species that bloom during other times photoperiod is also an important determinant of flowering time (Frenguelli and Bricchi, 1998; García-Mozo et al., 2002). Flowering in temperate grass species was generally determined by both photoperiod and temperature, although in Mediterranean grasses, the photoperiod requirement is low (Heide, 1994). The magnitude of pollen produced in a given season is mainly a function of precipitation in some tree and grass species, and of both temperature and precipitation in others (Recio et al., 2010; García-Mozo et al., 2006). Haroon and Rasul (2008) studied the meteorological factors affecting pollen concentration in Islamabad (Pakistan) and concluded that meteorological variables affect pollen concentration in the atmosphere in two moments: production and dispersion.

Some authors predicted onset and duration of the *Ambrosia* pollen season in Lyon (France) by applying statistical approaches based on meteorological data (Laaidi et al., 2003). Grinn-Gofron and Bosiacka (2015) determined the functional relationships between composition of atmospheric bioaerosols and meteorological factors using canonical correspondence analysis. Piotrowska and Kubik-Komar (2012) investigated the pattern of the birch atmospheric pollen seasons in Lublin (Poland) in the period 2001–2010. Their statistical analysis showed that minimum temperature of February and March and total rainfall in June in the year preceding pollen release had the greatest effect on the birch atmospheric pollen season and that low temperatures in February promoted the occurrence of high pollen concentrations. Piotrowska-Weryszko (2013) reported on the effect of the meteorological factors on the *Alnus* pollen season in Lublin (Poland). Stach et al. (2008a) emphasised how important is the weather during the few weeks or months preceding pollination for grass pollen production in Poznan (Poland). Zhang et al. (2013) designed a pollen production model for California taking into account that for tree and grass species that typically flower between March-June, temperature is the main driver controlling the timing of pollen release, while precipitation (and temperature, for some species) controls the magnitude of pollen produced. Galan et al. (2000) found that the most important meteorological parameter influencing Urticaceae pollen concentration in spring in Southern Spain was temperature, while rain did not appear to be significant.

In this chapter, we aim to investigate the influence of meteorology on the airborne pollen dynamics through correlation analysis between precipitation, insolation and temperature and the main pollen parameters characterizing the pollination season for 22 taxa collected at 6 localities in Catalonia during the 18-year period 1994-2011.

2.2. Data and Methodology

2.2.1. Pollen records

Airborne pollen data were recorded by the Aerobiological Network of Catalonia (XAC) at six stations located in Barcelona (BCN), Bellaterra (BTU), Girona (GIC), Lleida (LLE), Manresa (MAN) and Tarragona (TAU). 22 pollen taxa were considered: *Alnus*, *Ambrosia, Artemisia*, *Betula*, *Castanea*, Chenopodiaceae/Amaranthaceae, *Corylus*, Cupressaceae, *Fagus*, *Fraxinus*, *Olea*, *Pinus*, *Pistacia*, *Plantago*, *Platanus*, Poaceae, Polygonaceae, Total *Quercus, Quercus* deciduous type, *Quercus* evergreen type, *Ulmus* and Urticaceae.

The pollen parameters included in this study were: Annual Pollen Integral (**APIn**, sum of the mean daily pollen concentrations in a year), Monthly Pollen Integral (**MPIn**, sum of the mean daily pollen concentrations in a month), the dates of **Start** and **End** of the Main Pollen Season and the **Length** (number of days between the Start and the End). The Main Pollen Season (**MPS**) has been established as the period beginning the date (Start) in which the sum of the daily mean pollen concentrations reaches 2.5% of the annual sum until the date (End) in which the sum reaches 97.5% (Andersen, 1991).

2.2.2. Meteorological data

Meteorological data were provided by the Servei Meteorològic de Catalunya (SMC). Daily values of precipitation (PRE), insolation (INS), maximum temperature (Tmax) and minimum temperature (Tmin) were recorded at the closest meteorological stations to airborne sampling sites (all of them are 5-15 km away). From Tmax and Tmin, the mean daily temperature (Tmid) was computed. Some missing data reduced quite a bit our database: years 1999, 2008 and 2009 in LLE for precipitation; year 1997 in BCN, 1996 in BTU and 1999 in LLE for temperature; years 2000 and 2001 in GIC for temperature and precipitation and year 2004 in GIC for insolation.

2.2.3. Statistical methods

Spearman's rank correlation coefficient was applied to measure the relationship between pollen data (APIn, MPIn, Start, End and Length of the MPS) and the meteorological variables (PRE, INS, Tmax, Tmin and Tmid). Considering that the MPS of most of the taxa in Catalonia lasts from spring to summer or autumn, correlations between the pollen parameters and winter (from December to March) values of meteorological variables were calculated. Correlations between MPIn and monthly values of the meteorological variables were also calculated.

The Spearman correlation was used because it is considered more robust and resistant to outlying data than the conventional Pearson correlation coefficient (Wilks, 2011; Fernandez-Llamazares et al. 2012). Two levels of significance were considered: $p<0.01$ and $p<0.05$.

2.3. Results and Discussion

2.3.1. MPIn and monthly values of the meteorological variables

Correlations between Monthly Pollen Integral (**MPIn**, sum of the mean daily pollen concentrations in a month) and monthly values of the meteorological variables were calculated in order to explore the immediate effect of meteorological variables on the pollen concentrations (Table 2.1). Besides the 22 individual pollen taxa, we also considered the Total Pollen concentration. Then, the number of total correlations is 22 pollen taxa + total pollen = 23 x 6 locations = 138.

Only negative significant correlations between MPIn and monthly **PRE** (total amount of precipitation during a month) were obtained and represent 13% of the cases (18/138). This result could be explained as a washing out effect of the airborne pollen by precipitation. Several authors have published about the direct negative effect that precipitation has on the amount of pollen collected during the pollination season (Frei 1998; Jato et al. 2002a; De la Guardia et al. 2003; Peternel et al. 2004; Green et al. 2004; Janati et al. 2004; Khwarahm et al., 2014; De Linares et al. 2017; Vélez Pereira 2017). Recio et al. (2010) gives also an explanation to this negative correlation, expressing that the content of water in the soil facilitates the vegetative growth better than the flowering. The negative association of pollen concentrations and precipitation could also be explained by the phenological pattern of the plants flowering out of the rainy season. The pollen taxon most affected by PRE is Poaceae, with negative significant correlations in BTU, GIC and TAU, possibly due to the long pollination period what gives more opportunities to coincide with rains. This is in concordance with the bibliography, as seven of the ten papers above cited refer to Poaceae pollen. The locality giving a higher number of significant results MPIn/PRE is GIC. This location is the one showing highest annual precipitations (Table 1.3) but also the highest amount of total pollen during the year (Table 1.2). This is not contradictory because the pollen production in GIC is very high for some taxa (*Castanea*, *Alnus*, *Betula*, *Fraxinus*, *and Quercus*) that are very abundant in the region. On the other hand, the effect of the washout by precipitation, as we see in our results, has an immediate effect reducing the monthly pollen levels in GIC.

The significant correlations between MPIn and monthly **INS** (sum of daily sunshine hours during a month) represented 11% of the total correlations (15/138) and were mostly positive (13/15). This result confirms that pollen production and release are enhanced by sunlight, and that this effect is relatively immediate because it affects the pollen production in the forthcoming days. Only *Castanea* in BCN and MAN presented negative correlations, while in GIC (where *Castanea* APIn is the highest of all the stations) the correlation was positive.

On the other hand, 7 of the 22 taxa showed no correlation with either, PRE or INS: *Ambrosia*, *Betula*, *Fagus*, *Pistacia*, Total *Quercus*, *Quercus* evergreen type and *Urticaceae*. The pollen concentrations of *Ambrosia*, *Fagus* and *Pistacia,* with short pollination periods, are usually low in the atmosphere of Catalonia and, in the case of the two first taxa and *Betula* their presence have been related to long range transport episodes (Fernández-Llamazares et al. 2012; Belmonte et al. 2008; Izquierdo et al. 2015b). Regarding Total *Quercus*, *Quercus* evergreen type and *Urticaceae,* the lack of correlations could be due to the non-synchronous occurrence of their long pollination period and the seasonal variations of meteorological variables. *Pinus* is the pollen type most influenced by INS (BTU, GIC and LLE), followed by *Chenop./Amar*., *Olea* and *Plantago* (BTU and LLE). BTU and LLE are the localities giving a higher number of significant correlations MPIn/INS. There is a lack of bibliography relating airborne pollen concentration and INS. Again, Poaceae is the pollen type more studied. The authors Kizilpinar et al. (2011) and Khwarahm et al. (2014) show a strong positive correlation of grass pollen with INS.

The significant correlations between MPIn and monthly values of **Tmax**, **Tmin** and **Tmid** are always positive, except for *Chenop./Amar*. in TAU, possibly because autumn, when temperatures are decreasing, is the period of the year with highest pollen concentration of this taxon in TAU. The significant correlations with Tmax represent 25% of total correlations (34/138), 11% of total for Tmin (15/138) and 23% for Tmid (30/138). *Alnus, Ambrosia*, *Artemisia*, *Castanea* and *Ulmus* showed no correlation with temperature. Temperature is, together with precipitation, one of the common parameters studied and it is cited to show a positive correlation with pollination intensity (Teranishi et al. 2000, Zisca & Caufield 2000, Rasmussen 2002, Ribeiro et al. 2003, Peternel et al. 2004, Green et al. 2004, Ziello et al. 2012, Fernandez-Llamazares et al 2014, Khwarahm et al. 2014, Janati et al. 2017).

2.3.2. APIn and winter values of meteorological variables

Considering that the pollination season of most of the taxa in Catalonia occur between spring and summer or autumn, correlations between APIn and winter (from December to March) values of meteorological variables were calculated (Table 2.2). Here, we have also considered the Total Pollen concentration. Then, the number of total correlations is 22 pollen taxa + total pollen = 23 x 6 locations = 138.

APIn and winter **PRE** correlated always positively and represented 16% of the total possible correlations (22/138). This means that high (low) amounts of winter PRE induced high (low) pollination in the following spring to autumn. Half of the taxa showed no correlation in any of the stations (*Alnus*, *Ambrosia*, *Betula*, *Castanea*, *Corylus*, *Fagus*, *Pistacia*, Poaceae, Polygonaceae, *Ulmus* and Urticaceae). Here it is necessary to take into account that the precipitation regime of the previous year may also influence the pollen production in the following year of some trees, e.g. *Betula* (Stach et al. 2008b, Nielsen et al. 2010). Another argument is that woody and herbaceous species respond differently to precipitation, trees being more related to conditions prior to flowering and herbaceous plants responding more immediately to the precipitation events (Cariñanos et al. 2004, Galán et al. 2016). In our study, this argument is the explanation for trees and shrubs pollinating during winter and very early spring (*Alnus*, *Ulmus*, Cupressaceae and *Corylus*) and herbaceous plants with a long-lasting pollination (Urticaceae, Poaceae, *Plantago*, and *Chenop./Amar*.) giving very few, if any, correlations. Spring flowering trees (*Pinus*, *Platanus*, *Quercus*, and *Olea*) correlate with winter PRE while those pollinating in summer (*Castanea*) doesn't. A different explanation for the lack of correlations is for plants that are scarce in the territory (*Betula* and *Fagus*) and arrive mainly through long-range transport (Belmonte et al. 2008, Izquierdo et al. 2017). In this study, they have shown only 1 correlation. *Quercus* decidous type was the taxon which presented positive correlations with winter PRE in a greater number of stations (BTU, GIC and MAN), as well as Total Pollen (BCN, BTU, MAN). On the other hand, BCN was the station in which a greater number of taxa presented positive correlations (Cupressaceae, *Olea*, *Pinus*, *Plantago*, Total *Quercus*, *Q*. evergreen type and Total Pollen) with winter precipitation, followed by BTU (*Olea*, *Pinus*, Total *Quercus*, *Q*. deciduous type, *Q*. evergreen type and Total Pollen). García Mozo et al. (2006) also found that PRE during the month prior to the *Quercus* pollination period makes the greatest contribution to pollen production. On the contrary, Fernández-Martínez et al. (2012) found that the amount of PRE and its temporal distribution barely influenced airborne pollen production.

The significant correlations between APIn and winter **INS** are positive or negative depending on the taxa and the sampling station, but represent only 8% (11/138) of the total possible correlations. Only 10 of the 22 taxa show some significant correlation, mostly negative (9/11). Only *Platanus* in GIC and Total *Quercus* in TAU were positive. It can be because *Platanus* and deciduous *Quercus* pollen type pollinate by the end of winter - beginning of spring and more sunny winters can contribute to better pollinations. The negative correlations could be explained by the fact that the pollen production is favoured by winter precipitation, as we saw previously, and rainy winters probably lead to fewer hours of sunshine, together with the fact that most of the taxa pollinate from spring on, far from the effect of winter INS. There is a second possible explanation for that and it is that, in the recent years, end of winter coincides with a notable increase of temperatures and plants become exhausted before. MAN is the locality showing a higher number of correlations, all negative, 6 for winter INS (*Chenop./Amar*., *Plantago*, Poaceae, Polygonaceae, Total *Quercus* and *Q*. deciduous type). The coincidence between the stabilization of the INS values once winter is over with the beginning of the pollination of these taxa can be the explanation for this negative relationship.

The significant correlations between APIn and winter **temperatures** were mostly negative. Regarding Tmax, they represented 14% (19/138) and were negative in all cases, while positive and negative correlations were obtained for Tmin (7% in total, 9/138; being 4% negative) and Tmid (8% in total, 11/138; being 7% negative). The positive correlations corresponded to *Artemisia* in LLE, *Platanus*, in BCN, and Poaceae and *Ulmus* in BTU. As LLE is the locality with the highest *Artemisia* APIn and BCN the one with the highest *Platanus* APIn, these results could be representative, showing that the higher the minimum winter temperature the higher the pollen production in the year. In the case of *Artemisia*, López et al (2017) have found that, although the pollination takes place from summer to autumn, it is more intense when winters are warmer. Other interesting results are obtained for TAU and the taxon *Corylus*, and for TAU and MAN for Cupressaceae and *Fraxinus*, all negative with, at least, winter Tmin. In the case of *Corylus* and Cupressaceae TAU is the site presenting highest APIn and pollination occurs mostly during winter, thus meaning that low temperatures favour the pollination. *Fraxinus* results need deeper consideration. It is difficult to stablish a general interpretation of the relationship between APIn and temperature because of the variability of results obtained (Jato et al. 2004).

Summarising, **APIn** was specially influenced by winter precipitation and winter maximum temperature. The positive correlations between **APIn** and winter precipitation indicate the positive effect of precipitation during the winter months before the flowering period on the annual pollen production for most of the taxa. This result agree with those obtained by Izquierdo et al., (2015a) reporting the negative correlation between Seasonal Pollen Integral and Northern Hemisphere teleconnection patterns (NAO, AO and WeMO indices) and the positive effect of precipitation on the annual pollen during the negative phase of the three climatic indices. In accordance with this study, we have obtained a link between higher rainfall in winter and increased pollen production for the following taxa: *Artemisia*, *Chenop./Amar*., Cupressaceae, *Fraxinus*, *Olea*, *Pinus*, *Plantago*, *Platanus*, *Quercus*, *Quercus* deciduous type, *Quercus* evergreen type, as well as for Total Pollen.

Beside the correlations with winter values of meteorological variables, the correlation between **APIn** and annual values of precipitation, insolation and temperatures were also calculated. These results are summarised in Tables A2.1, A2.2 and A2.3 included as appendix material at the end of this chapter

Regarding the correlations between APIn and annual PRE (Table A2.1) only 2% (3/138) were significant. This lack of correlation could be explained by the opposite effect of the precipitation in the pollen concentrations by wash out depending on the time when the rainfall occurs.

In the same way, the significant correlations between APIn and annual INS (Table A2.2) are positive or negative depending on the taxa and the sampling station, and represent only 9% (12/138) of the total. These significant correlations are half positive (6/12) and half negative (6/12)

The significant correlations between APIn and annual temperatures (Table A2.3) represented a very low percentage of the total correlations: only 2/138 for Tmax, 6/138 for Tmin and 5/138 for Tmid. Besides, these correlations were positive or negative depending on the taxa and the sampling station, not being observed a clear predominance of any sign.

2.3.3. Influence of meteorological variables in the Start, End and Length of the Main Pollen Season

The influence of precipitation, insolation and temperature in the timing of the pollination season was evaluated by analysing the dates of **Start** and **End** of the Main Pollen Season (**MPS**) and the **Length** (number of days between the Start and the End). The significant correlations between phenology (Start, End and Length of the MPS) and Precipitation (**PRE**), Insolation (**INS**) and Maximum (**Tmax**), Minimum (**Tmin**) and Mean (**Tmid**) Temperatures for each taxon are shown in Table 2.3 (Start), Table 2.4 (End) and Table 2.5 (Length). The number of total correlations is 22 pollen taxa x 6 locations = 132.

Beside the correlations with winter values of meteorological variables, the correlation between phenology and annual values of precipitation, insolation and temperatures were also calculated. These results are also summarised in Tables A2.1, A2.2 and A2.3.

2.3.3.1. Precipitation

Precipitation has a little influence on the main parameters that characterise the MPS. Regarding the sign of the correlations, they are positive or negative depending on the taxon and the sampling station.

Significant correlations between **Start** and winter precipitation accounted around 8% of total correlations (11/132). Positive correlations were obtained for *Artemisia*, *Chenop./Amar.*, Cupressaceae, *Olea, Plantago*, *Platanus*, Poaceae and Polygonaceae while negative correlations were obtained for *Alnus*, *Ambrosia* and *Quercus* deciduous (Table 2.3).

Fewer significant correlations were obtained with **End**, around 6% of total correlations (8/132). Significant correlations were negative for *Olea*, *Pistacia*, Poaceae, *Quercus* and *Quercus* evergreen type while positive correlations were obtained for *Artemisia* and *Ulmus* (Table 2.4).

Significant correlations between **Length** and winter precipitation accounted 14% of total correlations (19/132). Correlations were negative for *Alnus*, *Artemisia*, *Chenop./Amar*., *Olea*, *Pinus*, *Pistacia*, *Platanus*, Poaceae, *Quercus*, *Quercus* deciduous type, *Quercus* evergreen type and Urticaceae, and positive for *Fagus*, *Plantago* and *Ulmus* (Table 2.5).

The winter PRE gave a highest number of positive correlations with **Start** (8) and the highest number of negative correlations with **Length** (16). This is consistent with the results already indicated in this paper for PRE as a washing out agent. With regard to **Start**, our result are also in accordance with Vélez-Pereira (2017) who found that precipitation in the same day had a relevant effect in eliminating the low concentration levels of Urticaeae, Poaceae and *Chenop./Amar*. pollen.

Significant correlations with annual values of PRE (Table A2.1) accounted around 2% (3/132) of total for the Start, 6% (6/132) for the End and 7% (3/132) for the Length. Furthermore, not a clear predominance of any sign has been observed.

2.3.3.2. Insolation

Evenly with precipitation, the significant correlations with winter values of insolation were positive or negative depending on the taxa and the sampling station, but represented only 4-7% (5-9/132). Significant correlations between **Start**, **End** and **Length** of the MPS and winter INS for each taxon in each station can be found in Table 2.3, Table 2.4 and Table 2.5.

Significant correlations with annual values of INS (Table A2.2) represent only 2-5% (3-6/132). Thereby, we can conclude that insolation has little effect over the timing of the pollen season.

2.3.3.3. Temperatures

Significant correlations between the **Start** of the MPS and winter temperatures represented 20% (79/396) and were mostly negative (74/79), meaning that high (low) winter temperatures in Catalonia coincide with earlier (later) pollination. Only *Ambrosia* in LLE, *Castanea* in GIC and *Fagus* in BCN showed positive correlation. According to Piotrowska and Kubik-Komar (2012), in temperate climate regions, air temperature recorded at the end of winter and early spring has the greatest effect on the Start of the MPS. Other studies have established that temperature is the main factor controlling the start of the MPS (Frei, 1998; Laaidi, 2001; Root et al. 2003; Fernández-Martínez et al. 2012). The different behaviour of the Start for *Ambrosia* and *Fagus* with temperatures could be explained since these taxa are scarce in Catalonia and long-range transport from other regions could mask correlations. Different studies of transport episodes of *Ambrosia* (Belmonte et al., 2000; Fernández-Llamazares et al., 2012) and *Fagus* (Belmonte et al., 2008) from Central Europe to Catalonia have been documented. On the other hand, *Ambrosia* and *Castanea* are usually airborne in summer and thus easily not affected by winter temperatures. Significant correlations between the **Start** of the MPS and winter values of Maximum (Tmax), Minimum (Tmin) and Mean (Tmid) Temperatures for each taxon in each station can be found in the Table 2.3. Regarding annual temperatures (Table A2.3), significant correlations represented only 4% (17/396) and were also mostly negative (16/17).

Significant correlations between the **End** of the MPS and winter values of Maximum (Tmax), Minimum (Tmin) and Mean (Tmid) temperatures represented only 4 % (14/396) meaning that winter temperatures have little influence on the End of the MPS. Significant correlations between the End of the MPS and winter values of Maximum (Tmax), Minimum (Tmin) and Mean (Tmid) Temperatures for each taxon in each station can be found in the Table 2.4. In contrast, significant correlations with annual temperatures (Table A2.3) represented 12% (48/396) being mostly negatives (36/48). These results conclude that the End of the MPS is mainly influenced by annual temperatures: high (low) temperatures during the year delay (advance) the end of the pollen season.

Significant correlations between the **Length** of the MPS and winter values of Maximum (Tmax), Minimum (Tmin) and Mean (Tmid) temperatures represented 11% (45/396) and were mainly positive (39/45), meaning that high (low) winter temperatures in Catalonia enlarge (shorten) the pollination season. Negative correlations corresponded to *Fagus* (4) and *Artemisia* (2). This result can be explained by the combined effect of the negative correlation between Start and winter temperature and the no correlation between End and winter temperature: high winter temperatures advance the Start but not affect the End, thus an enlargement of the MPS is expected. Significant correlations between the **Length** of the MPS and winter values of Maximum (Tmax), Minimum (Tmin) and Mean (Tmid) Temperatures for each taxon in each station can be found in the Table 2.5. Regarding annual temperatures, significant correlations represented only 4% (17/396) and were also mostly positive (13/17).

2.4. Conclusions

In this chapter, a correlation analysis between precipitation, insolation and temperature and the main airborne pollen parameters (MPIn. APIn and Start, End and Length of the MPS) of 22 taxa collected at 6 aerobiological stations in Catalonia (NE Spain) have been performed in order to determine the effect of meteorological variability on their dynamics.

A summary of the main results about the correlations with winter values of meteorological variables are showed in Table 2.6. Regarding the pollen type, *Olea* and *Pinus* show a higher number of significant correlations (30), followed by *Platanus* (27), *Quercus* deciduous type (23), *Plantago* (22) and Total *Quercus* (22). On the other hand, *Ambrosia* is the only pollen type that shows no correlation between meteorological variables and the amounts of pollen (APIn and MPIn) while *Castanea* and *Corylus* are the taxa presenting the least number of correlations (only 2) between the parameters that characterise the MPS and the meteorological variables.

The pollen parameter with the highest number of significant correlations with the meteorological variables was MPIn (104), followed by Start (95), Length (73), APIn (67) and End (28).

Temperature was the meteorological variable that showed a major influence in the pollen production and in the timing of the MPS. Maximum (104) and mean (94) temperature presented the greatest number of significant correlations, followed by precipitation (74), minimum temperature (50) and insolation (45).

A clear positive correlation has been detected between the pollen production and the winter precipitation for most of the pollen taxa included in this study. In addition, the MPS seems to advance its Start and extend its Length in years with warm winters. Nevertheless, the End of the MPS does not seem clearly influenced by winter weather, but annual temperatures, especially minimum and mean values, explain an advance or delay of the End of the MPS.

Results show that airborne pollen levels and its dynamics are influenced by meteorological conditions. Improving knowledge about the influence of meteorology on the pollen dynamics is essential to improve modelling and obtain better forecast of the start and the severity of the pollen season. Most of the results obtained in this study corroborate results shown by other researchers; although, there are some limitations due to the time resolution of the data (monthly and yearly) used in our work. Therefore, more research is needed for better comprehend the interaction between meteorology and airborne pollen levels and its dynamics. For a future research, the results regarding correlations between temperature and pollen concentrations may improve by splitting the annual period in two sections, one since the beginning of the pollination until the peak date and the other from this moment to the end of the pollination. This will be the case for most taxa pollinating between spring and summer.

Table 2.1: Significant correlations between Monthly Pollen Integral (**MPIn**) and **monthly** values of Precipitation (**PRE**), Insolation (**INS**) and Maximum (**Tmax**), Minimum (**Tmin**) and Mean (**Tmid**) Temperatures. (P: Positive, N: Negative, significance level of 0.05) (**P**: Positive, **N**: Negative, significance level of 0.01)

MPIn	PRE						INS						Tmax						Tmin						Tmid					
	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU
Alnus					N																									
Ambrosia																														
Artemisia		N																												
Betula													P				P								P				P	
Castanea			N				**N**		P		N																			
Chenop./Amar.			N					P		**P**					**P**						P	**P**		**N**			**P**			**N**
Corylus	**N**		N											P			**P**					P				P			P	
Cupressaceae			**N**																									P		P
Fagus													P	**P**				P		P					P	**P**			P	
Fraxinus		N														P		P				**P**	P					**P**		P
Olea	N							P		**P**							P				P					P	P	**P**	P	
Pinus		N	N					P	P	**P**				**P**		P							P			**P**				
Pistacia																		P										P		**P**
Plantago								P		P						**P**						P	P					**P**		
Platanus			**N**												**P**			P	P								P			
Poaceae		**N**	N			N		P						**P**												P		**P**		
Polygonaceae			N											P		**P**														
Total *Quercus*														P		**P**		P												
Q. deciduous t.									P						P	P		**P**												**P**
Q. evergreen t.														P		**P**		P			**P**						P			
Ulmus						**N**																								
Urticaceae														**P**		**P**						**P**				**P**		**P**		
Total Pollen			**N**							P				**P**	P	**P**						P				**P**		**P**		
								5P	**3P**	**5P**			**2P**	**9P**	**4P**	**9P**	**3P**	**7P**	**1P**	**1P**	**3P**	**6P**	**3P**		**2P**	**7P**	**4P**	**8P**	**4P**	**4P**
	2N	**4N**	**9N**		**1N**	**2N**	**1N**				**1N**													**1N**						**1N**
	18N						**13P / 2N**						**34P**						**14P / 1N**						**29P / 1N**					

Table 2.2: Significant correlations between Annual Pollen Integral (**APIn**) and **winter** (from December to March) values of Precipitation (**PRE**), Insolation (**INS**) and Maximum (**Tmax**), Minimum (**Tmin**) and Mean (**Tmid**) Temperatures. (P: Positive, N: Negative, significance level of 0.05) (**P**: Positive, **N**: Negative, significance level of 0.01)

APIn	**PRE**						**INS**						**Tmax**						**Tmin**						**Tmid**					
	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU
Alnus																		N												
Ambrosia																														
Artemisia				P	P																	**P**						**P**		
Betula										N																				
Castanea																														
Chenop./Amar.					P						**N**																			
Corylus																								N						
Cupressaceae	**P**											N						N			N		N	N						N
Fagus													N				N	N							N					N
Fraxinus						P											**N**	**N**						**N**					N	**N**
Olea	P	**P**															N													
Pinus	**P**	P													N															
Pistacia																														
Plantago	**P**										N																			
Platanus				P		P			P								N		P						P					
Poaceae											**N**						N									P				
Polygonaceae											N																			
Total *Quercus*	**P**	**P**									N	P			N		N										N			
Q. deciduous t.		**P**	P		P						N		N		N		N								N					
Q. evergreen t.	**P**	P															N													
Ulmus																				P				N						N
Urticaceae									N																					
Total Pollen	P	**P**			P												N	N												
	7P	**6P**	**1P**	**2P**	**4P**	**2P**			**1P**			**1P**							**1P**	**1P**		**1P**			**1P**	**1P**		**1P**		
									1N	**1N**	**6N**	**1N**	**2N**		**3N**		**9N**	**5N**			**1N**		**1N**	**4N**	**2N**		**1N**		**1N**	**4N**
	22P						**2P / 9N**						**19N**						**3P / 6N**						**3P / 8N**					

Table 2.3: Significant correlations between the **Start** of the Main Pollen Season and **winter** (from December to March) values of Precipitation (**PRE**), Insolation (**INS**) and Maximum (**Tmax**), Minimum (**Tmin**) and Mean (**Tmid**) Temperatures. (P: Positive, N: Negative, significance level of 0.05) (**P**: Positive, **N**: Negative, significance level of 0.01)

Start	PRE						INS						Tmax						Tmin						Tmid					
	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU
Alnus				N										**N**		**N**						**N**		N		**N**		**N**		
Ambrosia					N					N						P												P		
Artemisia					P				N													N								
Betula																N						N						N		
Castanea																					P						P			
Chenop./Amar.					**P**										**N**												N			
Corylus																						N						N		
Cupressaceae			P																											
Fagus																									P					
Fraxinus																**N**						**N**						**N**		
Olea	P												**N**	N					N						**N**	N				
Pinus													N	**N**		N	**N**		**N**						**N**	**N**			**N**	
Pistacia													N	**N**			**N**		**N**				N		**N**	**N**			**N**	
Plantago	P									P			**N**				N		**N**						**N**				N	
Platanus	P												**N**	**N**			**N**		**N**						**N**	**N**			**N**	
Poaceae	**P**																**N**												N	
Polygonaceae	**P**												N						N						N					
Total *Quercus*													**N**	**N**		**N**									N	**N**				
Q. deciduous t.						**N**							N	**N**					**N**						**N**	**N**				
Q. evergreen t.							N							**N**		N	N									**N**				
Ulmus							N																							
Urticaceae														N		N	N									**N**			N	
	5P		**1P**		**2P**					**1P**						**1P**					**1P**				**1P**		**1P**	**1P**		
				1N	**1N**	**1N**	**2N**		**1N**	**1N**			**8N**	**9N**	**1N**	**7N**	**7N**		**7N**			**5N**	**1N**	**1N**	**8N**	**9N**	**1N**	**4N**	**6N**	
	8P / 3N						**1P / 4N**						**1P / 32N**						**1P / 14N**						**3P / 28N**					

Table 2.4: Significant correlations between the **End** of the Main Pollen Season and **winter** (from December to March) values of Precipitation (**PRE**), Insolation (**INS**) and Maximum (**Tmax**), Minimum (**Tmin**) and Mean (**Tmid**) Temperatures. (P: Positive, N: Negative, significance level of 0.05) (**P**: Positive, **N**: Negative, significance level of 0.01)

End	**PRE**						**INS**						**T max**						**T min**						**T mid**					
	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU
Alnus																														
Ambrosia																					**P**						**P**			
Artemisia	P					P																								
Betula																														
Castanea																														
Chenop./Amar.									N																					
Corylus																														
Cupressaceae																						P						P		
Fagus																														
Fraxinus																										N				
Olea		**N**														P														
Pinus												P													N					
Pistacia				N			N									N														
Plantago									**N**							P												P		
Platanus										N						N														
Poaceae				N			P																							
Polygonaceae																**P**												**P**		
Total *Quercus*		**N**																												
Q. deciduous t.																														
Q. evergreen t.		**N**																		N										
Ulmus			P																											
Urticaceae																														
	1P		**1P**			**1P**	**1P**					**1P**				**3P**					**1P**	**1P**					**1P**	**3P**		
		3N		**2N**			**1N**		**2N**	**1N**						**2N**				**1N**					**1N**	**1N**				
	3P / 5N						**2P / 4N**						**3P / 2N**						**2P /1N**						**4P / 2N**					

Table 2.5: Significant correlations between the **Length** of the Main Pollen Season and **winter** (from December to March) values of Precipitation (**PRE**), Insolation (**INS**) and Maximum (**Tmax**), Minimum (**Tmin**) and Mean (**Tmid**) Temperatures. (P: Positive, N: Negative, significance level of 0.05) (**P**: Positive, **N**: Negative, significance level of 0.01)

Length	PRE						INS						T max						T min						T mid					
	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU	BCN	BTU	GIC	LLE	MAN	TAU
Alnus				N								N																P		
Ambrosia																														
Artemisia					N					P												N						N		
Betula																														
Castanea																														
Chenop./Amar.					N						**P**				P						P						P			
Corylus																														
Cupressaceae																P						P								
Fagus					P						N	P	N				N							N	N					
Fraxinus																														
Olea	N	**N**									P		**P**	**P**			**P**		**P**						**P**	P			P	
Pinus		N											P	P			P		**P**						P	P			P	
Pistacia				N*																	P						P			
Plantago				P					**N**			**N**																P		
Platanus	N	N												P			P									P			P	
Poaceae	N															P														
Polygonaceae																**P**						P						**P**		
Total *Quercus*		**N**								P				P		**P**										P		P		
Q. deciduous t.	N	N														P										P				
Q. evergreen t.	N	N														**P**														
Ulmus	P																			P										
Urticaceae	N																													
	1P			**1P**	**1P**					**2P**	**2P**	**1P**	**2P**	**4P**	**1P**	**6P**	**3P**		**2P**	**1P**	**2P**	**2P**			**2P**	**5P**	**2P**	**4P**	**3P**	
	6N	**6N**		**2N**	**2N**				**1N**		**1N**	**2N**	**1N**				**1N**					**1N**		**1N**	**1N**			**1N**		
	3P / 16N						**5P / 4N**						**16 P / 2N**						**7P / 2N**						**16P / 2N**					

Table 2.6: Number of significant correlations for each taxon, depending on pollen parameters and meteorological variables

	APIn	MPIn	Start	End	Length	PRE	INS	T max	T min	T mid	TOTAL
Olea	3	9	6	2	10	7	3	8	3	9	**30**
Pinus	3	9	8	2	8	5	4	10	3	8	**30**
Platanus	6	5	8	2	6	6	2	9	3	7	**27**
Q. deciduous t.	8	5	6	0	4	6	2	9	1	5	**23**
Plantago	2	6	7	3	4	3	7	4	3	5	**22**
Total *Quercus*	7	3	5	1	6	4	3	10	0	5	**22**
Chenop./Amar.	2	9	3	1	5	4	5	3	4	4	**20**
Fagus	5	7	1	0	7	1	2	8	2	7	**20**
Q. evergreen t.	3	5	5	2	3	5	1	8	2	2	**18**
Fraxinus	6	7	3	1	0	2	0	5	4	6	**17**
Pistacia	0	3	8	3	3	2	1	5	3	6	**17**
Poaceae	3	7	3	2	2	6	3	4	0	4	**17**
Cupressaceae	7	3	1	2	2	3	1	2	5	4	**15**
Artemisia	4	1	3	2	4	7	2	0	3	2	**14**
Polygonaceae	1	3	4	2	3	2	1	5	2	3	**13**
Alnus	1	1	7	0	3	3	1	3	2	3	**12**
Urticaceae	1	5	5	0	1	1	1	5	1	4	**12**
Corylus	1	7	2	0	0	2	0	2	3	3	**10**
Betula	1	4	3	0	0	0	1	3	1	3	**8**
Ulmus	3	1	1	1	2	3	1	0	3	1	**8**
Ambrosia	0	0	4	2	0	1	1	1	1	2	**6**
Castanea	0	4	2	0	0	1	3	0	1	1	**6**
	67	**104**	**95**	**28**	**73**	**74**	**45**	**104**	**50**	**94**	**367**

Table A2.1: Number of significant correlations ($p < 0.05$) between pollen parameters (**APIn**, **Start**, **End** and **Length** of the pollination season) versus winter (**W**) and annual (**A**) amounts of **Precipitation** (**P**: positive, **N** negative)

			BCN		BTU		GIC		LLE		MAN		TAU		Total		Total	Sum	
			P	N	P	N	P	N	P	N	P	N	P	N	P	N			
Precipitation	APIn	W	7	-	6	-	1	-	2	-	4	-	2	-	22	-	**22**	**25**	89
		A	-	-	-	-	-	1	-	-	2	-	-	-	2	1	**3**		
	Start	W	5	-	-	-	1	-	-	1	2	1	-	1	8	3	**11**	**21**	
		A	3	-	1	1	-	1	-	3	1	-	-	-	5	5	**10**		
	End	W	1	-	-	3	1	-	-	2	-	-	1	-	3	5	**8**	**15**	
		A	-	1	-	1	1	1	3	-	-	-	-	-	4	3	**7**		
	Length	W	1	6	-	6	-	-	1	2	1	2	-	-	3	16	**19**	**28**	
		A	-	1	-	3	-	1	1	-	1	2	-	-	2	7	**9**		
			17	8	7	14	4	4	4	11	11	5	3	1	49	40			
			25		**21**		**8**		**15**		**16**		**4**		**89**				

Table A2.2: Number of significant correlations ($p < 0.05$) between pollen parameters (**APIn**, **Start**, **End** and **Length** of the pollination season) versus winter (**W**) and annual (**A**) values of **Insolation** (**P**: positive, **N** negative)

			BCN		BTU		GIC		LLE		MAN		TAU		Total		Total	Sum	
			P	N	P	N	P	N	P	N	P	N	P	N	P	N			
Insolation	APIn	W	-	-	-	-	1	1	-	1	-	6	1	1	2	9	**11**	**23**	55
		A	-	-	1	1	1	-	4	1	-	3	-	1	6	6	**12**		
	Start	W	-	2	-	-	-	1	1	1	-	-	-	-	1	4	**5**	**8**	
		A	-	-	-	1	1	-	-	-	-	-	-	1	1	2	**3**		
	End	W	1	1	-	-	-	2	-	1	-	-	1	-	2	4	**6**	**12**	
		A	1	-	-	2	1	1	1	-	-	-	-	-	3	3	**6**		
	Length	W	-	-	-	-	-	1	2	-	2	1	1	2	5	4	**9**	**12**	
		A	-	-	1	1	1	-	-	-	-	-	-	-	2	1	**3**		
			2	3	2	5	5	6	8	4	2	10	3	5	22	33			
			5		**7**		**11**		**12**		**12**		**8**		**55**				

Table A2.3: Number of significant correlations ($p < 0.05$) between pollen parameters (**APIn**, **Start**, **End** and **Length** of the pollination season) versus winter (**W**) and annual (**A**) values of **Maximum**, **Minimum** and **Mean Temperature** (**P**: positive, **N** negative)

			BCN		BTU		GIC		LLE		MAN		TAU		Total		Total	Sum	
			P	N	P	N	P	N	P	N	P	N	P	N	P	N			
Maximum Temperature	APIn	W	-	2	-	-	-	3	-	-	-	9	-	5	-	19	**19**	21	102
		A	-	-	-	-	-	1	1	-	-	-	-	-	1	1	**2**		
	Start	W	-	8	-	9	-	1	1	7	-	7	-	-	1	32	**33**	41	
		A	-	1	-	2	-	-	-	4	-	1	-	-	-	8	**8**		
	End	W	-	-	-	-	-	-	3	2	-	-	-	-	3	2	**5**	16	
		A	-	-	-	4	1	-	-	2	-	4	-	-	1	10	**11**		
	Length	W	2	1	4	-	1	-	6	-	3	1	-	-	16	2	**18**	24	
		A	1	-	-	-	2	-	3	-	-	1	-	-	5	1	**6**		
Minimum Temperature	APIn	W	1	-	1	-	-	1	1	-	-	1	-	4	3	6	**9**	15	68
		A	-	-	3	-	-	-	1	-	1	-	-	1	5	1	**6**		
	Start	W	-	7	-	-	1	-	-	5	-	1	-	1	1	14	**15**	19	
		A	-	1	-	1	1	-	-	1	-	-	-	-	1	3	**4**		
	End	W	-	-	-	1	1	-	1	-	-	-	-	-	2	1	**3**	21	
		A	-	3	-	3	4	-	1	5	-	2	-	-	5	13	**18**		
	Length	W	2	-	1	-	2	-	2	1	-	-	-	1	7	2	**9**	13	
		A	-	1	-	-	2	-	-	1	-	-	-	-	2	2	**4**		
Mean Temperature	APIn	W	1	2	1	-	-	1	1	-	-	1	-	4	3	8	**11**	16	102
		A	-	-	-	-	-	2	1	-	-	-	1	1	2	3	**5**		
	Start	W	1	8	-	9	1	1	1	4	-	6	-	-	3	28	**31**	36	
		A	-	1	-	1	-	-	-	3	-	-	-	-	-	5	**5**		
	End	W	-	1	-	1	1	-	3	-	-	-	-	-	4	2	**6**	25	
		A	-	-	-	4	5	-	1	5	-	4	-	-	6	13	**19**		
	Length	W	2	1	5	-	2	-	4	1	3	-	-	-	16	2	**18**	25	
		A	2	-	-	-	3	-	1	1	-	-	-	-	6	1	**7**		
			12	37	15	35	27	10	31	42	7	38	1	17	92	180			
			49		**50**		**37**		**73**		**45**		**18**		**272**				

3. INFLUENCE OF THE WIND ON THE DAILY AIRBORNE POLLEN CONCENTRATIONS

3.1. Introduction

3.2. Data and Methodology

3.2.1. Pollen data

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3.5. Discussion

3.6. Conclusions

3.1. Introduction

Most of the plants depend for pollination on insects or other animal visitors such as hummingbirds and bats. However, many plants rely on other agents for pollination. Among these agents, the most important one is, by far, wind. The clouds of pollen blowing like yellow smoke from pines and other conifers are a familiar sight in early summer. Other wind-pollinated plants include many of the commonest forest trees of temperate climate, almost all the grasses, sedges, and rushes. Wind pollination has the obvious advantage of being independent of the possibly erratic occurrence and capricious behaviour of insects and is effective when insects are scarce or absent (Proctor et al., 1996).

Several works indicated that the wind is capable of transporting pollen grains over long distances (Gregory et al., 1978; Bourgeois et al., 1985). While its importance in dispersing the pollen of anemophilous plants is clearly recognized, separating its influence from that of other meteorological variables is more complicated (Emberlin and Norris-Hill, 2018). Wind speed is recognized as being one of the most important factors in some cases (Ljunkuist et al., 1977; McDonald et al., 1979). The effect of wind direction is well known in coastal areas, where pollen concentrations increase when the wind is coming from the interior and decline when it blows from the sea (McDonald et al., 1977&1980; González Minero el al., 1993).

Several works describe the effect of the wind in the airborne pollen levels. Riera et al. (2002) established a mathematical relationship between allergenic pollen in the air and clinical cases of pollinosis (hay fever) in humans and evaluated the immediate effect of wind and rain on such cases. Altintas al. (2004) reported the relationship between pollen concentrations and weather variables in the Eastern Mediterranean coast of Turkey. Damialis et al. (2005) examined the effect of the wind vector analysed into its three components (direction, speed, and persistence), on the circulation of pollen from different plant taxa prominent in the Thessaloniki area. Houta et al. (2008) conducted field experiments to study the diurnal cycle of corn pollen emission and its relation to local meteorological conditions, including temperature, relative humidity, solar radiation, mean wind speed, and turbulence quantities.

Latorre and Belmonte (2011) carried out a preliminary study to compare Poaceae pollen data at six locations in Catalonia (Spain) over a 6-year period (1996 – 2001) and to determine possible differences in pollen productivity. They concluded that year-to-year Poaceae pollen index variability in Lleida and Manresa is higher than in Girona, Tarragona, and Bellaterra, while in Barcelona this index shows the lowest variability.

Maya-Manzano et al. (2017) generated maps of the main land cover in influence areas of 10 km in radius surrounding pollen traps and analysed the atmospheric content of most abundant 14 pollen types in relation to the predominant wind directions measured in three localities of SW of Iberian Peninsula, for a four year period. By comparing the pollen content with the prevailing winds and land cover, they found that the atmospheric pollen concentration is related to some source areas and that some pollen types come from local sources but other pollen types are mostly coming from far distances. Recio et al., (2018) analysed airborne *Quercus* pollen released during last 25 years in the southwest Mediterranean. They established the correlation of this type of pollen with meteorological variables. They concluded that the increase of temperature and atmospheric aridity is the probable cause or the observed increasing trend in spring *Quercus* pollen in the west Mediterranean area. Kubik-Komar et al. (2018) analysed *Fraxinus* pollen seasons and developed a forecast model based on meteorological factors. Bruffaerts et al. (2018) assessed statistical correlations between pollen concentration and meteorological conditions using long-term daily data sets of 11 pollen types observed in Brussels between 1982 and 2015. They found that the rates of change in annual pollen cycles were associated with the rates of change in the annual cycles of several meteorological parameters.

Despite the complexity of the interactions among different scales, we can distinguish between local transport (within a horizontal distance of a few hundred kilometres) and long-range transport. The first one occurs in the boundary layer under the prevailing influence of local winds, such as breezes and topographic features. Long-range transport occurs in the free troposphere and is managed by global circulation patterns and synoptic scale systems.

The aim of this chapter is to analyse and study the influence of local transport (wind speed and wind direction) on the daily airborne pollen concentration for 12 pollen taxa recorded at 6 aerobiological stations in Catalonia during the 11 years-period 2004-2014.

3.2. Data and Methodology

3.2.1. Pollen data

We have focused on those pollen types which sources are situated near the station (local transport) and have a major representation in the atmosphere (Table 3.1). The mean values of the Main Pollen Season (MPS) for the 12 pollen types at the six sampling stations during the years included in the study (2004-2014) are shown in Table 3.2.

Table 3.1: Pollen taxa under study.

Taxa	Plant type			Plant biogeography					Plant use			
	T	**B**	**H**	**BA**	**ES**	**SM**	**M**	**Cm**	**S**	**R**	**C**	**O**
Artemisia			H					Cm	S	R		
Chenop./Amar.			H					Cm	S	R		
Corylus		B			ES				S		C	
Cupressaceae	T	B			ES		M		S		C	O
Olea	T						M		S		C	O
Pinus	T			BA	ES	SM	M		S		C	O
Pistacia		B					M		S			
Plantago			H					Cm	S	R		
Platanus	T					SM	M		S		C	O
Poaceae			H					Cm	S		C	O
Quercus Total	T	B			ES	SM	M		S			O
Urticaceae			H					Cm	S	R		
	T - tree **B** - bush **H** - herb			**BA** - Boreo Alpine region **ES** - Euro-Siberian region **SM** - Sub-Mediterranean province **M** - Mediterranean region **Cm** – Cosmopolitan (all regions)					**S** - Silvestre or wild (not urban) **R** - Ruderal **C** – Cultivated (agriculture &forestry) **O** - Ornamental			

Table 3.2: Dates of Start and End of the MPS for 12 pollen taxa.

Station / Taxa	Barcelona (BCN)		Bellaterra (BTU)		Girona (GIC)		Lleida (LLE)		Manresa (MAN)		Tarragona (TAU)	
	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
Artemisia	24-4	29-11	26-6	22-11	26-3	15-11	21-6	1-12	1-4	1-12	16-4	5-12
Chenop./Amar.	31-3	26-10	17-4	23-10	24-4	23-10	5-5	2-10	25-4	26-10	4-4	5-11
Corylus	18-1	11-5	18-1	10-4	18-1	26-3	24-1	22-4	18-1	30-3	14-1	9-5
Cupressaceae	19-1	12-11	26-1	2-11	18-1	17-9	3-2	28-8	28-1	25-10	25-1	17-10
Olea	5-5	1-7	9-5	22-6	9-5	27-6	11-5	24-6	16-5	16-6	10-5	22-6
Pinus	15-3	3-7	17-3	19-6	13-3	3-7	26-3	29-6	21-3	26-6	11-3	24-6
Pistacia	1-4	21-5	29-3	13-5	28-3	9-5	27-3	23-5	4-4	11-5	25-3	10-5
Plantago	8-4	16-9	19-4	25-8	22-4	1-9	18-4	2-9	3-5	14-8	3-4	26-8
Platanus	23-3	4-6	19-3	20-4	19-3	20-4	21-3	28-4	26-3	24-4	17-3	28-4
Poaceae	30-3	4-10	1-4	18-9	11-4	1-9	31-3	29-9	3-4	16-9	25-3	14-10
Quercus Total	14-4	23-7	5-4	9-6	15-4	15-6	17-4	13-6	14-4	11-6	12-4	16-6
Urticaceae	10-2	9-11	3-3	20-10	4-3	11-10	10-3	1-11	10-3	4-11	29-1	30-11

The MPS has been established as the period beginning on the date when the sum of the daily mean pollen concentrations reaches 2.5% of the annual sum (Start) and ending on the date when the sum reaches 97.5% (End).

For a particular taxon, the Start and the End of the MPS are different at each station depending on the geographic and climatic characteristics.

Figures 3.1 show the location of the spore trap (indicated by the green star symbol) and the distribution of the vegetation around each of the six stations: Barcelona (BCN), Bellaterra (BTU), Girona (GIC), Lleida (LLE), Manresa (MAN) and Tarragona (TAU).

3.2.2. Wind data

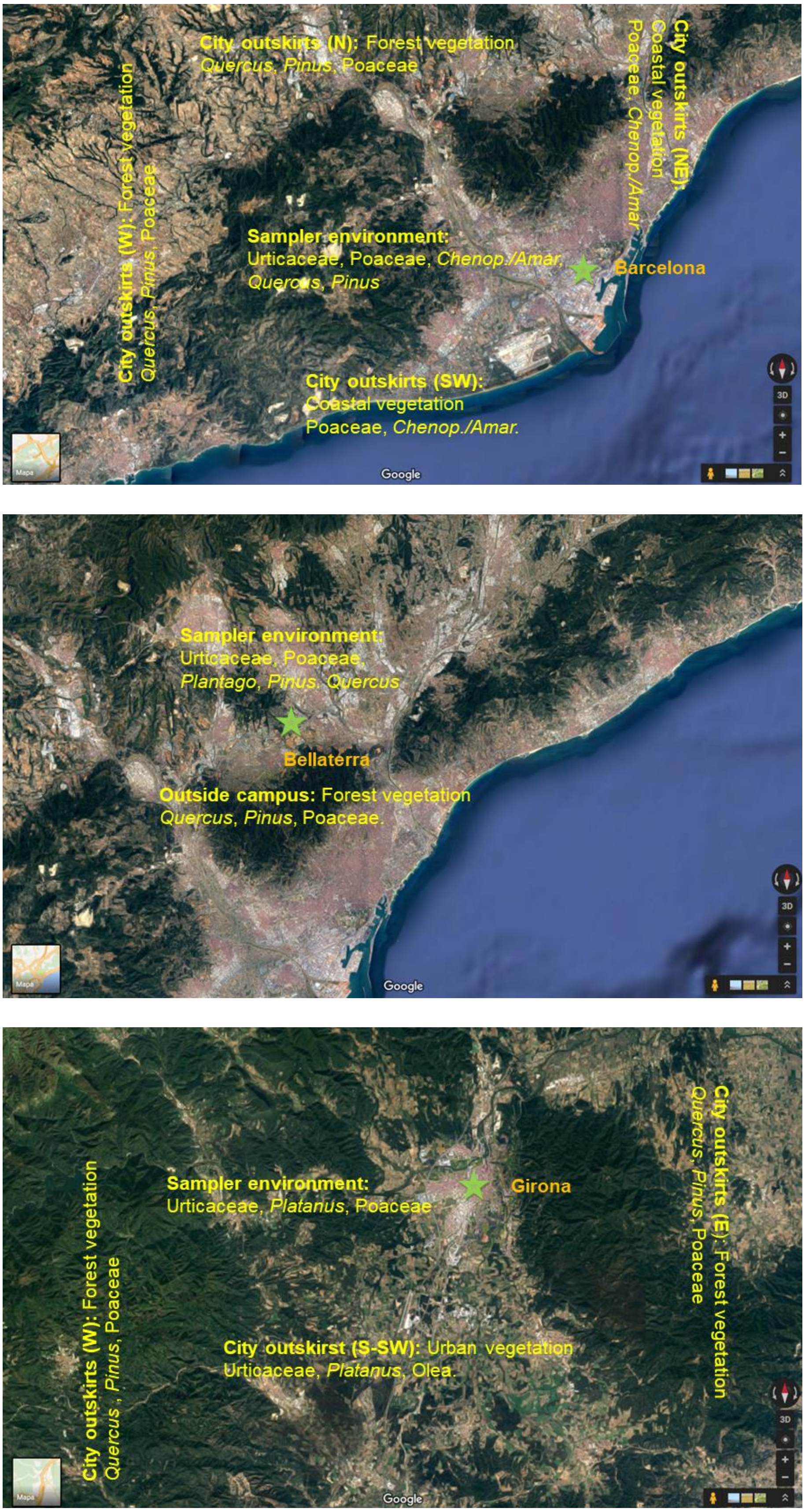
The daily wind data used in this study is based on the wind values for speed and direction recorded by the Spanish Agency of Meteorology (AEMET). However, in Barcelona, wind data was available for 2004-2014; data in Bellaterra and Lleida only for the period 2006-2014; and in Girona, Manresa and Tarragona for 2008-2014.

3.2.3. Statistical methods

In order to analyse the effect of the wind, the wind direction was divided into 8 sectors: north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W) and northwest (NW). For each sector, the correlation between the daily pollen concentration and the daily mean wind speed was computed using Spearman's rank correlation coefficient. We limited our study to days without precipitation during the MPS of each taxon. Table 3.3 gives the number of days without precipitation at each station.

Table 3.3: Number of days without precipitation.

Station	Days without precipitation	% of total
Barcelona	2438	77%
Bellaterra	1683	75%
Girona	1176	71%
Lleida	1383	69%
Manresa	1462	74%
Tarragona	1219	73%



Figures 3.1: Location of the spore trap (indicated by the green star symbol) and the distribution of the vegetation around each of the stations: BCN, BTU and GIC.

Figures 3.1 (cont): Location of the spore trap (indicated by the green star symbol) and the distribution of the vegetation around each of the stations: LLE, MAN and TAU.

3.3. Prevailing winds

In order to visualize wind patterns at the aerobiological stations, Figures 3.2 show the frequency distribution of wind speed and the corresponding wind rose diagrams for each station.

The wind rose diagram shows the frequency and speed of wind blowing from each sector. The length of each spoke indicates the frequency of wind coming from a particular sector. The colour bands show wind speed ranges.

Barcelona is the windiest site among the six stations. Winds above 3 m/s represent almost 45% of the total. Nevertheless, the prevailing wind comes from SW sector and represents almost 30% of the total. No strong wind comes from E and SE sector.

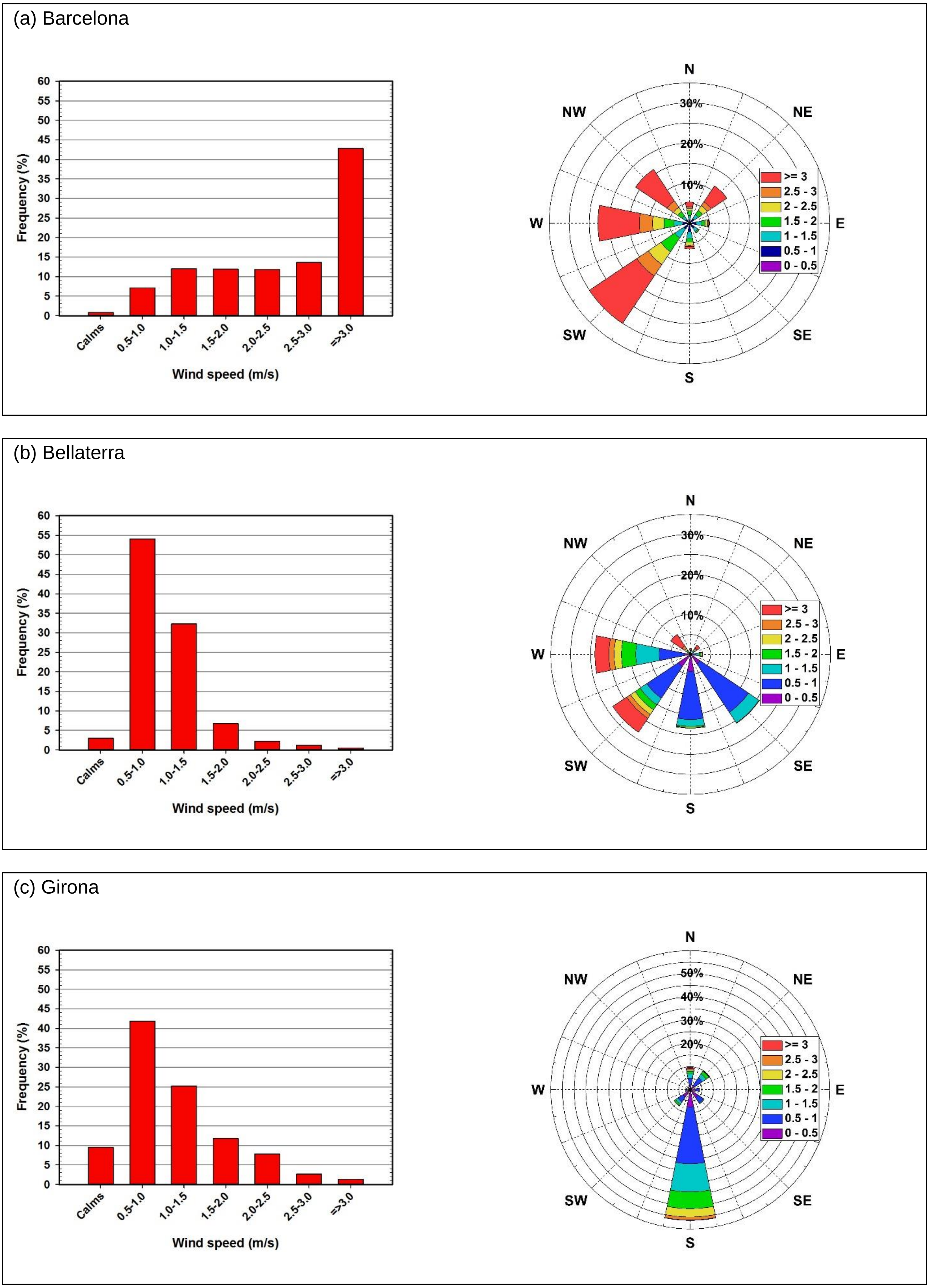
In Bellaterra, winds between 0 and 1.5 m/s represent almost 60% of the total. The prevailing winds come from the SE, S, SW and W sectors and represent 85% of the total. However, this station has low wind speeds (not exceed 3 m/s), maybe due to its situation behind the Littoral chain.

In Girona, most of the winds come from the S sector and represent 55% of the total. Nevertheless, wind speeds lower than 2 m/s represents 90% of the total, maybe due to its situation between the Pre-Littoral and the Littoral chains.

Lleida is characterized by light winds (70% of winds have speeds less than 1 m/s) and mostly blow from the SW and W directions. Winds coming from SW and W sectors represent 50% of the total, but only winds coming from the W sector exceed 3 m/s speed.

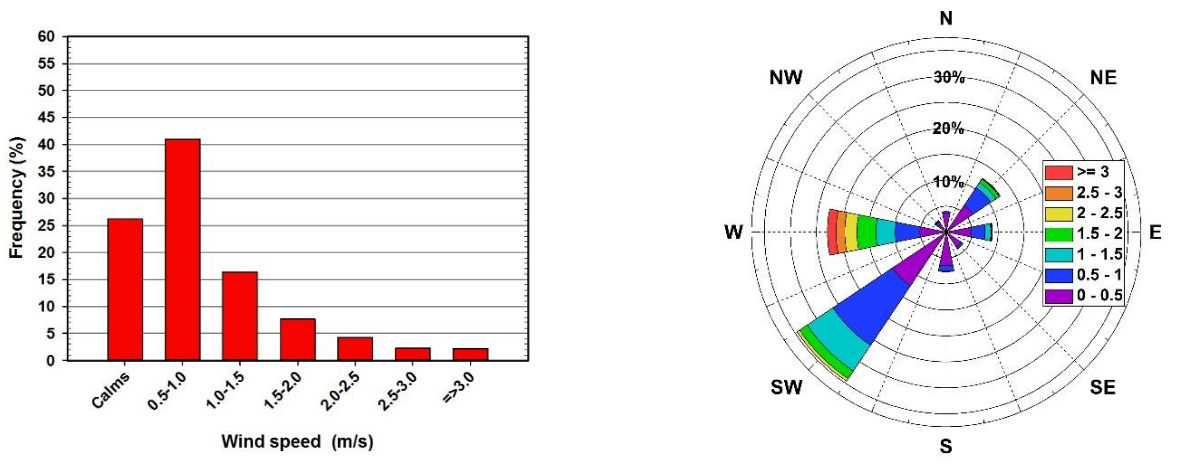
In Manresa, more than 75% of winds have speeds less than 1 m/s. The prevailing winds come from the SE and S sectors (50%) but the wind speed does not exceed 2 m/s. This station is protected against the Mediterranean advection by the Littoral and Pre-littoral chains and against northern outbreaks by the Pyrenees.

In Tarragona, the wind may reach more than 3 m/s particularly winds from the NW and W sectors. In this station, the wind does not show a clear prevailing direction because the city is wide open to the sea.

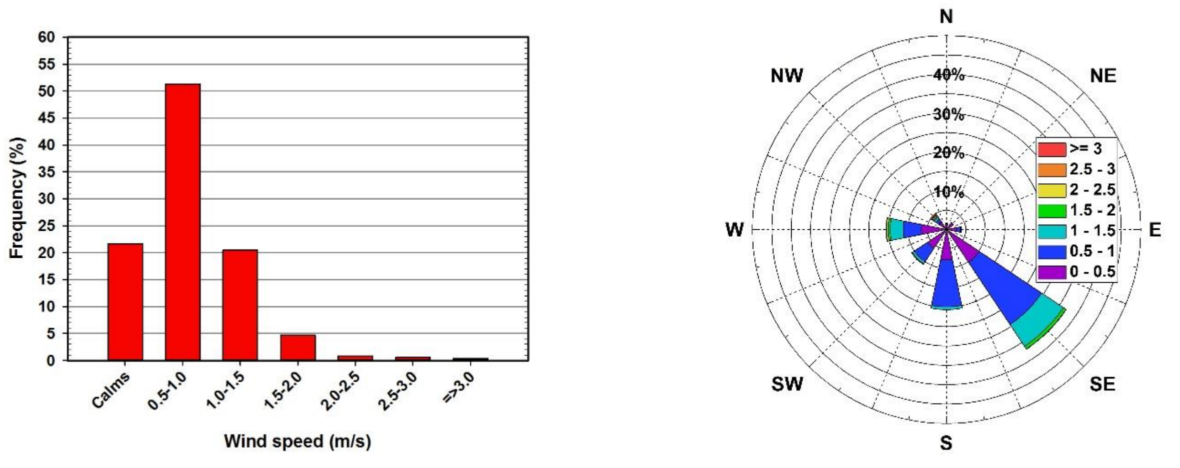


Figures 3.2: Frequency distribution of wind speed (m/s) and wind rose diagrams for a) Barcelona (2004-2014), b) Bellaterra (2006-2013), c) Girona (2008-2014)

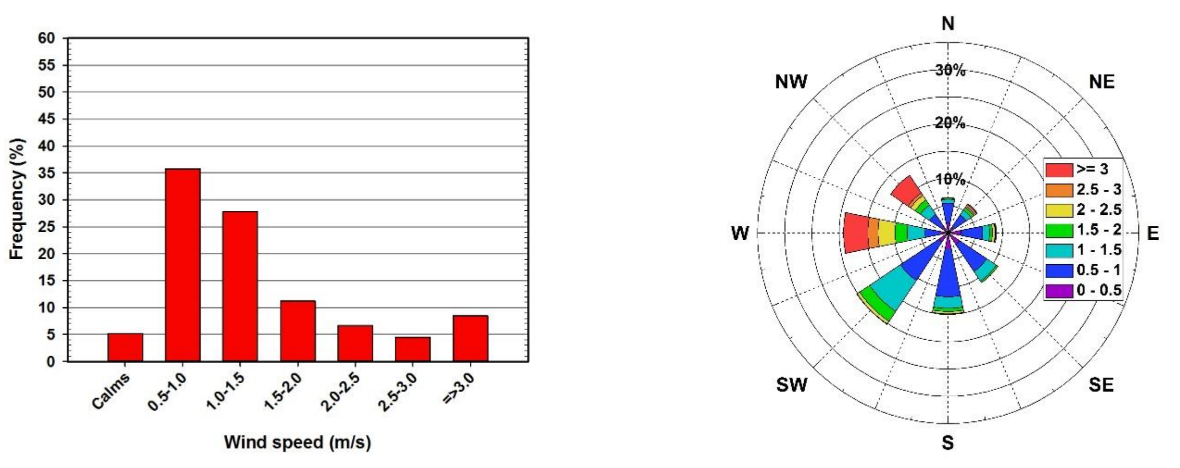
(d) Lleida



(e) Manresa



(f) Tarragona



Figures 3.2 (cont): Frequency distribution of wind speed (m/s) and wind rose diagrams for d) Lleida (2006-2014), e) Manresa (2008-2014) and f) Tarragona (2008-2014).

3.4. Correlations between pollen and wind

The Spearman's correlation coefficient between daily pollen concentration and daily wind speed blowing from 8 different directions (sectors) has been calculated. Significant correlations at the six sampling stations for each sector and for all the taxa are shown in Tables 3.4.

3.4.1. BCN station

In Barcelona, all the significant correlations for winds coming from SW, W and NW sectors are positive except for Urticaceae, which correlation is negative for NW winds. Otherwise, all the significant correlations for SE and S sectors are negative but involve only 4 of 12 taxa (*Artemisia*, *Olea*, *Platanus* and *Quercus*). Finally, no correlations have been found for N, NE and E sectors neither for *Corylus*, *Pistacia* and Poaceace (Table 3.4a).

Results show that concentrations of some taxa (*Artemisia*, *Olea*, *Platanus* and *Quercus*) have a negative correlation with the wind blowing from S and SE sectors. These negative correlations exist because southerly winds come from the sea towards the city of Barcelona (coastal city) and disperse and clean the pollen away from the city. Positive correlations have also been found between westerly winds (SW, W and NW) and some taxa (*Chenop./Amar*., Cupressaceae, *Olea*, *Pinus*, *Plantago*, *Platanus* and *Quercus*) originated in the west region (green spaces) of the city. In addition, the wind blowing from this region is characteristic of this area, it is an intense wind and maybe it can transport the pollen. So we can conclude that this wind direction is largely responsible for changes in the concentration. Only Urticaceae is affected negatively by the NW winds, maybe because this source of pollen is situated in the immediate proximity of the sampler, so the wind coming from the west region dilutes and carries off the pollen amassed in the zone. This explanation has also been stated by Muñoz et al (2000b) and Molina et al. (2001).

3.4.2. BTU station

In Bellaterra, 6 of the 12 taxa have only negative correlations with E, SE, S and SW winds and 3 of 12 have only positive relationships with E, SE, SW, and W directions. Cupressaceae and *Pinus* have both positive and negative correlations depending on the sector. No correlations have been found for winds coming from NE, N and NW sectors (Table 3.4b).

For Bellaterra, the results indicated that a southerly wind (SE, S and SW) negatively affects the pollen concentration of *Artemisia*, *Chenop./Amar*., Cupressaceae, *Olea*, *Pinus, Pistacia*, *Plantago,* and *Platanus*, a similar case as in Barcelona. This is because this city is located close to Barcelona and is affected by the wind coming from the sea. On the other hand, the pollen concentration of Poaceae has a positive correlation with SE wind because this taxon is the coastal vegetation and large sources of this taxon exist surrounding the city where the trap is located. Also, the results for *Pinus* and Urticaceae indicate a positive correlation with W and SW winds, respectively; and the concentration of *Quercus* is also positively correlated with E winds. This is because the areas located in these directions with respect to the city are covered with types of vegetation that are considered a source of this kind of taxa. Finally, Cupressaceae also shows a positive correlation when the wind comes from the W despite this plant is not present in the area. The explanation can be that the strong westerly winds coming from the area of Lleida carry this type of taxa.

3.4.3. GIC station

In Girona, the significant correlations for winds coming from the NE sector are always positive but involve only 3 of the 12 taxa (Cupressaceae, *Pistacia* and Urticaceae). Regarding the negative significant correlations, only 3 of 12 (*Artemisia*, *Chenop./Amar*. and *Corylus*) have negative correlation with E, S and SW directions. Finally, no correlations have been for N, SE, W and NW sectors neither for the rest of the taxa (Table 3.4c).

In Girona, the correlation between pollen concentration and the wind was relatively low for some taxa due to the geographical location of the city. It was found that winds blowing from E, S, and SW negatively affect some taxa (*Artemisia*, *Chenop./Amar*., and *Corylus*). This is because this location has almost no green areas in the south. In contrast, the concentration of the Cupressaceae *and Pistacia* was positively correlated with NE winds. This is expected, because green areas and forests can be found surrounding the city (except in the south, as was mentioned above). Finally, Urticaceae also shows a positive correlation with NE winds because sources of this species can be found at the north-east of the trap.

3.4.4. LLE station

In Lleida, only *Corylus* and *Quercus* have no correlation with any of the 8 wind directions. The rest of the taxa exhibit either positive or negative correlations or both, not being observed a clear pattern (Table 3.4d).

In Lleida, a positive correlation exists between NW wind and the concentration of *Artemisia*; this is explained by the fact that vast sources of this kind of taxa exist at the northwest of the city. In addition, wind speeds from this direction are higher than those blowing from other directions.

The results also showed a negative correlation of the concentration of the same taxa with winds blowing from N, NE, SE, and S directions; this could be attributed to a cleaning and dispersion effect over the pollen in the station. For Cupressaceae, *Olea, Pinus,* and Poaceae, their concentrations are positively correlated with north, east and south directions; because these regions are characterized by high concentrations of these taxa from these directions (see Fig. 3.1). The negative correlation of the *Platanus* and Urticaceae, with W and SW winds is a result of the speedy wind from this sector carrying the pollen away from the trap. Urticaceae also has a positive correlation for SE winds because this type of vegetation is found in this area. Finally, *Pistacia and Plantago,* give positive correlations for winds coming from the NE and the SW-W, despite these plants are not present in the area, which suggests that they are carried by wind from other areas.

3.4.5. MAN station

In Manresa, 3 of the 12 taxa (*Plantago*, Poaceae, and *Quercus*) show no correlation with any of the wind sectors. *Chenop./Amar*. has a positive correlation in the W direction and Urticaceae has negative correlations in the SE, SW, and W directions. The other 7 taxa have positive correlations, except for *Corylus*, which also has a negative correlation in the E direction. Finally, no correlations have been found from the N and NE wind directions (Table 3.4e).

Most of the correlations between pollen concentration and wind are negative due to the geographical location of this town and the shortage of pollen sources at the south of the town. Exceptions are the pollen of Urticaceae, which has a positive correlation with SE, SW and W winds, and *Chenop./Amar* with a positive correlation with W winds. This can be explained by the fact that sources of these taxa are located close or around the trap and the weak wind results in high concentrations of this kind of pollen. Finally, *Corylus* taxa are also positively correlated with E winds and this may be due to the existence of forests and vegetation areas at the east of the city.

3.4.6. TAU station

In Tarragona, *Olea*, *Pistacia*, and *Platanus* have no correlation with any of the wind sectors. *Corylus*, Cupressaceae, and *Pinus* have only negative correlations and *Chenop./Amar.*, *Plantago*, Poaceae, and *Quercus* have only positive correlations with winds mainly coming from SW, W, and NW sectors. Finally, *Artemisia* and Urticaceae have both positive and negative correlations. No correlations have been found for the NE sector (Table 3.4f).

In Tarragona, the wind can blow from most directions due to the coastal location of this city. The results illustrate that the positive correlations of the pollen are with W and NW winds for *Chenop./Amar.*, Poaceae, *Quercus* and Urticaceae. This is a result of the existence of vegetation cover in these locations, which provides local sources of the pollen. It must also be noted that Poaceae and Urticaceae pollen have positive correlations with S and E winds. This is because these types of taxa exist near and around the trap. This same conclusion can be found in Maya-Manzano et al. 2017. Urticaceae shows a negative correlation with N wind, probably because no sources can be found in this direction. On the other hand, *Artemisia* and *Chenop./Amar*. show some positive correlations despite no sources are located around the area; these are carried by intense winds coming from inland, W and NW. *Plantago* has also a positive correlation with SW winds, but no sources can be found near the trap. Finally *Corylus* and Cupressaceae show negative correlations with winds coming from the sea (E, S and SW), which we know have a dispersion effect.

3.5. Discussion

Results show high variability in the correlation coefficient and this variation depends on the type of the pollen taxa and the location of the sampling station.

The number of the significant correlations between daily pollen concentration and daily wind speed for each wind sector in each sampling station are summarized in Table 3.5. Tarragona and Lleida were the stations with the highest number of significant correlations (23 and 22 respectively) followed by Bellaterra (18), Manresa (17), and Barcelona (13), while Girona was the station with the lowest number of significant correlation (7).

The number of significant correlations for each taxon and each sector are summarized in Table 3.6. It can be observed that *Artemisia* is the taxon with the highest number of correlations (18% of the total) and these correlations were mainly negative. On the other hand, *Pistacia* and *Quercus* are the taxa with the lowest number of correlations (4% of the total). The results also show that southerly winds present the highest number of correlations (20% of the total) and these correlations are manly negative. The northerly winds have the least number of correlations (2% of the total). Finally, it can be highlighted that Poaceae is the only taxon that shows all positive correlations with the winds coming from any direction.

Radar charts were employed to investigate the effect of wind speed and direction on daily pollen concentrations. Figures 3.3 show the radar charts for some selected cases in which the concentration is well-correlated with the wind speed. These correlations are interpreted as follows:

a) *Artemisia* in Tarragona.

The correlation is significantly positive for W and NW sectors, where the stronger winds come from, meaning that the contribution of pollen comes from a localized source in the W-NW of the city and inland of Catalonia (possibly from LLE station). At the same time, significant negative correlations with the winds blowing from SE and SW sectors have been found. This result could be interpreted as a cleaning and dispersion effect over the pollen recorded in the station possibly due to winds coming from the sea.

b) *Chenop./Amar.* in Tarragona.

The significant positive correlations for *Chenop./Amar.* in Tarragona are very similar to the case (a) for *Artemisia*. This correlation is a result of strong winds from W-NW, so the contribution of pollen comes from a localized source in the W-NW of the city and inland of Catalonia (possibly from LLE station).

c) Cupressaceae in Manresa.

The correlations are negative for winds blowing from SE-S-SW sectors. These winds contribute to a cleaning and dispersing effect of the Cupressaceae pollen over the station. Following the radar charts, a positive correlation with wind coming from NW sector should be obtained. This fact could be explained because NW winds in Manresa are not predominant and represent only a 5% of the total.

d) Cupressaceae in Bellaterra.

The SE, S and SW winds, coming from the sea, dilute the concentration of Cupressaceae pollen over Bellaterra, thus resulting in a negative correlation. In contrast, W winds result in a positive correlation. These correlations, both negative and positive, could be explained by the contribution of pollen from a localized source in the west of Bellaterra (possibly from LLE station)

e) *Platanus* in Lleida.

The negative correlation between *Platanus* pollen concentrations and wind speed from the W sector can be interpreted as a cleaning and dispersion effect of the pollen over the station due to strong winds coming from the W sector often associated with frontal situations.

The results obtained here are similar to those found by many researchers (Solomon, 1988; Keynan et al., 1991; Rantio-Lehtimäki et al., 1994; Campbell et al., 1999; Silva et al., 2000; Adams-Groom et al., 2002; Damialis et al., 2005; Williams et al., 2007; Rojo et al., 2015). When the wind is blowing towards the city from the direction of the source location, the correlation is positive while negative correlation results from the wind blowing from the opposite direction or coming from the sea. Therefore, positive correlations increase the pollen concentration in the station and negative correlations indicate cleaning and dispersion processes of the pollen concentration.

Tables 3.4: Significant correlations between daily pollen concentration and daily wind speed. (Green = positive, Orange = negative)

(a) Barcelona								
Taxa \ Sector	N	NE	E	SE	S	SW	W	NW
Artemisia					-0,192*			
Chenop./Amar.						0,094*		
Corylus								
Cupressaceae								0,117*
Olea				-0,630**				0,456**
Pinus							0,154*	0,285*
Pistacia								
Plantago								0,337**
Platanus					-0,345*			0,342**
Poaceae								
Quercus Total				-0,509**				0,420**
Urticaceae								-0,233**

(b) Bellaterra								
Taxa \ Sector	N	NE	E	SE	S	SW	W	NW
Artemisia				-0,332**	-0,384**	-0,204**		
Chenop./Amar.			-0,607*					
Corylus								
Cupressaceae				-0,209**	-0,321**	-0,138*	0,246**	
Olea				-0,200*	-0,245*			
Pinus					-0,232**		0,273*	
Pistacia					-0,293*			
Plantago					-0,188**			
Platanus				-0,941**				
Poaceae				0,171**				
Quercus Total			0,899*					
Urticaceae						0,140*		

(c) Girona								
Taxa \ Sector	N	NE	E	SE	S	SW	W	NW
Artemisia			-0,388*		-0,085*			
Chenop./Amar.						-0,345*		
Corylus					-0,261**			
Cupressaceae		0,235*						
Olea								
Pinus								
Pistacia		0,473*						
Plantago								
Platanus								
Poaceae								
Quercus Total								
Urticaceae		0,232**						

Tables 3.4 (cont): Significant correlations between daily pollen concentration and daily wind speed. (Green = positive, Orange = negative)

(d) Lleida								
Sector / Taxa	N	NE	E	SE	S	SW	W	NW
Artemisia	-0,372**	-0,194*		-0,477**	-0,343**			0,391*
Chenop./Amar.					-0,229*			
Corylus								
Cupressaceae		0,203**	0,308**				0,168**	
Olea				0,448*				0,727*
Pinus			0,246*					
Pistacia		0,392*						
Plantago						0,158**	0,381**	
Platanus							-0,367*	
Poaceae				0,313*		0,136**		0,460**
Quercus Total								
Urticaceae				0,345**		-0,183**	-0,238**	

(e) Manresa								
Sector / Taxa	N	NE	E	SE	S	SW	W	NW
Artemisia				-0,167**	-0,163**			-0,339*
Chenop./Amar.							0,265*	
Corylus			0,477*		-0,355*	-0,360		
Cupressaceae				-0,188**	-0,435**	-0,165*		
Olea						-0,751**		
Pinus					-0,225*			
Pistacia								-0,664*
Plantago								
Platanus					-0,464*			
Poaceae								
Quercus Total								
Urticaceae				0,277**		0,294**	0,274**	

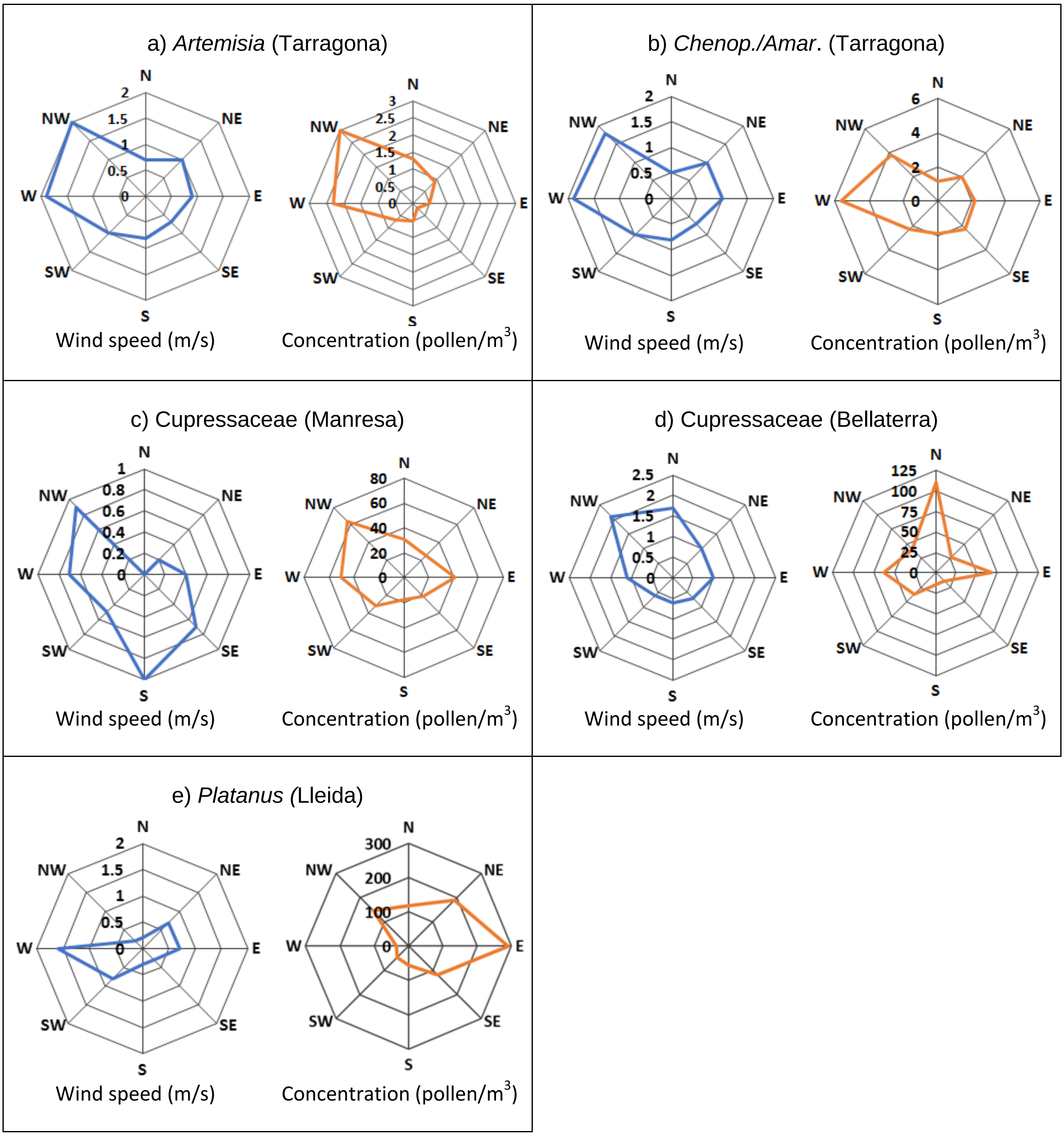
(f) Tarragona								
Sector / Taxa	N	NE	E	SE	S	SW	W	NW
Artemisia				-0,212*		-0,223**	0,219**	0,244**
Chenop./Amar.							0,364**	0,411**
Corylus			-0,413*		-0,273*			
Cupressaceae					-0,215**	-0,182**		
Olea								
Pinus							-0,246*	
Pistacia								
Plantago						0,169*		
Platanus								
Poaceae			0,224*		0,198**	0,288**	0,465**	0,385**
Quercus Total								0,649**
Urticaceae	-0,250*		0,189*			0,168**	0,207**	0,211**

Table 3.5: Significant correlations between daily pollen concentration and daily wind speed for all the taxa for each sector in each sampling station.

Station / Sector	Barcelona		Bellaterra		Girona		Lleida		Manresa		Tarragona				
Correlation	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**Total**
N	-	-	-	-	-	-	-	1	-	-	-	1	-	2	**2**
NE	-	-	-	-	3	-	2	1	-	-	-	-	5	1	**6**
E	-	-	1	1	-	1	2	-	1	-	2	1	6	3	**9**
SE	-	2	1	4	-	-	3	1	1	2	-	1	5	10	**15**
S	-	2	-	6	-	2	-	2	-	5	1	2	1	19	**20**
SW	1	-	1	2	-	1	2	1	1	3	3	2	8	9	**17**
W	1	-	2	-	-	-	2	2	2	-	4	1	11	3	**14**
NW	6	1	-	-	-	-	3	-	-	2	5	-	14	3	**17**
Total	8	5	5	13	3	4	14	8	5	12	15	8	**50**	**50**	**100**
	13		**18**		**7**		**22**		**17**		**23**				

Table 3.6: Significant correlations between daily pollen concentration and daily wind speed for all the stations for each taxon and each sector.

Sector / Taxa	N		NE		E		SE		S		SW		W		NW				
Correlation	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**Total**
Artemisia	-	1	-	1	-	1	-	4	-	5	-	2	1	-	2	1	3	15	**18**
Chenop./Amar.	-	-	-	-	-	1	-	-	-	1	1	1	2	-	1	-	4	3	**7**
Corylus	-	-	-	-	1	1	-	-	-	3	-	1	-	-	-	-	1	5	**6**
Cupressaceae	-	-	2	-	1	-	-	2	-	3	-	3	2	-	1	-	6	8	**14**
Olea	-	-	-	-	-	-	1	2	-	1	-	1	-	-	2	-	3	4	**7**
Pinus	-	-	-	-	1	-	-	-	-	2	-	-	2	1	1	-	4	3	**7**
Pistacia	-	-	2	-	-	-	-	-	-	1	-	-	-	-	-	1	2	2	**4**
Plantago	-	-	-	-	-	-	-	-	-	1	2	-	1	-	1	-	4	1	**5**
Platanus	-	-	-	-	-	-	-	1	-	2	-	-	-	1	1	-	1	4	**5**
Poaceae	-	-	-	-	1	-	2	-	1	-	2	-	1	-	2	-	9	-	**9**
Quercus Total	-	-	-	-	1	-	-	1	-	-	-	-	-	-	2	-	3	1	**4**
Urticaceae	-	1	1	-	1	-	2	-	-	-	3	1	2	1	1	1	10	4	**14**
Total	-	2	5	1	6	3	5	10	1	19	8	9	11	3	14	3	**50**	**50**	**100**
	2		**6**		**9**		**15**		**20**		**17**		**14**		**17**				



Figures 3.3: Radar charts of mean daily wind speed (m/s) and mean daily pollen concentration (pollen/m^3) for: a) *Artemisia* (Tarragona), b) *Chenop./Amar* (Tarragona), c) Cupressaceae (Manresa), d) Cupressaceae (Bellaterra) and e) *Platanus* (Lleida)

3.6. Conclusions

It is well known that the wind plays a major role in transporting and dispersing pollen in the atmosphere (Mandrioli, 1990; Gioulekas et al. 2004; Dehghanpour et al., 2014). Wind speed and direction have to be taken into account to explain the airborne pollen concentrations recorded in the sampling stations. It is accepted that the major part of the pollen trapped comes from local sources, although some taxa not representative of regional vegetation are also recorded arriving due to long-range transport mechanism.

This work has investigated the effect of wind on pollen distribution in Catalonia. For this purpose, daily wind and daily pollen concentration data recorded at six stations in Catalonia during 2004-2014 period, have been analysed. We have focused on 12 pollen types which sources are situated near the station and have a major representation in the atmosphere.

A positive correlation exists when the wind blows towards the station from the direction of the source location, and negative correlation results when the wind blows in a direction from the station towards the source of pollen or coming from the sea. Therefore, positive correlations mean an increase the pollen concentration in the station and negative correlations indicate dispersing and cleaning processes of the pollen concentration. Many works have found similar results (Silva et al. 2000; Williams et al. 2007; Recio et al., 2018).

The cleaning and dispersion effect over the pollen concentrations has been observed on the coastal stations (BCN, BTU and TAU) mainly due to the wind induced by the sea breeze effect (SW and SE) and on the inland stations (LLE and MAN) when westerly frontal synoptic situations are produced.

Poaceae pollen grains are an important cause of allergies and this plant are ubiquitously present in Catalonia and 296 species have been identified (de Bolòs & Vigo, 2005). The sources of this type of pollen are distributed near and around the trap in almost all directions as it shown on the maps (Figures 3.1), explaining why the correlations were only positive in all directions.

This study could also be useful not only to identify and locate airborne pollen sources but to detect changes in in the geographical distribution of vegetation near the sampling stations.

4. INFLUENCE OF ATMOSPHERIC TELECONNECTION PATTERNS ON AIRBORNE POLLEN LEVELS

4.1. Introduction

4.2. Data and Methodology
4.2.1. Pollen records
4.2.2. Climatic indices
4.2.3. Statistical methods

4.3. Results
4.3.1. Climatic indices
4.3.2. APIn and Climatic Indices
4.3.3. Start, End and Length of the MPS and Climatic Indices
4.3.4. Influence of the Climatic Indices in the Pollen Dynamics

4.4. Discussion

4.5. Conclusions

4.1. Introduction

The influence of climate and climatic changes on ecosystems has been often recognized in the literature in the recent years (Walther 2010). It is apparent that large-scale climate variability affects ecosystems not only through a single weather variable, but rather through a blend of weather features (Stenseth & Mysterud 2005). Climate change may result in an increase in the frequency of extreme events which are more relevant in the phenology of the ecosystems than fluctuations in the mean climate (Stenseth et al. 2002, 2003). Climate indices reducing complex space and time variability and gathering different climatic variables into simple measures have been shown to be of great use in the field of ecology.

One of the more interesting climate indices for the correlation with ecological processes in the Northern Hemisphere is the **North Atlantic Oscillation (NAO)** index (Barnston & Livezey 1987), the major driving force of the climate system of the Northern Hemisphere (Hurrell 1995) quantifying the interannual variability in the atmospheric circulation of the northern Atlantic region. The NAO index (NAOi) is based on the sea level pressure difference between the sub-polar low-pressure centre over Iceland and the subtropical high-pressure centre over the Azores (Gomes 2001, Stenseth et al. 2002). Many studies have discussed over the databases of the different meteorological stations (Punta Delgada, Lisbon, Gibraltar, Reykjavik, Akureyri, Stykkisholmur, among others) that could be used to measure this difference of pressure (Hurrell 1995, Jones et al. 1997, Osborn 2006). For the purposes of this study, the NAOi is defined as the difference between the normalized pressure anomaly at Gibraltar (Iberian Peninsula) and Reykjavik (southwestern Iceland).

According to Hurrell (1995), the NAO is the main large-scale pattern that influences the variability of the Euro-Mediterranean climate. The NAO regulates the cyclone trajectories and cyclogenesis in the Mediterranean area which influences its climatic variability (Bolle 2003). This phenomenon is particularly important in the western Mediterranean region, which is strongly affected by the NAO atmospheric dipole (Von Storch et al. 1993). Thus, a positive NAO phase results into a positive level pressure anomaly over the Mediterranean Basin, which, in turn, corresponds to a northward deflection trajectory followed by Atlantic cyclones and to a lesser cyclogenesis in the Basin (Hurrell et al. 2003). In other terms, a positive NAO phase corresponds to a lower cyclone frequency in the area, a smaller cloud cover and, therefore, a greater insolation. So, taking into account that the surface temperature in the Mediterranean area relies much on the insolation (Muñoz-Díaz & Rodrigo 2003) and that temperature has been identified as the most important factor affecting the start date of pollen seasons in temperate ecosystems (Emberlin et al. 1993, Van Vliet et al. 2002, Galán et al. 2005), the hypothesis of an advance in the pollen seasons of different taxa, correlated with the NAOi, can be inferred. In contrast, the NAO negative mode produces high-pressure blocking in the NE Atlantic with more meridional circulation and wetter conditions in the western Mediterranean (Figure 4.1).

Some effects of climate variability on plant phenology include advances on some parameters such as the deployment of the new leaves or the flowering (Menzel et al. 2006), shifts in the timing of the pollen seasons (Jäger et al. 1996, Emberlin et al. 2007) or an increase of the pollen production of different plants (Teranishi et al. 2000, Ziello et al. 2012). According to Clot (2003), atmospheric pollen can be considered a very sensitive indicator of climate variability. That is the reason why many recent studies are addressing this issue from an aerobiological perspective. D'Odorico et al. (2002) were able to find relationships between some phases of the NAO and different parameters of the pollen season. Later, Avolio et al. (2008) found that the climatic interannual variability due to the NAO was unequivocally tied to the olive pollen seasons in Central Italy. More recently, a study by Smith et al. (2009) showed the importance of considering large-scale patterns of climate variability like the NAO for the prediction of the start and magnitude of the grass pollen seasons across Europe.

On the other hand, the western Mediterranean is under the **Western Mediterranean Oscillation (WeMO)** domain. This recently defined secondary oscillation form in the Western Mediterranean basin (Martín-Vide & López-Bustins 2006) accounts for the eastern Iberian Peninsula regions that are weakly or not related to the NAO pattern. The WeMO index (WeMOi) is defined using the dipole San Fernando (Cadiz, Spain) - Padua (Italy). The positive mode corresponds to high pressures over the Azores and SW Iberian Peninsula and low pressures in the Liguria Gulf. In the positive phase rainfall is more abundant in the Cantabrian peninsular coast and lower in the Mediterranean one, being fluxes over Catalonia mostly from the north (France and Northern Iberian Peninsula). Its negative mode is produced when an anticyclone is situated in central Europe and the north of Italy and low pressures in the SW Iberian Peninsula. In this negative phase fluxes over Catalonia are predominantly from the Mediterranean Sea and northern Africa and wetter conditions occur over the eastern coast of the Iberian Peninsula and the Ebro basin (Figure 4.2).

There is another natural mode of variability that greatly affects Europe and the Mediterranean area, the **Arctic Oscillation (AO)**, which represents the state of atmospheric circulation over the Arctic (López-Bustins et al. 2008). The AO index (AOi) is defined as the first principal component time-series of the mean sea-level pressure field over the Northern Hemisphere, north of 20º (Stenseth et al. 2003). Despite there is a high correlation between AO and NAO, the basic physical mechanisms are different (Zhou et al. 2001). While NAO refers to a local mechanism associated to a physical dipole affecting the North Atlantic, the AO has a zonal structure reflecting the variations of the circumpolar flow (Ambaum et al. 2001). In its positive mode, lower-than-normal pressures over the polar region are registered, driving Atlantic storms northward, thereby wetter weather over northern Europe and drier conditions to the Mediterranean regions (Figure 4.3).

As a summary, the positive phases of the NAO, WeMO and AO indices suppose sunnier and drier conditions in Catalonia than their negative phases that coincide with wetter and rainier conditions.

The most recent studies on the subject have focused on the spatial variability of the pollination seasons in relation with the NAO index (Stach et al. 2008a,b, Smith et al. 2009, Dalla Marta et al. 2011), but, for instance, there are no studies to assess the influence of the NAO over the different taxa representative of the surrounding vegetation. No studies have been done relating airborne pollen data with WeMO and AO indices.

In this chapter, we aim to investigate the correlation between the NAO, WeMO and AO indices and the main standardized airborne pollen parameters (Annual Pollen Integral, Start, End and Length of the main pollen season) of 22 taxa collected at 6 localities in Catalonia (NE Spain) during the 18 years-period 1994-2011, in order to determine the effect of climate variability on their pollen dynamics.

4.2. Data and Methodology

4.2.1. Pollen records

Airborne pollen data were recorded by the Aerobiological Network of Catalonia (XAC) at six stations located in Barcelona (BCN), Bellaterra (BTU), Girona (GIC), Lleida (LLE), Manresa (MAN) and Tarragona (TAU). The Annual Pollen Integral (APIn, sum of the mean daily pollen concentrations in a year for the main pollen season) has been used as the measure of the pollen, and obtained for 22 pollen taxa: *Alnus*, *Ambrosia, Artemisia*, *Betula*, *Castanea*, Chenopodiaceae/Amaranthaceae, *Corylus*, Cupressaceae, *Fagus*, *Fraxinus*, *Olea*, *Pinus*, *Pistacia*, *Plantago*, *Platanus*, Poaceae, Polygonaceae, total *Quercus, Quercus* deciduous type, *Quercus* evergreen type, *Ulmus* and Urticaceae.

The pollen parameters studied here were: Annual Pollen Integral (**APIn**), the dates of **Start** and **End** of the main pollen season and the **Length** (number of days between the Start and the End). Besides, the Main Pollen Season (**MPS**) has been established as the period between the date (Start) in which the sum of the daily mean pollen concentrations reaches 2.5% of the annual sum and the date (End) in which the sum reaches 97.5% (Andersen 1991, Torben 1991).

4.2.2. Climatic indices

The NAOi [(1)], the WeMOi [(2)] and the AOi [(3)] were correlated with APIn and Start, End and Length of the MPS. Considering that the climatic indices show their most relevant dynamics during the cold months, both, the annual and the winter (December to March) indices were used. Besides, the correlations between APIn and summer NAO (SNAO, July and August) were also computed. Though less robust and extensive than counterpart, the SNAO is nonetheless a prominent feature of summer atmospheric variability in the North Atlantic/European sector, which significantly affects precipitation in the Mediterranean area (Bladé et al. 2012).

4.2.3. Statistical methods

Standardized values of the variables were used in the pollen data and the climatic indices. Spearman's rank correlation coefficient was applied to measure the relationship between pollen data (API, MPI, Start, End and Length of the pollination season) and the climatic indices. The Spearman correlation was used because it is considered more robust and resistant to outlying data than the conventional Pearson correlation coefficient (Wilks, 2011; Fernandez-Llamazares et al. 2012).

(1) Hurrell, James & National Center for Atmospheric Research Staff (https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based)

(2) Group of Climatology, University of Barcelona (http://www.ub.edu/gc/2016/06/08/wemo/)

(3) NOAA, National Weather Service, Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml)

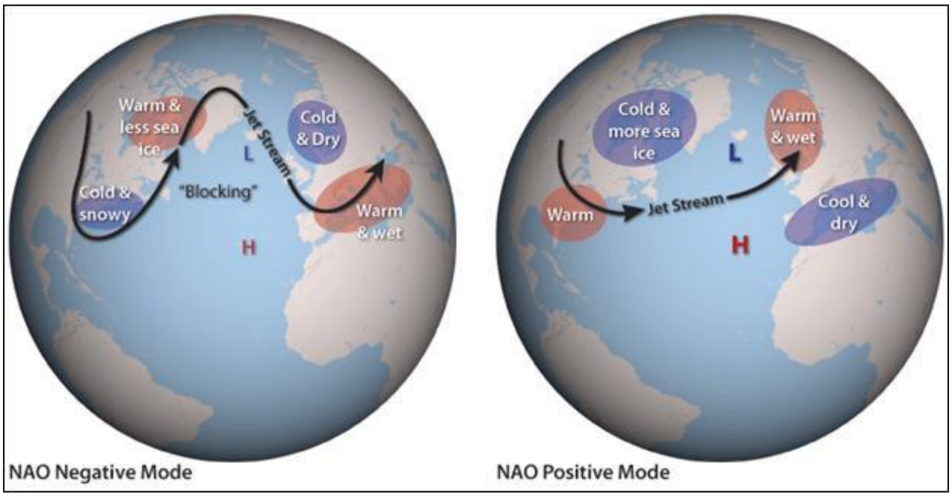


Figure 4.1: Positive and negative phases of NAO.

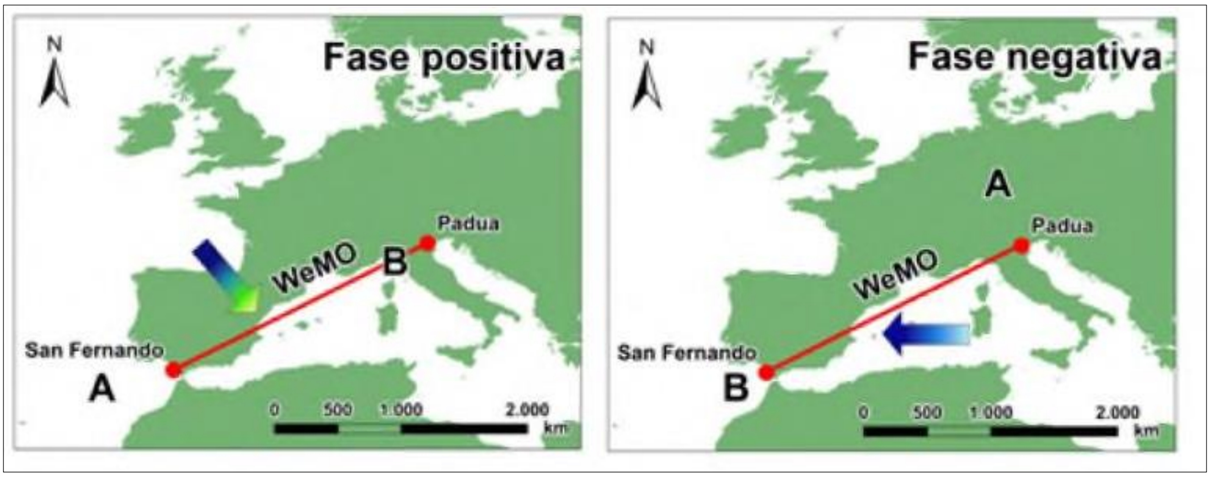


Figure 4.2: Positive and negative phases of WeMO.

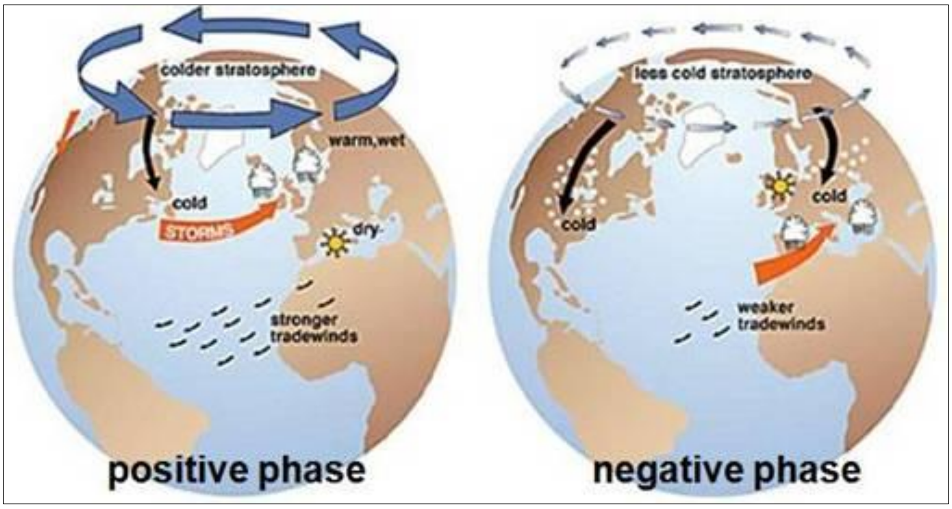


Figure 4.3: Positive and negative phases of AO.

4.3. Results.

4.3.1. Climatic indices.

In the 18-year period analysed here, NAOi and AOi showed a high positive Spearman bivariate correlation in both, their annual (0.794, $p<0.001$) and winter (0.796, $p<0.001$) dynamics, and a weaker but still significant (0.507, $p<0.05$) between the NAOi annual and the AOi winter. Regarding WeMOi, the winter index showed a positive correlation (0.645, $p<0.001$) with the NAOi winter but a weak and non-significant positive correlation between their annual values. No correlation was found between WeMOi and AOi (Table 4.1).

Figure 4.4 shows the decadal trends of climatic indices. Annual and winter trends of NAOi, AOi and WeMOi were negative during 1994-2011 period, but only the declining trend of annual WeMOi was significant (R^2=0.504, p=0.001).

Table 4.1: Spearman's rho between the climatic indices in their winter **(w)** and annual **(a)** dynamics. (*p<0.05; ****p<0.001**)

		NAOi (w)	NAOi (a)	WeMOi (w)	WeMOi (a)	AOi (w)	AOi (a)
NAOi (w)	rho p n	1.000 - 18	**0.562*** 0.015 18	**0.645**** 0.004 18	0.354 0.150 18	**0.796**** 0.000 18	0.410 0.091 18
NAOi (a)	rho p n	**0.562*** 0.015 18	1.000 - 18	0.253 0.311 18	0.051 0.842 18	**0.507*** 0.032 18	**0.794**** 0.000 18
WeMOi (w)	rho p n	**0.645**** 0.004 18	0.253 0.311 18	1.000 - 18	0.408 0.093 18	0.422 0.081 18	0.199 0.428 18
WeMOi (a)	rho p n	0.354 0.150 18	0.051 0.842 18	0.408 0.093 18	1.000 - 18	0.152 0.548 18	-0.102 0.687 18
AOi (w)	rho p n	**0.796**** 0.000 18	**0.507*** 0.032 18	0.422 0.081 18	0.152 0.548 18	1.000 - 18	0.406 0.095 18
AOi (a)	rho p n	0.410 0.091 18	**0.794**** 0.000 18	0.199 0.428 18	-0.102 0.687 18	0.406 0.095 18	1.000 - 18

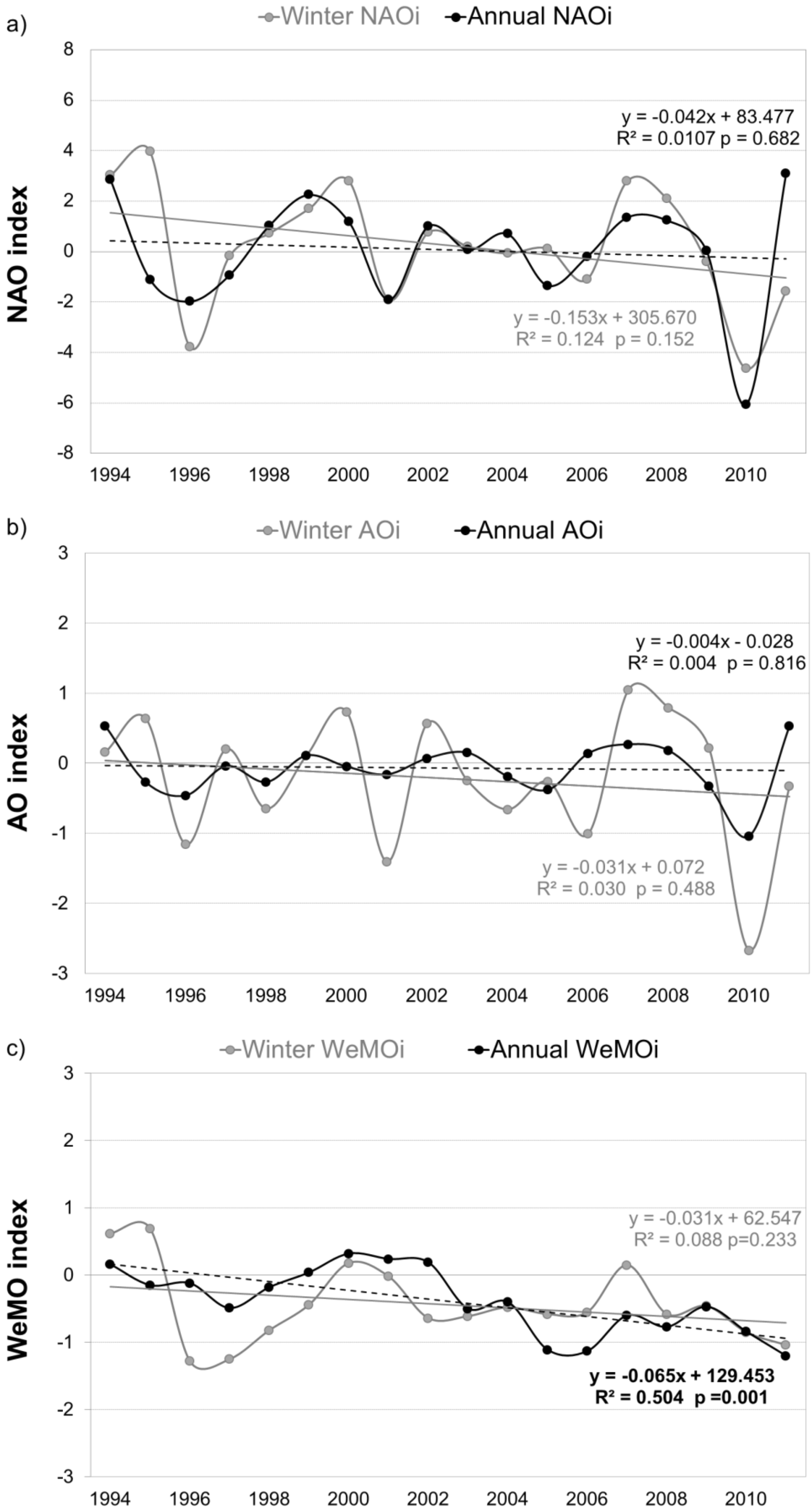


Figure 4.4: Winter and annual trends of **a)** North Atlantic Oscillation (NAO), **b)** Arctic Oscillation (AO) and **c)** Western Mediterranean Oscillation (WeMO) indices for 1994-2011 period.

4.3.2. APIn and Climatic Indices.

Results of Spearman correlations between APIn and the three climatic indices, which are detailed thereafter, correspond to significant correlations in at least one of the monitoring stations (Table 4.2). *Artemisia,* Cupressaceae, *Fraxinus, Olea, Pinus*, *Plantago*, total *Quercus*, *Q.* deciduous type, *Q.* evergreen type, *Ulmus* and total pollen were inversely correlated with the climatic indices, while *Castanea*, *Chenop./Amar*., *Corylus* and *Pistacia* were positively correlated. *Platanus*, Poaceae and Urticaceae showed both negative and positive correlations. *Corylus* with 8 positive correlations was the pollen taxon with the highest number of correlations, as well as the most sensitive taxon to the annual NAOi variability, although the 71% of the significant correlations between APIn and climatic indices were negative.

All the taxa presented significant correlations at least with one of the indices in at least one of the stations, except *Alnus*, *Ambrosia*, *Betula*, *Fagus* and Polygonaceae that did not present any. Bellaterra was the station with more correlations (19), followed by Barcelona (13), Lleida (10) and Manresa (8), while Tarragona and Girona were the stations with fewer correlations (4).

Regarding the influence of summer NAO index (SNAOi) on APIn, negative correlations were observed for: *Ambrosia, Chenop./Amar*., *Fraxinus, Olea, Pinus, Platanus*, total *Quercus*, *Q.* evergreen type, *Ulmus* and Urticaceae (Table 4.3). SNAOi was only positively correlated with APIn of *Ambrosia* in Girona, and no correlations were found for the rest of pollen taxa.

In general, annual pollen integral (APIn) recorded at the six sampling stations correlated better with WeMOi (a total of 34 significant correlations) than with NAOi (17) and AOi (7) (Table 4.4).

4.3.3. Start, End and Length of the MPS and Climatic Indices.

The influence of the NAO, WeMO and AO indices in the dates in which the pollination occurs was evaluated. The greatest number of significant correlations was obtained for WeMOi (76), followed by NAOi (43) and AOi (36) (Table 4.4).

The pollen season parameter with the highest number of correlations was Start (62) followed by Length (49) and End (44) (Table 4.5).

Different behaviour between stations was found, showing more significant correlations in Bellaterra (a total of 42 significant correlations), followed by Lleida (32) and Barcelona (24), and being Girona the one which showed the slightest influence (16) (Tables 4.6, 4.7, 4.8).

Spearman correlations between the **Start** of the MPS and the climatic indices were mainly negative, which accounted for 87% of total correlations (Table 4.6). Negative correlations were obtained for *Alnus, Ambrosia, Artemisia,* Cupressaceae, *Olea, Pinus, Pistacia, Plantago, Platanus,* total *Quercus*, *Q.* deciduous type, *Q.* evergreen type, *Ulmus* and Urticaceae. *Platanus* was the taxon with more significant correlations (11), followed by Cupressaceae (7), *Pistacia* and Urticaceae (6). However *Platanus* was more sensitive to winter AOi variability, while Cupressaceae and *Pistacia* were to winter NAOi and annual WeMOi, respectively. Positive significant correlations were obtained between *Betula*, *Castanea* and *Fagus vs.* winter NAOi, and *Castanea* and *Fagus vs.* annual WeMOi. *Corylus* and Polygonaceae showed both negative and positive correlations. Meanwhile there were no significant correlations with *Chenop./Amar*., *Fraxinus* and Poaceae.

Fewer significant correlations were obtained with the **End** of the MPS (Table 4.7). The number of positive and negative correlations was balanced, however negative accounted for 55% of total correlations. Spearman correlations were negative for *Alnus, Artemisia, Betula, Corylus, Pistacia, Platanus, Ulmus* and *Urticaceae*, and positive for *Ambrosia, Castanea, Olea, Pinus,* Polygonaceae, total *Quercus*, *Q.* deciduous type and *Q.* evergreen type. Some taxa showed positive and negative significant correlations depending on the station (*Chenop./Amar*., *Fagus*, *Plantago* and *Poaceae*). *Olea* was the taxon with more significant correlations (4), being the half of them with winter WeMOi. No significant correlations were found for Cupressaceae and *Fraxinus.*

Spearman correlations between **Length** of the MPS and the climatic indices (Table 4.8) were mostly positive, which represented 71% of total correlations. Correlations were positive for *Artemisia,* Cupressaceae, *Olea, Pinus, Pistacia,* Poaceae, Polygonaceae, total *Quercus*, *Q.* deciduous type and *Q.* evergreen type and Urticaceae. Negative significant correlations were obtained for *Alnus, Betula, Corylus, Fraxinus, Plantago* and *Ulmus*. In the case of *Fagus* and *Platanus*, positive and negative correlations were obtained, depending on the station. The taxon that exhibit major influence in the Length of the MPS was *Olea* (7). *Ambrosia*, *Castanea* and *Chenop./Amar*.did not show significant correlations.

4.3.4. Influence of the Climatic Indices in the Pollen Dynamics.

Summarizing, the influence of atmospheric teleconnection patterns on pollen dynamics in Catalonia showed:

(1) A clear predominance of negative correlations between APIn and Start with the climatic indices for most pollen taxa, with the exception of positive correlations between APIn of *Corylus vs.* annual NAO and AO indices, and Start of *Castanea* and *Fraxinus vs.* annual WeMOi and winter AOi, respectively. These results suggested an increase of pollen levels

and a delay of the MPS for most pollen taxa during the negative phases of climatic indices in Catalonia.

(2) An enlargement of the MPS due to a delay in the End of the MPS of *Fagus* and *Ulmus* has been also expected during the negative phase of NAO and AO.

(3) A delay in the End of the MPS of *Chenop./Amar*. during the negative phase of NAO and AO has been observed, but in this case the Length of the MPS didn't show variations.

(4) Conversely, results pointed out an enlargement of the MPS of *Artemisia*, Cupressaceae, *Pinus* and *Quercus* deciduous type during the positive phase of NAO and WeMO.

(5) Finally, the lack of correlation between pollen season parameters of *Alnus, Ambrosia* and Urticaceae *vs.* climatic indices suggested that their pollen dynamics in Catalonia were not affected by these teleconnection patterns.

4.4. Discussion

The individual rhythms of plant pollination and phenological phenomena are modified by the effects of atmospheric conditions (Bringfelt 1982, Emberlin et al. 1993). Changes in phenology (seasonal activity driven by environmental factors) from year to year may be a sensitive and easily observable indicator of changes in the biosphere (Menzel & Fabian, 1999, Jochner & Menzel 2015). Climate variability associated with teleconnection patterns may affect the ecological processes as the breeding phenology of the plants. Over the Iberian Peninsula there is strong evidence that positive (negative) values of winter NAO induce low (high) vegetation activity in the following spring and summer. This feature was mainly associated with the impact of NAO on winter precipitation, together with the strong dependence of spring and summer Normalised Difference Vegetation Index (NDVI) on water availability during the previous winter (Gouveia et al. 2008). Most of the studies of the Northern Hemisphere teleconnection patterns focus on the winter months, when the atmosphere is most active dynamically and perturbations grow to their largest amplitudes (Hurrell & Deser 2010). In the Mediterranean region, during winter, a strong correlation exists between the regional precipitation patterns and upper-air large-scale circulation anomalies (Quadrelli et al. 2001, Goodess & Jones 2002). However, during high SNAO summers, when strong anticyclonic conditions and suppressed precipitations prevail over the UK, the Mediterranean regions are anomalously wet (Bladé et al. 2012).

In this context, the primary aim of this study was to investigate the possible effect of the NAO, WeMO and AO on the pollen production and timing of the MPS of wind-pollinated plants in Catalonia (NW Mediterranean area). First, correlations between the three climatic indices for the 1994-2011 period were performed. As expected (Thompson & Wallace 2000, Wallace 2000), high positive correlations between NAOi and AOi for both annual and winter data were observed. The positive correlation obtained between the winter NAOi and WeMOi is consistent with the 50-year period 1950-2000 analyzed by Martín-Vide & López-Bustins (2006), in which winter WeMOi and NAOi correlated positively, although non-significantly (Pearson +0.122, p-value 0.399). In contrast, non-significant correlation was found between WeMOi and AOi, whereas Martín-Vide & López-Bustins (2006) found a negative correlation for the 50-year period (Pearson -0.386, p-value 0.005).

Annual airborne pollen levels correlated better with WeMOi than with NAOi and AOi. Negative correlations between APIn and climatic indices accounted for 71%, which indicated the positive effect of precipitation on the annual pollen production for most of the taxa during the negative phase of indices. According with this study, an increase of pollen production of *Artemisia,* Cupressaceae, *Fraxinus, Olea, Pinus*, *Plantago*, total *Quercus*, *Q.* deciduous type, *Q.* evergreen type, *Ulmus* and total pollen linked to an increase of winter rainfall is expected in Catalonia during the negative phase of winter climatic indices. Annual indices were also negatively correlated with these pollen taxa, excepting *Artemisia* and *Pinus*. The *Quercus* pollen behavior in NE Iberian Peninsula was according with patterns observed in Denmark, where February precipitation showed a positive influence on *Quercus* and *Corylus* pollen accumulation, but the effect was negative for *Betula* and *Tilia* (Nielsen et al. 2010). However, biological responses to climate changes could vary depending on the location of the plant, therefore different responses could be observed for the same species in different areas. This could explain the differences between *Corylus* and *Betula* pollen dynamics in Catalonia and Denmark. On the other hand, it is necessary to take into account that the precipitation regime of the previous year may also influence the success of flowers development and pollen production in the flowering year of some trees, e.g. *Betula* (Stach et al. 2008b, Nielsen et al. 2010). This could explain the lack of correlation between the APIn of *Alnus, Betula* and *Fagus* and the climatic indices of the same year. In addition, pollen transported from distant regions could mask the correlations between APIn and climatic indices, since long range transport pollen episodes of *Ambrosia* (Belmonte et al. 2000, Fernández-Llamazares et al. 2012), *Corylus* (Belmonte et al. 2008a) and *Fagus* (Belmonte et al. 2008a, 2008b) have been documented in Catalonia.

Precipitation during the flowering season can have a direct negative effect on pollen release and dispersion; daily pollen concentrations in the atmosphere show a clear negative relationship to precipitation (Sommer & Rasmussen 2008). Precipitation washes out pollen from the atmosphere, so that both its intensity and annual distribution can be related to the duration and intensity of the pollen season (Jato et al. 2002b). *Corylus* pollinates in winter, consequently positive correlations between APIn of *Corylus* and the three climatic indices have been interpreted as a washing-out effect. Negative correlations between SNAOi and APIn of *Ambrosia, Chenop./Amar*., *Fraxinus, Olea, Pinus, Platanus*, total *Quercus*, *Q.* evergreentype, *Ulmus* and Urticaceae have been also related with this process. Nevertheless, the increase of APIn of *Castanea* and *Chenop./Amar*., with pollen seasons in summer and spring-summer respectively, may be associated with greater insolation during the positive phase of WeMO. Conversely, the relationship between APIn of *Platanus*, Poaceae and Urticaceae and climatic indices were not clear, with both positive and negative correlations observed. Despite Poaceae APIn was negatively correlated with winter NAO in Córdoba (southern Spain) (Smith et al. 2009), in Catalonia this was only negatively correlated with annual AOi and positively with annual WeMOi.

Positive correlations between the Length of the MPS and climatic indices obtained for *Artemisia,* Cupressaceae, *Olea, Pinus, Pistacia,* Poaceae, Polygonaceae, total *Quercus*, *Q.* deciduous type and *Q.* evergreen type and Urticaceae observed in Catalonia (71%) are linked to an enlargement of the MPS for these taxa in years with positive phase of the climatic indices, that is, in drier and with higher insolation years. However, the relationship between the End of the MPS season and climatic indices did not show a clear pattern for most pollen taxa. The number of positive (45%) and negative (55%) correlations were balanced, and the sign of correlation varied depending on the pollen taxa. In addition, End was the pollen season parameter less correlated with teleconnection patterns, despite the fact that 44 correlations were obtained and 15 of them were with annual WeMOi. End date of Cupressaceae and *Fraxinus* were not correlated with climatic indices. In contrast, negative correlations between End date of Cupressaceae and NAO in March and February-March periods in central Italy were found, which could mostly be ascribed to the relationship between winter NAO and winter air temperature (Dalla Marta et al. 2011).

Results suggest that the most influence of the Northern Hemisphere teleconnection patterns occurs in the spring flowering taxa (i.e. *Olea, Pinus, Plantago, Quercus*) but the cases in summer (*Artemisia*) and winter (i.e. *Cupressaceae, Fraxinus, Ulmus*) are not negligible.

NAO and AO were in a positive trend for much of the 1970s and 1980s with historic peaks in the early 1990s, and it has been suggested that they contributed significantly to the global warming signal (Hurrell 1995, Cohen & Barlow 2005). Despite NAO and AO trends along the period 1984-2011 were slightly negative (Fig. 2), our results showed that when positive phases of these indices occurred a decrease of APIn and an advance and enlargement of the MPS were observed. These observations agree with previous studies that showed an increase in the length of the active growing season of terrestrial plants in the northern part of the Northern Hemisphere (Myneni et al. 1997), and particularly in Europe (Menzel & Fabian 1999), as a result of warming during winter-spring in the last decades, possibly related with positive NAO index values. Besides, there is an evident signal of advancing leaf unfolding, flowering and fruiting in wild plants all across Europe in almost 80% of the records (Menzel et al. 2006). It is quite obvious that changes in the pollination may affect the prevalence and severity of allergic diseases, but what are the ecological effects? Changes in severity and timing of the MPS could have direct effects e.g. on timing and quantity of fruit production, but it could also alter indirectly other ecological processes. Responses by individual species to climate change are connected through interactions with other species at the same or adjacent trophic level (Walther 2010). For instance, some evidences indicate that warmer spring weather in Europe has disrupted the synchrony between caterpillars *Operophtera brumata* and oak budburst (Visser & Holleman 2001), leading to a mismatch between the peak in insect availability and the peak demands of insectivorous birds nestlings (Visser et al. 2006). Therefore, the timing of change in different taxonomic groups is not always synchronous and may have huge ecological consequences, despite that some communities are already undergoing re-assembly (Both et al. 2005).

WeMO showed a negative phase throughout the nineteenth century and a positive one in the twentieth century up to late 1960. Besides, opposite phases of similar periodicities during the second half of the twentieth century between AO and WeMO have been observed, which seem to show an increase of modulation of the Mediterranean pattern by the Arctic one in the last decades (Martín-Vide & López-Bustins 2006). Negative correlation between annual WeMO and AO indices was also observed during the period 1994-2011, however it was non-significant, and a decreasing trend was detected for WeMO during our study period, being significant for the annual timeframe. Considering that WeMOi was the climatic index better correlated with pollen parameters, more research is needed to confirm the sense of the trend of WeMOi in the future, as it could be used as an indicator to predict the pollen production, timing and length of the MPS in the Western Mediterranean Basin.

4.5. Conclusions

Results showed that pollen production and timing (start and length) of the MPS can be partly explained as an effect of Northern Hemisphere teleconnection patterns, suggesting the possibility of predicting the onset and severity of pollination through their atmospheric modes. Generally an increase of pollen production for most of pollen taxa studied linked to an increase of rainfall was detected in Catalonia during the negative phase of climatic indices. Besides, a tendency to advance and extend the MPS in years in which the indices have high positive values, which are characterized by less rainfall and higher insolation and temperature in Western Mediterranean Basin, was also observed. However, the relationship between the End of the MPS and climatic indices didn’t show a clear pattern for mostly of pollen taxa. Finally, negative correlations between SNAOi and APIn of *Ambrosia, Chenop./Amar*., *Fraxinus, Olea, Pinus, Platanus*, total *Quercus*, *Q.* evergreen type, *Ulmus* and Urticaceae has been interpreted as a washing-out effect.

This information about the timing and magnitude of the MPS are valuable data for the prevention and treatment of allergic diseases. According with the persistent duration of NAO and AO in its positive phase since 1970, although showing a slightly declining trend over the last two decades, a decrease of APIn accompanied by an advance and enlargement of the MPS is expected in the Western Mediterranean Basin. Furthermore, WeMO variability plays a key role in production and timing of the MPS in the Iberian Peninsula. The sense of the trend of WeMOi needs to be confirmed to identify what are its effects on ecosystems and public health. Intensifying efforts to understand the dependencies and strengths of the linkages between the different Northern Hemisphere teleconnection patterns and the ecological processes taking into account the complexity of ecosystems would also be advisable.

Table 4.2: Significant correlations between APIn *vs.* winter (from December to March) and annual climatic indices at the 6 sampling stations. Only species that have significant correlations (p<0.05) are listed.
w: winter (DJFM) / a: annual N: negative correlation / P: positive correlation *p<0.05 / **p<0.01

APIn	BCN						BTU						GIC						LLE						MAN						TAU								
	NAO		WeMO		AO		NAO		WeMO		AO		NAO		WeMO		AO		NAO		WeMO		AO		NAO		WeMO		AO		NAO		WeMO		AO				
	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	N	P	Total
Artemisia			N*						N*																		N*										3		**3**
Castanea										P*																												1	**1**
Chenop./Amar.				P*			P*																															2	**2**
Corylus								P*	P*		P*							P*		P*			P*			P*						P*						8	**8**
Cupressaceae			N*																			N**															2		**2**
Fraxinus																							N*	N*				N*						N**			4		**4**
Olea	N*						N*												N*	N**								N**									5		**5**
Pinus	N*		N**																																		2		**2**
Pistacia							P*																															1	**1**
Plantago			N**																									N*									2		**2**
Platanus				P**				P*		N*						N**		P*			N*							N**									4	3	**7**
Poaceae										P*														N*													1	1	**2**
Quercus	N*		N*				N*		N*																												4		**4**
Q. deciduous t.	N*						N*																				N*				N*		N*				5		**5**
Q. evergreen t.			N*						N*	N*																											3		**3**
Ulmus										N*																		N**									2		**2**
Urticaceae				P*												N**																					1	1	**2**
Total Pollen									N*	N*												N*															3		**3**
N	4		6				3		4	4						2			1	1	1	2	1	2			2	5			1		1	1			**71%**		41
P				3			2	2	1	2	1							2		1			1			1						1						**29%**	17
Total	4	0	6	3	0	0	5	2	5	6	1	0	0	0	0	2	0	2	1	2	1	2	2	2	0	1	2	5	0	0	1	1	1	1	0	0	41	17	58
	13						**19**						**4**						**10**						**8**						**4**								

Table 4.3. Significant Spearman correlations between APIn *vs.* SNAOi at the 6 sampling stations and mean of Catalonia. Only species that have significant correlations (p<0.05) are listed.
*p<0.05 / **p<0.01

	BCN	BTU	GIC	LLE	MAN	TAU	Catalonia
Ambrosia	-0.47*		0.70**				
Chenop./Amar.				-0.67**			-0.51*
Fraxinus						-0.59*	
Olea							-0.50*
Pinus						-0.55*	-0.47*
Platanus		-0.65**	-0.53*		-0.64**		
Quercus		-0.60**					
Q. evergreen t.		-0.59**				-0.55*	-0.49*
Ulmus		-0.48*			-0.59*		
Urticaceae	-0.47*						

Table 4.4: Number of significant Spearman correlations (**p<0.05**) between pollen parameters (APIn, Start, End and Length) *vs.* winter (w) and annual (a) climatic indices at the 6 sampling stations.
(N: negative correlation, P: positive correlation)

Climatic index	Pollen parameters	w/a	N	P	Total			
NAOi	APIn	w	9	2	11	17		**60**
		a	1	5	6			
	Start	w	7	3	10	21	43	
		a	11	0	11			
	End	w	1	2	3	10		
		a	7	0	7			
	Length	w	2	4	6	12		
		a	3	3	6			
WeMOi	APIn	w	14	1	15	34		**110**
		a	14	5	19			
	Start	w	3	0	3	23	76	
		a	16	4	20			
	End	w	2	5	7	23		
		a	4	12	16			
	Length	w	3	7	10	30		
		a	2	18	20			
AOi	APIn	w	1	2	3	7		**43**
		a	2	2	4			
	Start	w	9	1	10	18	36	
		a	8	0	8			
	End	w	5	0	5	11		
		a	5	1	6			
	Length	w	1	1	2	7		
		a	3	2	5			

Table 4.5: Number of significant Spearman correlations ($p<0.05$) between Start, End and Length *vs.* winter (from December to March) and annual climatic indices at the 6 sampling stations.
N: negative correlation / P: positive correlation

	Start			End			Length		
	N	P	Total	N	P	Total	N	P	Total
Alnus	1		1	3		3	2		2
Ambrosia	1		1		1	1			0
Artemisia	5		5	1		1		2	2
Betula		1	1	1		1	2		2
Castanea		3	3		1	1			0
Chenop./Amar.			0	3	2	5			0
Corylus	2	1	3	1		1	1		1
Cupressaceae	7		7			0		1	1
Fagus		2	2	2	1	3	4	1	5
Fraxinus			0			0	1		1
Olea	2		2		4	4		7	7
Pinus	5		5		1	1		5	5
Pistacia	6		6	2		2		1	1
Plantago	1		1	2	1	3	2		2
Platanus	11		11	2		2	1	5	6
Poaceae			0	2	1	3		1	1
Polygonaceae	2	1	3		2	2		2	2
Quercus	1		1		3	3		2	2
Q. deciduous t.	1		1		1	1		2	2
Q. evergreen t.	1		1		2	2		4	4
Ulmus	2		2	3		3	1		1
Urticaceae	6		6	2		2		2	2
Total	**54**	**8**	**62**	**24**	**20**	**44**	**14**	**35**	**49**
%	87%	13%	100%	55%	45%	100%	29%	71%	100%

Table 4.6: Significant correlations between the **START** of the MPS *vs.* winter (from December to March) and annual climatic indices at the 6 sampling stations. Only species that have significant correlations ($p<0.05$) are listed.
w: winter (DJFM) / a: annual N: negative correlation / P: positive correlation *p<0.05 / **p<0.01

START	**BCN**						**BTU**						**GIC**						**LLE**						**MAN**						**TAU**								
	NAO		**WeMO**		**AO**		**NAO**		**WeMO**		**AO**		**NAO**		**WeMO**		**AO**		**NAO**		**WeMO**		**AO**		**NAO**		**WeMO**		**AO**		**NAO**		**WeMO**		**AO**				
	w	**a**	**w**	**a**	**w**	**a**	**w**	**a**	**w**	**a**	**w**	**a**	**w**	**a**	**w**	**a**	**w**	**a**	**w**	**a**	**w**	**a**	**w**	**a**	**w**	**a**	**w**	**a**	**w**	**a**	**w**	**a**	**w**	**a**	**w**	**a**	**N**	**P**	Total
Alnus																						N*															1		**1**
Ambrosia																				N*																	1		**1**
Artemisia														N*			N*									N*						N**			N*		5		**5**
Betula																															P*							1	**1**
Castanea													P*															P*						P*				3	**3**
Corylus														N*				N*										P*									2	1	**3**
Cupressaceae		N*						N**						N*				N*													N**	N*			N*		7		**7**
Fagus																P*									P*													2	**2**
Olea																								N*												N*	2		**2**
Pinus				N*			N*			N*												N**						N*									5		**5**
Pistacia				N*						N*									N*				N**					N*						N*			6		**6**
Plantago						N**																															1		**1**
Platanus	N*			N*	N*		N*			N*	N*						N**		N*				N**					N**							N*		11		**11**
Polygonaceae	N*		N*																										P*								2	1	**3**
Quercus																		N*																			1		**1**
Q. deciduous t.				N*																																	1		**1**
Q. evergreen t.										N*																											1		**1**
Ulmus																						N**										N*					2		**2**
Urticaceae		N*				N**			N*									N*				N**											N*				6		**6**
N	2	2	1	4	1	2	2	1	1	4	1			3			2	4	2	1		4	2	1		1		3			1	3	1	1	3	1	**87%**		54
P													1			1									1			2	1		1			1				**13%**	8
Total	2	2	1	4	1	2	2	1	1	4	1		1	3		1	2	4	2	1		4	2	1	1	1		5	1		2	3	1	2	3	1	54	8	**62**
	12						**9**						**11**						**10**						**8**						**12**								

Table 4.7: Significant correlations between the **END** of the MPS *vs.* winter (from December to March) and annual climatic indices at the 6 sampling stations. Only species that have significant correlations (p<0.05) are listed.
w: winter (DJFM) / a: annual N: negative correlation / P: positive correlation *p<0.05 / **p<0.01

END	BCN						BTU						GIC						LLE						MAN						TAU								
	NAO		WeMO		AO		NAO		WeMO		AO		NAO		WeMO		AO		NAO		WeMO		AO		NAO		WeMO		AO		NAO		WeMO		AO				
	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	N	P	Total
Alnus				N*						N*														N*													3		**3**
Ambrosia																		P*																				1	**1**
Artemisia																																			N*		1		**1**
Betula											N*																										1		**1**
Castanea																					P*																	1	**1**
Chenop./Amar.						N*				P*						P*										N*									N*		3	2	**5**
Corylus																						N*															1		**1**
Fagus						N*			P**								N**																				2	1	**3**
Olea							P**		P*	P**																		P**										4	**4**
Pinus																						P**																1	**1**
Pistacia												N*																		N*							2		**2**
Plantago																	N*											P*					N*				2	1	**3**
Platanus								N*																								N**					2		**2**
Poaceae								N*																				P*							N*		2	1	**3**
Polygonaceae										P*												P**																2	**2**
Quercus							P**		P*													P*																3	**3**
Q. deciduous t.																						P**																1	**1**
Q. evergreen t.									P*													P**																2	**2**
Ulmus								N*	N*																	N*											3		**3**
Urticaceae														N*					N*																		2		**2**
N				1		2		3	1	1	1	1		1			2		1			1		1		2				1		1	1		3		**55%**		24
P							2		4	3						1		1			1	5						3										**45%**	20
Total	0	0	0	1	0	2	2	3	5	4	1	1	0	1	0	1	2	1	1	0	1	6	0	1	0	2	0	3	0	1	0	1	1	0	3	0	24	20	**44**
	3						**16**						**5**						**9**						**6**						**5**								

Table 4.8: Significant correlations between the **LENGTH** of the MPS *vs.* winter (from December to March) and annual climatic indices at the 6 sampling stations. Only species that have significant correlations (p<0.05) are listed.
w: winter (DJFM) / a: annual N: negative correlation / P: positive correlation *p<0.05 / **p<0.01

LENGTH	BCN						BTU						GIC						LLE						MAN						TAU								
	NAO		WeMO		AO		NAO		WeMO		AO		NAO		WeMO		AO		NAO		WeMO		AO		NAO		WeMO		AO		NAO		WeMO		AO				
	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	w	a	N	P	Total
Alnus				N*																				N*													2		**2**
Artemisia																										P*						P**						2	**2**
Betula							N*		N*																												2		**2**
Corylus																						N*															1		**1**
Cupressaceae																						P*																1	**1**
Fagus	N*	N*				N*																							N**				P*				4	1	**5**
Fraxinus																					N*																1		**1**
Olea				P*			P**		P*	P**										P*				P*				P**										7	**7**
Pinus				P*			P*			P**												P**						P**										5	**5**
Pistacia																					P*																	1	**1**
Plantago								N*																									N*				2		**2**
Platanus							P*		P**	P**	P*																	P*				N*					1	5	**6**
Poaceae																												P**										1	**1**
Polygonaceae										P*												P*																2	**2**
Quercus										P*												P*																2	**2**
Q. deciduous t.			P*																			P*																2	**2**
Q. evergreen t.							P**		P*	P*												P*																4	**4**
Ulmus																								N**													1		**1**
Urticaceae			P*			P**																																2	**2**
N	1	1		1		1	1	1	1												1	1		2					1			1	1				**29%**		14
P			2	2		1	4		3	6	1									1	1	6		1		1		4				1	1					**71%**	35
Total	1	1	2	3	0	2	5	1	4	6	1	0	0	0	0	0	0	0	0	1	2	7	0	3	0	1	0	4	1	0	0	2	2	0	0	0	14	35	**49**
	9						**17**						**0**						**13**						**6**						**4**								

5. FORECASTING THE START OF THE MAIN POLLEN SEASON

5.1. Introduction

5.2. Forecasting Methods

5.2.1. Summing Temperatures

5.2.2. Multiple Regression Analysis

5.2.3. Model Evaluation

5.3. Pollen data and Main Pollen Season

5.4. Results

5.4.1. Summing Temperatures

5.4.2. Correlations and Multiple Regressions

5.5. Discussion

5.5.1. The method of Summing Temperatures

5.5.2. The method of Multiple Regression

5.5.3. The RMSE and the comparison between the two methods

5.6. Conclusions

5.1. Introduction

Pollen monitoring and forecasting is well developed in many European countries. Pollen concentrations are greatly influenced by meteorological conditions before flowering occurs. Sunshine and temperature conditions, also called primary factors, influence the growth and development of vegetal species, and control the pollen production. At the time of blossoming, secondary meteorological factors (sunshine, rainfall, relative humidity) determined the opening of anthers and the release of pollen grains. Finally, tertiary factors (mostly wind) cause the grains to be scattered in the atmosphere (Laaidi et al., 1997).

Various methods have been developed for defining the variables which influence on the Start of the main Pollen Season (SPS) and it has been found that usually it depends on the weather and especially temperature and rainfall in a certain period before the season (Frenguelli et al., 1989; Spieksma et al., 1989b). Several studies based on different methods for forecasting the SPS have been published around the world. Emberlin et al. (1999) explained that mean temperatures and precipitation are the main controlling factors for the start of the grass pollen season. Recent works in Spain evaluated the presence of pollen types and their proportions in the atmosphere of relevant urban areas for different regions in Salamanca (Rodríguez-de la Cruz et al., 2010). Alcazar et al. (2011) analysed pollen season trends from 1992 to 2010 in Andalusia and constructed models to forecast the start of the season. Carsia-Mozo et al. (2014) used a statistical approach to analyse olive long-term pollen season trends in Southern Spain. Their results indicated that long-term pollen concentrations make it possible not only to chart pollen season trends, but also to track changing patterns in flowering phenology. Jato et al. (2015) charted airborne *Quercus* pollen concentrations over 20 years in the region of Galicia (NW Spain) to detect possible influences of climate change on pollen season. Ocana-Peinado et al. (2016) used regression models to forecast Cupressaceae pollen concentration in the city of Granada (SE of Spain) based on climatic variables.

Temperature has been widely accepted as the most important factor affecting processes that lead to the flowering of *Olea* (Orlandi et al., 2005). Numerous authors have reported on the significant relationship between the SPS of *Olea* and the temperature recorded during months prior to the flowering period, such as Perez-Lopez et al., 2008; Tommaso et al., 2008; Galan, et al., 2001; Fornaciari et al., 1998; Alba &Guardia, 1998 and Gonzalez Minero & Candau 1996. In all these studies, temperature during February was the best variable to predict the SPS of *Olea*.

5.2. Forecasting Methods

Aeropalynology is a useful tool to predict the Start of the main Pollen Season (SPS) of plants producing allergenic pollen (Spieksma & Nikels, 1998; Frenguelli et al., 1992). One of the most important aspects of aerobiological studies is to explore forecasting models that helps us to institute the date of the SPS. The forecast of the SPS has a particular importance because this information is very useful for accurate use of medicine for allergies and for the planning of the patient's activities. Several studies (Frenguelli et al., 1989, Emberlin et al., 1997, 2002; Alba & Díaz de la Guardia, 1998; Chuine, 2000; Fornaciari et al., 2000, 2005; Laaidi, 2001; Galán et al., 2001a, Galán et al., 2001b, 2005; Rodríguez-Rajo et al., 2003; Orlandi et al., 2004, 2005; Hoxha, 2007; Ribeiro et al., 2007; García-Mozo et al., 2008) have been published based on different methods for forecasting the SPS. Here we have applied and explored two different methods: the first method is based on the sum of mean temperatures and the second is based on a multiple regression analysis with maximum and minimum temperatures and precipitation.

5.2.1. Summing Temperatures

Temperature is the primary factor influencing the growth and development of plants and pollen production. The rate of phenological development of plant species increase linearly as a function of air temperature and they are assumed to be insignificant when the air temperature is below a threshold (Laaidi, 2001). Taking into account this behaviour, the method of summing temperatures consists of a cumulative sum of the daily mean temperature from an initial date, above a thermal threshold and until the observed SPS. Different initial dates were tested in order to determine the best one for starting the calculation. These dates ranged from 01–January to 31–May in steps of 10 days. Different thermal thresholds, ranged from 0ºC to 9ºC in steps of 1ºC, were tested. For each combination of initial date and thermal threshold, we calculated the sum of the daily mean temperature from the initial date and above the thermal threshold until the observed SPP. This sum was calculated for each year included in the forecasting method. Then, we calculated the mean (M) and the standard deviation (STD) of these sums of temperatures for all the years. The best initial date and the more appropriate threshold were those that minimized the ratio STD/M (coefficient of variation). This method was used in a previous work by Laaidi et al. (2003).

5.2.2. Multiple Regression Analysis

Regression analysis is a statistical process for estimating the relationships between variables, when the focus is on the relationship between a dependent variable and one or more independent variables (Pallant, 2001). Multiple regression analysis has been used to investigate the relationship between meteorological variables and the SPS (dependent variable). The selection of such meteorological variables was chosen after consulting other studies from different authors. In the forecasting of the SPS, the meteorological data included in the analysis were daily maximum temperature (T_{max}), daily minimum temperature (T_{min}) and daily rainfall (R). First, daily meteorological data from 01–January until the SPS was grouped in 10-day periods. Temperatures were averaged for each period while total amount of rainfall was quantified. These 10-day grouped meteorological data were used as independent variables in the multiple regression analysis. Forward stepwise regression has been chosen as selection method. This method starts with no variables in the model and tests the addition of each variable using a chosen model fit criterion, adding the variable (if any) whose inclusion gives the most statistically significant improvement of the fit, and repeating this process until none improves the model to a statistically significant extent.

5.2.3. Model Evaluation

In order to measure the quality of the models and also their predictability power, root mean squared error ($RMSE$) has been computed. The $RMSE$ is a frequently used measure of the differences between forecasted values predicted by a model (SPS_F) and the values actually observed (SPS_O).

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(SPS_F - SPS_O)^2}$$

Therefore, smaller errors imply that better is the model and the capability to predict future values. Following Appel et al. (2007), the model performance was evaluated using systematic and unsystematic root mean square errors, $RMSE_s$ (1) and $RMSE_u$ (2), in order to evaluate the intrinsic error in the model (systematic) and the random error (unsystematic).

The $RMSE_s$ and $RMSE_u$ are defined as:

$$RMSE_s = \sqrt{\tfrac{1}{N}\textstyle\sum_{i=1}^{N}(SPS - SPS_O)^2} \quad \textbf{(1)}$$

$$RMSE_u = \sqrt{\tfrac{1}{N}\textstyle\sum_{i=1}^{N}(SPS - SPS_F)^2} \quad \textbf{(2)}$$

$$SPS = a + b \cdot SPS_O \quad \textbf{(3)}$$

$$RMSE = \sqrt{(RMSE_u)^2 + (RMSE_s)^2} \quad \textbf{(4)}$$

Where SPS_F and SPS_O are forecasted and observed values, a and b are the least-squares regression coefficients derived from the linear regression between SPS_F and SPS_O, and N is the total number of forecasted/observed pairs.

The $RMSE_u$ and $RMSE_s$ help to identify the sources of the errors. The $RMSE_s$ represents the portion of the error that is attributable to systematic model errors and the $RMSE_u$ represents random errors in the model or model inputs that are less easily addressed. For a good model, the unsystematic portion of the error ($RMSE_u$) must be much larger than the systematic portion, whereas a high $RMSE_s$ value indicates a poor model.

5.3. Pollen data and Main Pollen Season

Airborne pollen data were recorded by the Aerobiological Network of Catalonia (XAC) at six stations located in Barcelona (BCN), Bellaterra (BTU), Girona (GIC), Lleida (LLE), Manresa (MAN) and Tarragona (TAU). Here we have focused on 6 of the 22 pollen taxa (*Olea, Pinus, Pistacia, Plantago, Platanus* and *Quercus* deciduous type) in order to forecast the Start of the main Pollen Season (SPS). We have chosen these pollen taxa because they have a well-defined pollination season.

In order to understand the different timing behaviour of the pollen taxa, Figure 5.1 shows the daily pollen concentrations for two different taxa, *Olea* and Urticaceae, in the station of Tarragona during 2012.

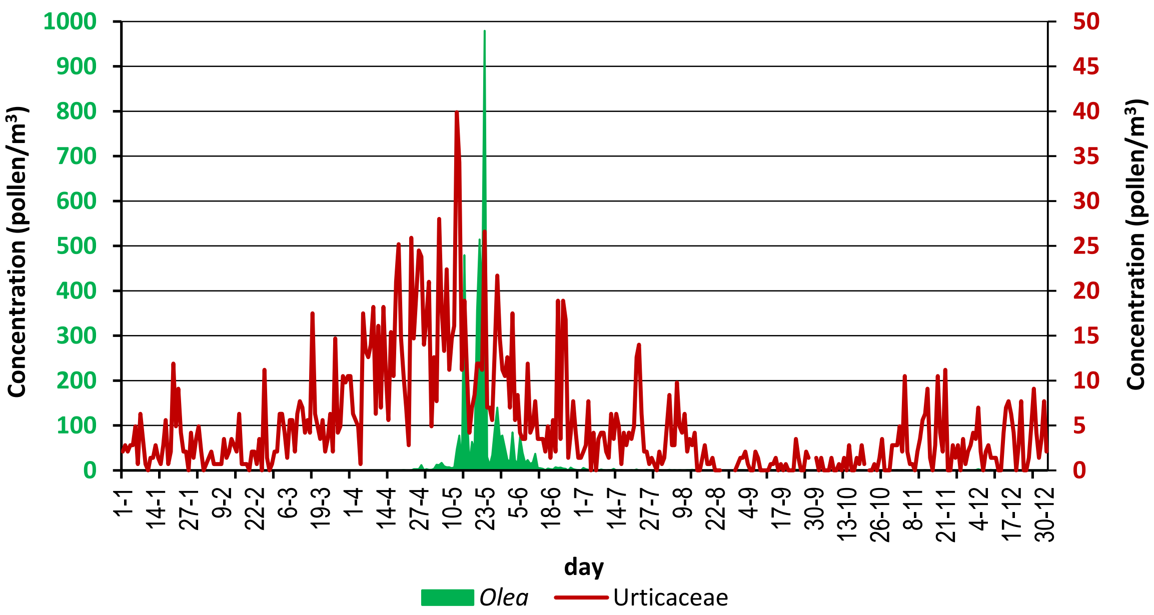


Figure 5.1 Daily pollen concentrations for two different taxa, *Olea* and Urticaceae, in the station of Tarragona during 2012.

In Table 5.1 we can see that Urticaceae pollinates almost throughout the year, but *Olea* have a main pollen season starting on the 10th of May and lasting only for 35 days. So, we will forecast the SPS for some taxa like *Olea*

Table 5.1: Main Pollen Season for *Olea* and Urticaceae in the station of Tarragona in 2012.

Pollen parameters	*Olea*	Urticaceae
APIn (pollen*day/m^3)	**4428**	**1824**
Start (2,5%)	131 (11-May)	19 (19-Jan)
End (97,5%)	166 (16-June)	352 (17-Dec)
Length (days)	35	333

Meteorological data were provided by the Servei Meteorològic de Catalunya (SMC). Daily values of precipitation, maximum and minimum temperature were recorded at the closest meteorological stations to airborne sampling sites (all of them are 5-15 km away). Forecasting methods were implemented for years 2001, 2005-2011 (8 years). Years 2002, 2003 and 2004 were excluded of the analysis because there were missing data for many days. Furthermore, many daily rainfall records in Lleida during the pollination season were missing; therefore, we have not considered this station in the multiple regression method.

The SPS for each year in each station are showed in Tables 5.2. The mean value and the standard deviation of the SPS for each taxon were calculated for all the stations during the years included in the study and the result is given in Table 5.3.

As it can be seen in Table 5.3, the spatial variability of the SPS for a given taxon ranges from 9 days for *Platanus* to 27 days for *Plantago*, while the temporal variability for a given taxon at a given location range from 7 days for *Plantago* in TAU to 20 days for *Pinus* in GIC.

Tables 5.2: Start of the Main Pollen Season.

(a) *Olea*

Station / Year	BCN		BTU		GIC		LLE		MAN		TAU	
	Day	Date	Day	Date	Day	Date	Day	Date	Day	Date	Day	Date
2001	105	14-4	104	13-4	105	14-4	114	23-4	109	18-4	107	16-4
2005	129	8-5	129	8-5	129	8-5	130	9-5	131	10-5	131	10-5
2006	124	3-5	128	7-5	129	8-5	129	8-5	129	8-5	128	7-5
2007	129	8-5	129	8-5	130	9-5	129	8-5	141	20-5	128	7-5
2008	115	24-4	123	2-5	117	26-4	124	3-5	134	13-5	125	4-5
2009	130	9-5	132	11-5	134	13-5	136	15-5	136	15-5	131	10-5
2010	131	10-5	143	22-5	144	23-5	144	23-5	147	26-5	144	23-5
2011	124	3-5	124	3-5	126	5-5	129	8-5	134	13-5	126	5-5

(b) *Pinus*

Station / Year	BCN		BTU		GIC		LLE		MAN		TAU	
	Day	Date	Day	Date	Day	Date	Day	Date	Day	Date	Day	Date
2001	45	14-2	55	24-2	39	8-2	69	9-3	64	4-3	45	14-2
2005	85	25-3	91	31-3	92	1-4	96	5-4	94	3-4	85	25-3
2006	79	19-3	83	23-3	82	22-3	94	3-4	87	27-3	74	14-3
2007	63	3-3	68	8-3	62	2-3	90	30-3	71	11-3	63	3-3
2008	59	28-2	69	9-3	61	1-3	86	26-3	74	14-3	60	29-2
2009	68	8-3	73	13-3	70	10-3	76	16-3	74	14-3	67	7-3
2010	83	23-3	87	27-3	89	29-3	95	4-4	95	4-4	85	25-3
2011	71	11-3	77	17-3	66	6-3	79	19-3	78	18-3	66	6-3

(c) *Pistacia*

Station / Year	BCN		BTU		GIC		LLE		MAN		TAU	
	Day	Date	Day	Date	Day	Date	Day	Date	Day	Date	Day	Date
2001	75	15-3	77	17-3	77	17-3	78	18-3	75	15-3	70	10-3
2005	102	11-4	105	14-4	106	15-4	111	20-4	109	18-4	103	12-4
2006	87	27-3	85	25-3	92	1-4	96	5-4	91	31-3	88	28-3
2007	76	16-3	76	16-3	76	16-3	73	13-3	83	23-3	76	16-3
2008	75	15-3	88	28-3	74	14-3	73	13-3	89	29-3	73	13-3
2009	83	23-3	94	3-4	88	28-3	86	26-3	95	4-4	85	25-3
2010	97	6-4	98	7-4	102	11-4	107	16-4	108	17-4	92	1-4
2011	85	25-3	90	30-3	91	31-3	91	31-3	93	2-4	85	25-3

(d) *Plantago*

Station / Year	BCN		BTU		GIC		LLE		MAN		TAU	
	Day	Date	Day	Date	Day	Date	Day	Date	Day	Date	Day	Date
2001	82	22-3	89	29-3	94	3-4	92	1-4	97	6-4	81	21-3
2005	101	10-4	107	16-4	113	22-4	120	29-4	112	21-4	98	7-4
2006	91	31-3	97	6-4	98	7-4	102	11-4	111	20-4	94	3-4
2007	91	31-3	110	19-4	113	22-4	115	24-4	115	24-4	92	1-4
2008	93	2-4	109	18-4	115	24-4	119	28-4	123	2-5	85	25-3
2009	104	13-4	108	17-4	112	21-4	95	4-4	113	22-4	91	31-3
2010	108	17-4	114	23-4	116	25-4	115	24-4	136	15-5	100	9-4
2011	94	3-4	101	10-4	105	14-4	98	7-4	124	3-5	93	2-4

(e) *Platanus*												
Station / Year	BCN		BTU		GIC		LLE		MAN		TAU	
	Day	Date	Day	Date	Day	Date	Day	Date	Day	Date	Day	Date
2001	67	7-3	68	8-3	79	19-3	75	15-3	73	13-3	67	7-3
2005	89	29-3	91	31-3	95	4-4	93	2-4	95	4-4	88	28-3
2006	80	20-3	84	24-3	84	24-3	84	24-3	87	27-3	79	19-3
2007	69	9-3	70	10-3	72	12-3	74	14-3	79	19-3	67	7-3
2008	66	6-3	72	12-3	74	14-3	74	14-3	80	20-3	70	10-3
2009	73	13-3	75	15-3	73	13-3	78	18-3	81	21-3	74	14-3
2010	84	24-3	88	28-3	87	27-3	91	31-3	95	4-4	86	26-3
2011	79	19-3	79	19-3	77	17-3	84	24-3	87	27-3	75	15-3

(f) *Quercus* deciduous type												
Station / Year	BCN		BTU		GIC		LLE		MAN		TAU	
	Day	Date	Day	Date	Day	Date	Day	Date	Day	Date	Day	Date
2001	80	20-3	76	16-3	80	20-3	78	18-3	79	19-3	80	20-3
2005	105	14-4	104	13-4	112	21-4	103	12-4	104	13-4	102	11-4
2006	100	9-4	94	3-4	102	11-4	97	6-4	95	4-4	95	4-4
2007	97	6-4	88	28-3	103	12-4	106	15-4	97	6-4	103	12-4
2008	80	20-3	86	26-3	93	2-4	79	19-3	91	31-3	90	30-3
2009	93	2-4	92	1-4	97	6-4	95	4-4	95	4-4	88	28-3
2010	100	9-4	99	8-4	109	18-4	101	10-4	105	14-4	100	9-4
2011	95	4-4	90	30-3	99	8-4	96	5-4	96	5-4	96	5-4

Table 5.3: Mean value and standard deviation of the SPS of 6 pollen taxa during the years included in the study in the six sampling stations.

	Olea		*Pinus*		*Pistacia*		*Plantago*		*Platanus*		*Quercus* deciduous type	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
BCN	122 (1-5)	10	69 (9-3)	15	86 (26-3)	11	97 (6-4)	9	76 (16-3)	9	92 (1-4)	10
BTU	126 (5-5)	13	75 (15-3)	13	92 (1-4)	10	105 (14-4)	9	79 (19-3)	9	91 (31-3)	10
GIC	126 (5-5)	14	70 (10-3)	**20**	90 (30-3)	13	109 (18-4)	8	81 (21-3)	9	98 (7-4)	12
LLE	130 (9-5)	10	84 (24-3)	11	91 (31-3)	15	107 (16-4)	13	83 (23-3)	8	92 (1-4)	11
MAN	132 (11-5)	13	80 (20-3)	12	95 (4-4)	13	118 (27-4)	13	85 (25-3)	9	110 (19-4)	14
TAU	127 (6-5)	12	68 (8-3)	15	85 (25-3)	12	91 (31-3)	**7**	77 (17-3)	8	93 (2-4)	8

5.4. Results

5.4.1. Summing Temperatures

Different initial dates were tested in order to determine the best one for starting the calculation. These dates ranged from 01–January to 31–May in steps of 10 days. Different thermal thresholds, ranged from 0ºC to 9ºC in steps of 1ºC, were tested. For each combination of initial date and thermal threshold, we calculated the sum of the daily mean temperature from the initial date and above the thermal threshold until the observed SPP. This sum was calculated for each year included in the forecasting method. Then, we calculated the mean (M) and the standard deviation (STD) of these sums of temperatures for all the years. The best initial date and the more appropriate threshold were those that minimized the ratio STD/M (coefficient of variation). Years 2001, 2005 and 2009-2011 (6 years) have been included in the calculation of the parameters of the model while 2013 has been used as control year to test the method.

Tables 5.4 show the initial date, the thermal threshold and the sum of daily mean temperature obtained for each station. From the parameters shown in Tables 5.4, forecasted values (SPS_F) are calculated for each year. Figures 5.2 show the linear regression between forecasted (SPS_F) and observed (SPS_O) values for the years included in the model. For each regression the $RMSE$ value are also included in the figures. The method was tested for forecasting the SPS of each taxon in the year 2013 (not include in the model data) and the results are shown in Tables 5.5.

Table 5.4a: Parameters obtained to forecast the SPS of *Olea*.

Olea			
Station	Initial date for the sum	Thermal threshold (ºC)	Sum of daily mean temperature (ºC)
BCN	01-Feb	7	977
BTU	01-Feb	3	1076
GIC	01-Feb	6	1052
LLE	01-Feb	2	972
MAN	01-Feb	2	1124
TAU	01-Feb	3	1136

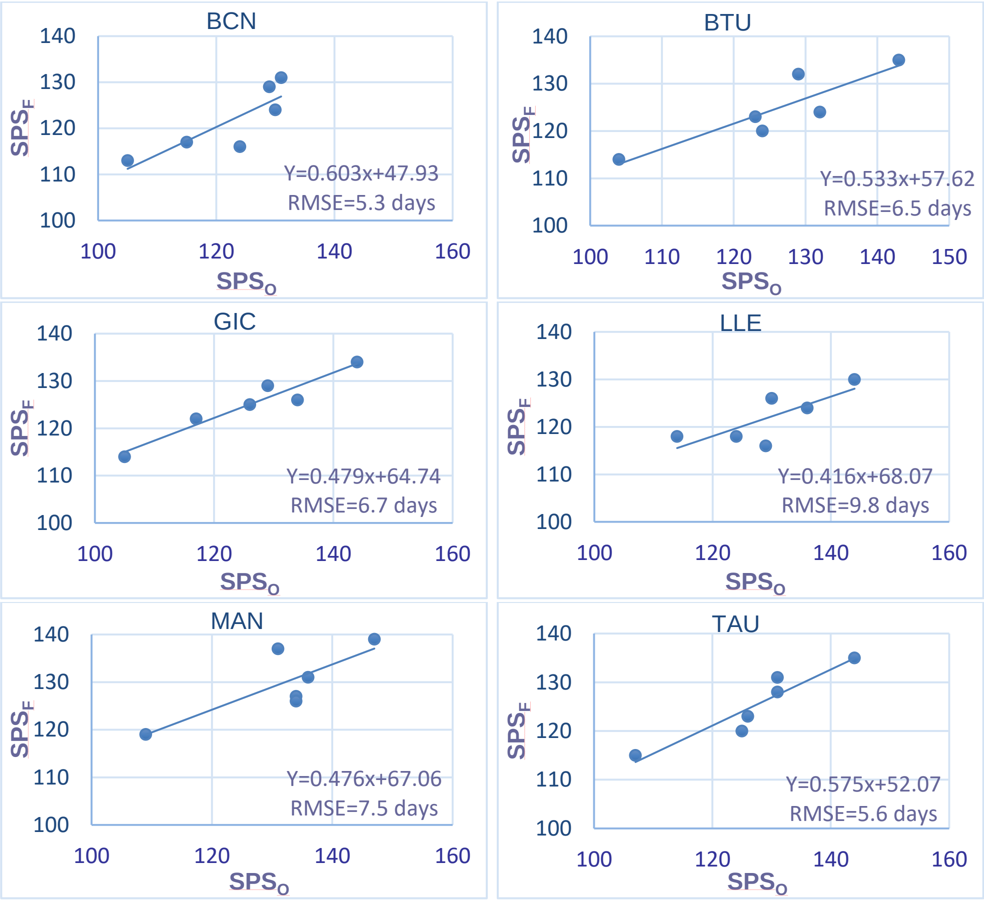


Figure 5.2a: Linear regression between forecast and observed SPS values of *Olea.*

Table 5.5a: Accuracy of the model predicting the SPS of *Olea* for the year 2013.

Olea			
Station	SPS_F (day)	SPS_O (day)	$SPS_F - SPS_O$ (days)
BCN	131	128	+5
BTU	128	128	0
GIC	136	133	+2
LLE	136	147	-11
MAN	135	137	-6
TAU	124	118	+13

Table 5.4b: Parameters obtained to forecast the SPS of *Pinus*.

Pinus			
Station	Initial date for the sum	Thermal threshold (ºC)	Sum of daily mean temperature (ºC)
BCN	21-Jan	8	285
BTU	01-Jan	4	619
GIC	01-Jan	7	473
LLE	01-Jan	2	561
MAN	01-Jan	2	577
TAU	01-Jan	6	551

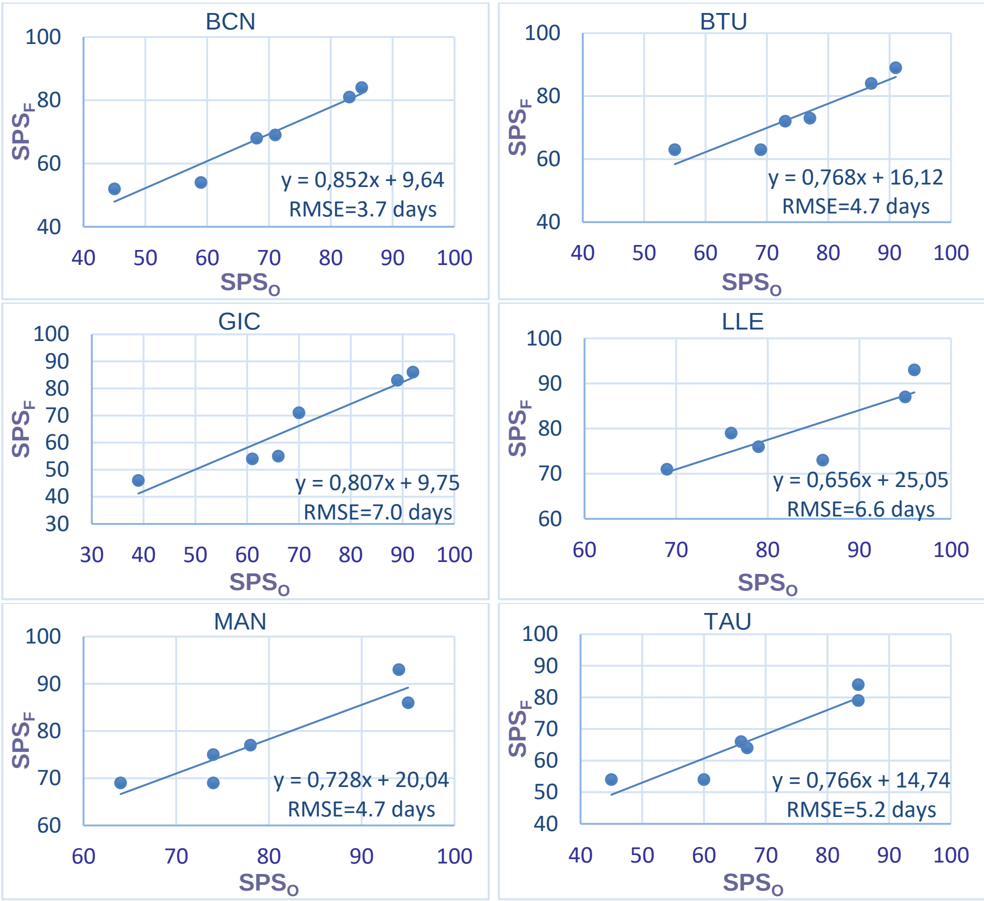


Figure 5.2b: Linear regression between forecast and observed SPS values of *Pinus*.

Table 5.5b: Accuracy of the model predicting the SPS of *Pinus* for the year 2013.

Pinus			
Station	SPS_F (day)	SPS_O (day)	$SPS_F - SPS_O$ (days)
BCN	73	67	+6
BTU	77	78	-1
GIC	94	72	+22
LLE	83	87	-4
MAN	91	78	+13
TAU	67	73	-6

Table 5.4c: Parameters obtained to forecast the SPS of *Pistacia*.

Pistacia			
Station	Initial date for the sum	Thermal threshold (ºC)	Sum of daily mean temperature (ºC)
BCN	01-Jan	0	706
BTU	01-Jan	0	832
GIC	01-Jan	0	807
LLE	01-Jan	5	617
MAN	01-Jan	2	753
TAU	01-Jan	6	747

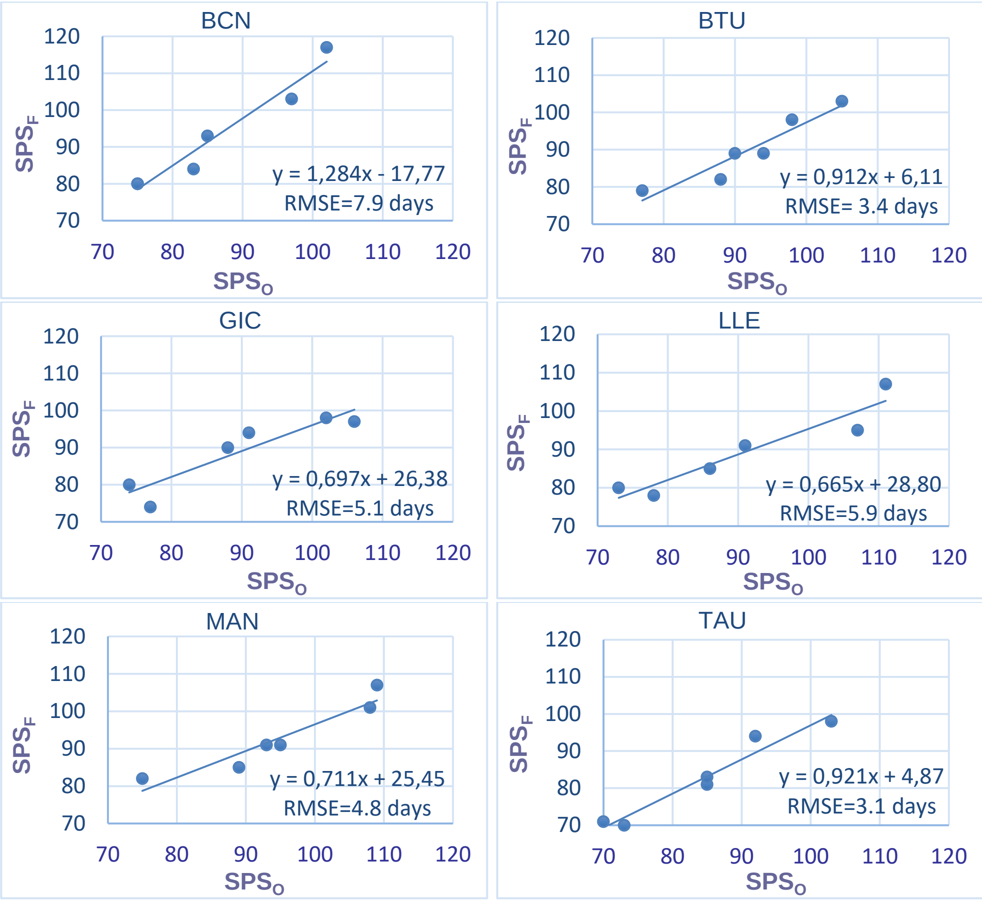


Figure 5.2c: Linear regression between forecast and observed SPS values of *Pistacia.*

Table 5.5c: Accuracy of the model predicting the SPS of *Pistacia* for the year 2013.

Pistacia			
Station	SPS_F (day)	SPS_O (day)	$SPS_F - SPS_O$ (days)
BCN	87	88	-1
BTU	90	91	-1
GIC	103	91	+12
LLE	91	84	+7
MAN	106	102	+4
TAU	80	73	+7

Table 5.4d: Parameters obtained to forecast the SPS of *Plantago*.

Plantago			
Station	Initial date for the sum	Thermal threshold (ºC)	Sum of daily mean temperature (ºC)
BCN	01-Jan	0	899
BTU	01-Jan	0	1008
GIC	31-Jan	0	831
LLE	01-Jan	2	881
MAN	01-Jan	0	1083
TAU	21-Jan	0	696

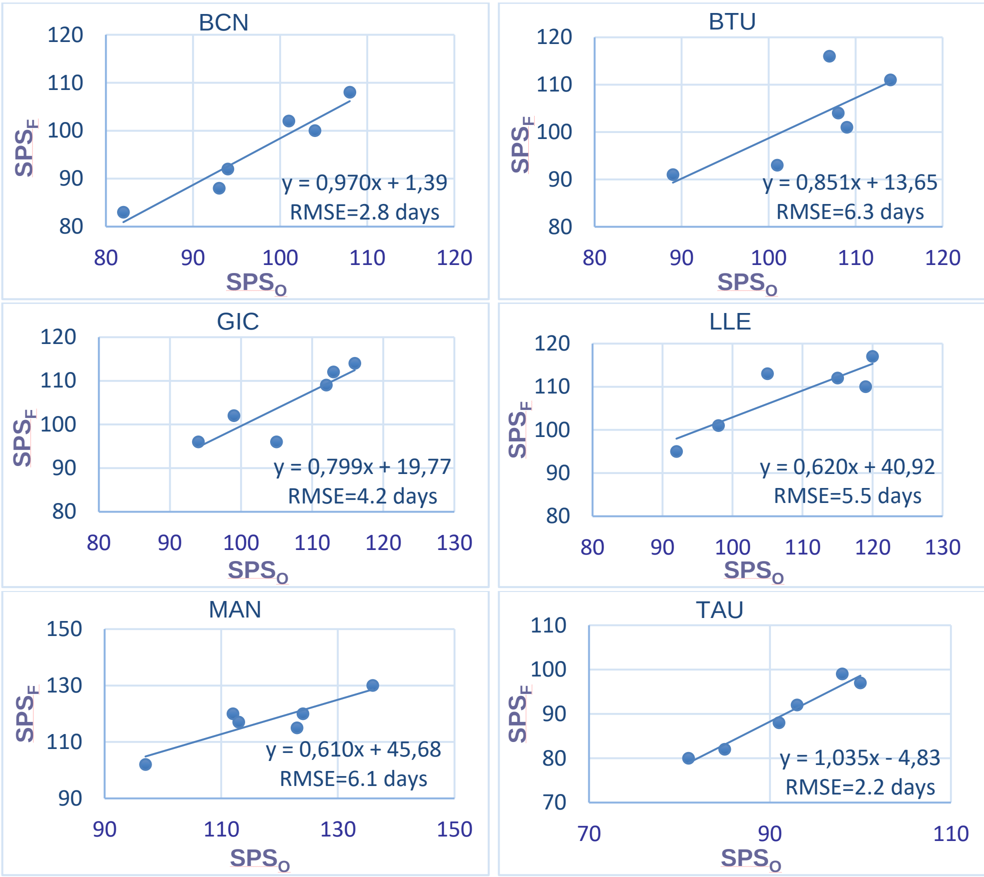


Figure 5.2d: Linear regression between forecast and observed SPS values of *Plantago.*

Table 5.5d: Accuracy of the model predicting the SPS of *Plantago* for the year 2013.

Plantago			
Station	SPS_F (day)	SPS_O (day)	$SPS_F - SPS_O$ (days)
BCN	103	103	0
BTU	106	102	+4
GIC	120	112	+8
LLE	107	103	+4
MAN	131	122	+9
TAU	91	93	-2

Table 5.4e: Parameters obtained to forecast the SPS of *Platanus*.

Platanus			
Station	Initial date for the sum	Thermal threshold (ºC)	Sum of daily mean temperature (ºC)
BCN	21-Jan	5	459
BTU	01-Jan	0	676
GIC	11-Jan	5	600
LLE	01-Jan	2	567
MAN	01-Jan	0	648
TAU	01-Jan	0	682

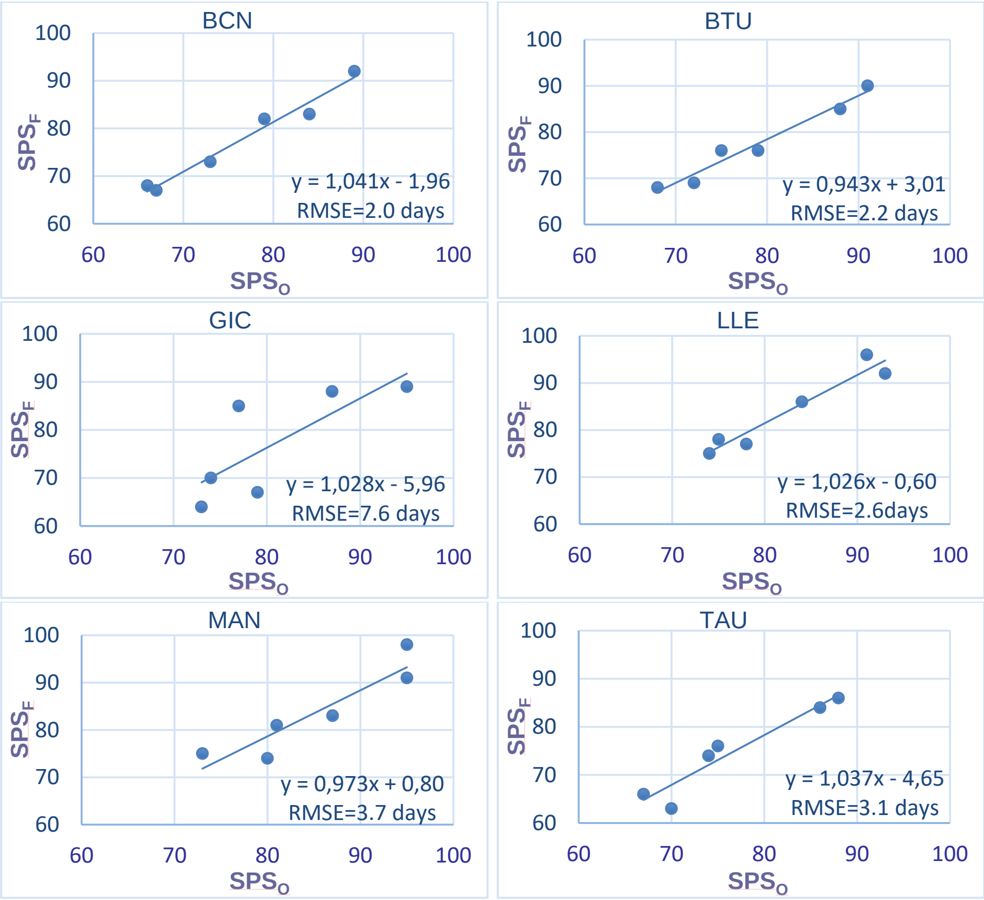


Figure 5.2e: Linear regression between forecast and observed SPS values of *Platanus*.

Table 5.5e: Accuracy of the model predicting the SPS of *Platanus* for the year 2013.

Platanus			
Station	SPS_F (day)	SPS_O (day)	$SPS_F - SPS_O$ (days)
BCN	82	82	0
BTU	81	84	-3
GIC	99	84	+15
LLE	84	87	-3
MAN	98	92	+6
TAU	77	75	+2

Table 5.4f: Parameters obtained to forecast the SPS of *Quercus* deciduous type.

Quercus deciduous type			
Station	Initial date for the sum	Thermal threshold (ºC)	Sum of daily mean temperature (ºC)
BCN	21-Jan	6	635
BTU	01-Jan	2	822
GIC	01-Jan	5	889
LLE	01-Jan	4	662
MAN	21-Jan	2	758
TAU	01-Jan	2	714

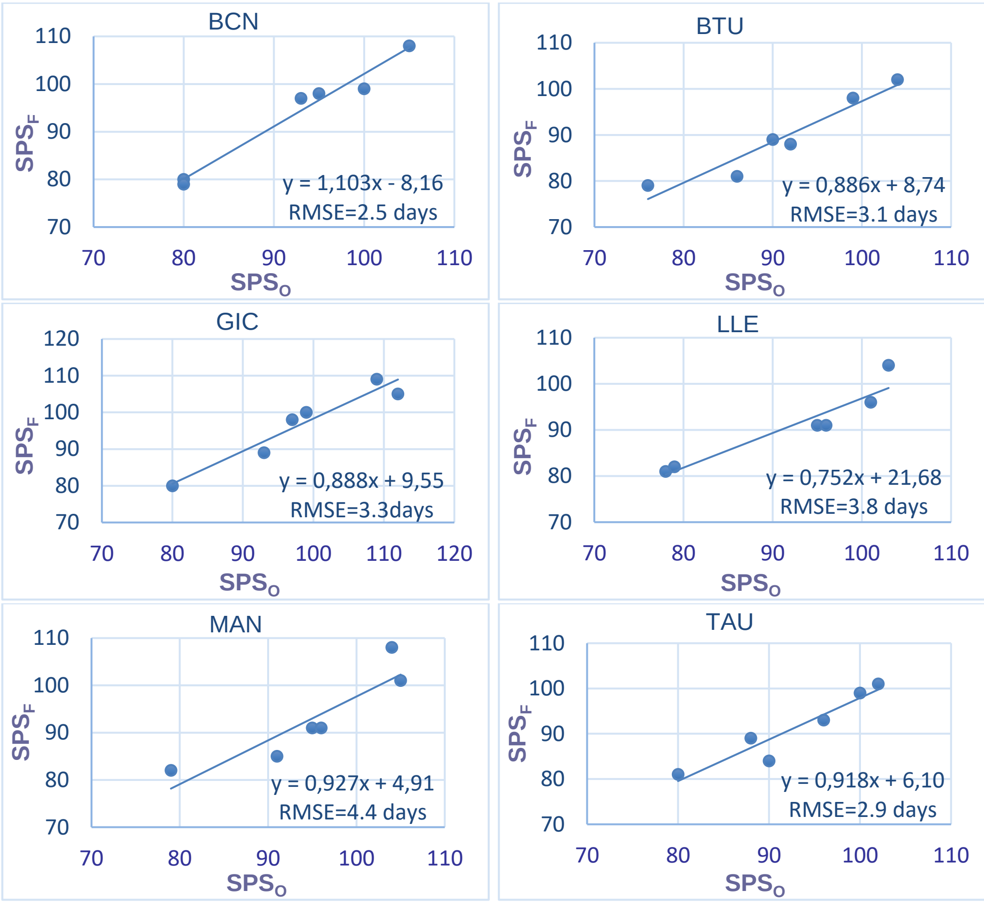


Figure 5.2f: Linear regression between forecast and observed SPS values of *Quercus* deciduous type.

Table 5.5f: Accuracy of the model predicting the SPS of *Quercus* deciduous type for the year 2013.

Quercus deciduous type			
Station	SPS_F (day)	SPS_O (day)	$SPS_F - SPS_O$ (days)
BCN	102	100	+2
BTU	92	96	-4
GIC	117	108	+9
LLE	93	102	-9
MAN	103	104	-1
TAU	92	102	-10

5.4.2. Correlations and Multiple Regressions.

In order to find more accurate forecast models, it is important to understand and investigate the relationship between SPS (dependent variable) and meteorological factors (independent variables) that have a great influence on the pollination season in the area under study.

The meteorological data considered in the analysis were daily maximum temperature (T_{max}), daily minimum temperature (T_{min}) and daily rainfall (R). Daily meteorological data from 01–January until the observed SPS was grouped in 10-day periods. Temperatures were averaged for each period while total amount of rainfall was quantified. These 10-day grouped meteorological data were considered as independent variables in the analysis of correlations and multiple regressions.

Spearman's rank correlation coefficient was applied to measure the relationship between the SPS of *Olea*, *Pinus*, *Pistacia*, *Plantago*, *Platanus* and *Quercus* deciduous type, and the independent meteorological variables (Tables 5.6). Years 2001 and 2005-2011 (8 years) have been included in the calculation of correlations and multiple regressions, while 2013 has been used as control year to test the method. Furthermore, many daily rainfall records in Lleida during the pollination season were missing; therefore, we have not considered this station in this forecasting method.

A multiple regression analysis was developed to determine which meteorological variables have the most significant effect on the SPS of each taxon. Tables 5.7 show the equations to forecast the SPS for each station.

From the equations shown in Tables 5.7, forecasted values (SPS_F) are calculated for each year. Figures 5.3 show the linear regression between forecasted (SPS_F) and observed (SPS_O) values for the years included in the model. For each regression the $RMSE$ value are also included in the figures. The method was tested for forecasting the SPS of each taxon in the year 2013 (not include in the model data) and the results are shown in Tables 5.8.

Table 5.6a: Spearman's rank correlation coefficient between the SPS of *Olea* and meteorological variables. Taking into account that the pollinations season of *Olea* starts in the beginning of May, daily meteorological data have been grouped from 01–February (day 32).
(*) Correlation is significant at the 0.05 level. (**) correlation is significant at the 0.01 level.

Olea					
Independent variables	BCN	BTU	GIC	MAN	TAU
Maximum temperature for days 32-41 (1-10 February)	**-,807***	**-,922****	**-,780***	-,301	**-,970****
Minimum temperature for days 32-41	**-,819***	,000	,012	,395	,048
Rainfall for days 32-41	**,790***	**,722****	,560	,675	**,771***
Maximum temperature for days 42-51 (11-20 February)	-,374	-,371	-,371	-,337	-,578
Minimum temperature for days 42-51	-,648	-,479	-,383	,299	-,615
Rainfall for days 42-51	,145	,024	-,012	,299	-,133
Maximum temperature for days 52-61 (21 Feb-2 March)	,120	-,036	,275	,587	-,229
Minimum temperature for days 52-61	,079	,000	,168	,659	-,229
Rainfall for days 52-61	-,337	-,108	-,347	-,072	-,602
Maximum temperature for days 62-71 (3-12 March)	-,542	-,611	-,503	-,455	**-,711***
Minimum temperature for days 62-71	-,494	-,596	-,240	-,228	-,566
Rainfall for days 62-71	,048	,252	-,192	,443	,091
Maximum temperature for days 72-81 (13-22 March)	-,193	-,263	,012	-,084	-,651
Minimum temperature for days 72-81	-,277	-,700	**-,755***	**-,838****	-,704
Rainfall for days 72-81	,048	,060	-,054	,338	,036
Maximum temperature for days 81-90 (23 March- 1 April)	-,530	-,359	-,323	**-,814***	-,445
Minimum temperature for days 81-90	-,265	,349	,359	-,108	,241
Rainfall for days 81-90	,206	,252	-,299	,587	,313
Maximum temperature for days 91-100 (2-11 April)	**-,771***	**-,743***	**-,755***	-,443	**-,687***
Minimum temperature for days 91-100	**-,699***	-,180	-,252	-,419	**-,807***
Rainfall for days 91-100	**,709***	**,709***	**,719***	**,822***	,446
Maximum temperature for days 101-110 (12-21 April)	-,181	-,371	-,422	-,145	-,470
Minimum temperature for days 101-110	,467	,446	-,355	,611	,390
Rainfall for days 101-110	,285	,313	,023	,515	,164

Table 5.7a: Equations to forecast the SPS of *Olea* and R_Square values.

Station	SPS of *Olea*	R_Square
BCN	$160.66 - 7.19\ T_{min1Feb} + 0.14\ R_{2Apr}$	0.919
BTU	$227.29 - 6.83\ T_{max1Feb}$	0.809
GIC	$213.63 - 5.66\ T_{max1Feb}$	0.718
MAN	$152.81 - 4.56\ T_{min13Mar}$	0.582
TAU	$244.43 - 7.78\ T_{max1Feb}$	0.720

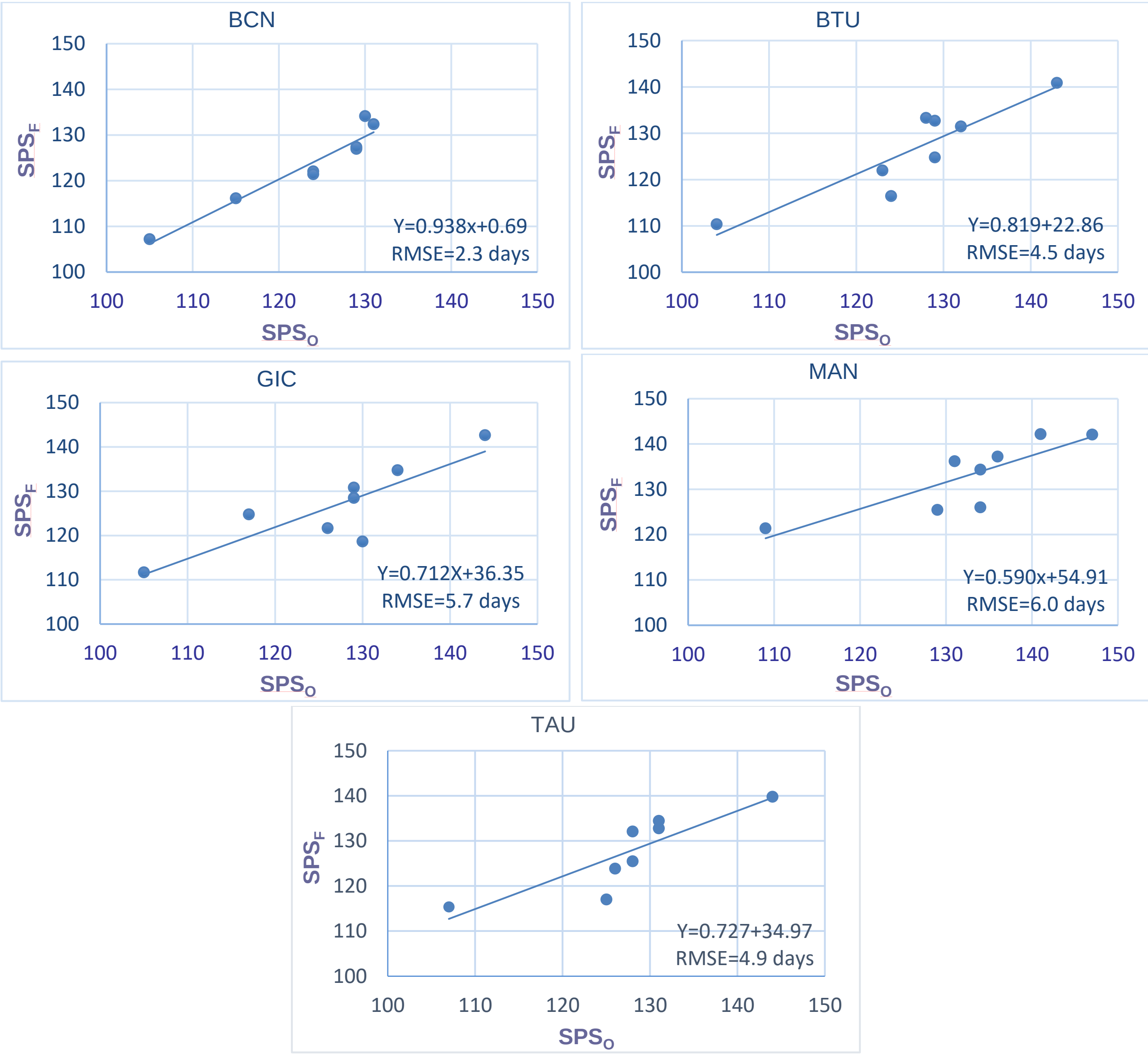


Figure 5.3a: Linear regression between forecast and observed SPS values of *Olea*.

Table 5.8a: Accuracy of the model predicting the SPS of *Olea* for the year 2013.

Olea			
Station	SPS_F (day)	SPS_O (day)	$SPS_F - SPS_O$ (days)
BCN	131	128	+3
BTU	133	128	+5
GIC	137	133	+4
MAN	145	137	+8
TAU	126	118	+8

Table 5.6b: Spearman's rank correlation coefficient between the SPS of *Pinus* and meteorological variables.
(*) Correlation is significant at the 0.05 level. (**) Correlation is significant at the 0.01 level.

Pinus					
Independent variables	BCN	BTU	GIC	MAN	TAU
Maximum temperature for days 1-10 (1-10 January)	-,333	-,500	-,524	-,386	-,695
Minimum temperature for days 1-10	-,619	-,575	**-,929****	-,467	-,422
Rainfall for days 1-10	,122	,216	-,024	,356	,455
Maximum temperature for days 11-20 (11-20 January)	-,143	-,238	-,383	-,096	-,431
Minimum temperature for days 11-20	-,619	-,476	-,571	-,181	**-,731***
Rainfall for days 11-20	,293	-,325	-,342	-,123	-,132
Maximum temperature for days 21-30 (21-30 January)	**-,786***	-,667	-,667	-,647	-,407
Minimum temperature for days 21-30	**-,714***	-,429	-,190	-,395	-,491
Rainfall for days 21-30	,390	,048	-,072	,223	-,030
Maximum temperature for days 31-40 (31 January-9 February)	-,667	**-,862****	**-,838****	-,707	**-,916****
Minimum temperature for days 31-40	**-,881****	**-,814***	-,419	-,599	-,252
Rainfall for days 31-40	,347	,347	,571	,331	,611
Maximum temperature for days 41-50 (10-19 February)	-,286	-,551	-,433	**-,759***	-,404
Minimum temperature for days 41-50	-,571	-,431	-,466	-,669	-,464
Rainfall for days 41-50	-,167	-,262	,026	-,192	-,120
Maximum temperature for days 51-60 (20 February- 1 March)	-,322	**-,757***	-,355	-,479	-,455
Minimum temperature for days 51-60	-,344	-,310	-,366	-,335	-,433
Rainfall for days 51-60	-,122	,455	,031	,241	,133
Maximum temperature for days 61-70 (2-11 March)	-,455	-,420	-,331	**-,886****	-,433
Minimum temperature for days 61-70	-,333	-,360	-,310	**-,886****	-,322
Rainfall for days 61-70	,044	,022	,035	-,060	,055
Maximum temperature for days 71-80 (12-21 March)	-,181	-,371	-,422	-,145	-,470
Minimum temperature for days 71-80	,467	,446	-,355	,611	,390
Rainfall for days 71-80	,285	,313	,023	,515	,164
Maximum temperature for days 81-90 (22 -31 March)	-,299	-,595	-,452	-,454	-,421
Minimum temperature for days 81-90	-,412	-,410	-,411	-,411	-,422
Rainfall for days 81-90	,021	,011	,022	,022	,011

Table 5.7b: Equations to forecast the SPS of *Pinus* and R_Square values.

Station	SPS of *Pinus*	R_square
BCN	$130.66 - 11.15\ T_{min31Jan}$	0.799
BTU	$160.15 - 4.93\ T_{max31Jan} - 4.98\ T_{min31Jan}$	0.924
GIC	$98.25 - 9.87\ T_{min1Jan}$	0.760
MAN	$119.82 - 2.55\ T_{max2Mar}$	0.788
TAU	$205.85 - 9.28\ T_{max31Jan}$	0.752

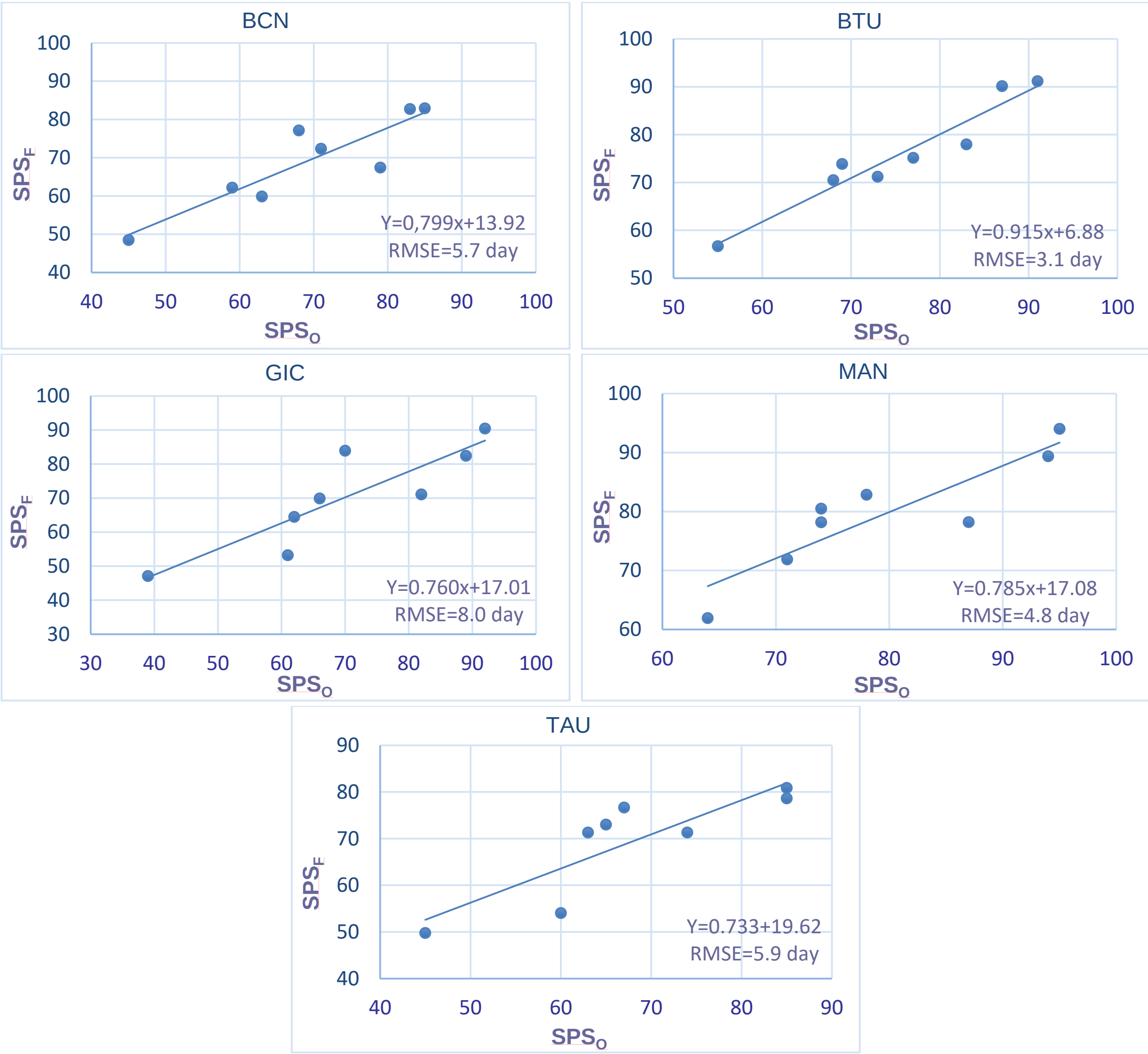


Figure 5.3b: Linear regression between forecast and observed SPS values of *Pinus*.

Table 5.8b: Accuracy of the model predicting the SPS of *Pinus* for the year 2013.

	Pinus		
Station	SPS_F (day)	SPS_O (day)	$SPS_F - SPS_O$ (days)
BCN	69	67	+2
BTU	75	78	-3
GIC	78	72	+6
MAN	88	78	+10
TAU	66	73	-7

Table 5.6c: Spearman's rank correlation coefficient between the SPS of *Pistacia* and meteorological variables.
(*) Correlation is significant at the 0.05 level. (**) Correlation is significant at the 0.01 level.

Pistacia					
Independent variables	BCN	BTU	GIC	MAN	TAU
Maximum temperature for days 1-10 (1-10 January)	-,299	-,595	-,452	-,443	-,623
Minimum temperature for days 1-10	-,599	-,455	**-,786***	-,381	-,404
Rainfall for days 1-10	,074	,132	-,095	,171	,358
Maximum temperature for days 11-20 (11-20 January)	-,180	-,262	-,575	-,071	-,347
Minimum temperature for days 11-20	-,611	-,524	-,524	-,467	**-,731***
Rainfall for days 11-20	,245	-,361	-,220	-,317	-,180
Maximum temperature for days 21-30 (21-30 January)	**-,802***	-,286	**-,762***	-,452	-,503
Minimum temperature for days 21-30	**-,731***	-,143	-,071	-,214	-,599
Rainfall for days 21-30	,393	-,381	,156	-,108	-,006
Maximum temperature for days 31-40 (31 January-9 February)	-,635	-,690	-,659	-,500	**-,767****
Minimum temperature for days 31-40	**-,862****	-,571	-,563	-,405	-,359
Rainfall for days 31-40	,307	,635	,262	,634	,551
Maximum temperature for days 41-50 (10-19 February)	-,228	**-,790***	-,429	**-,850****	-,343
Minimum temperature for days 41-50	-,695	-,695	-,262	-,599	-,599
Rainfall for days 41-50	-,180	-,357	-,335	-,429	-,240
Maximum temperature for days 51-60 (20 February- 1 March)	-,527	-,405	-,667	-,429	-,443
Minimum temperature for days 51-60	-,515	-,286	-,643	-,381	-,503
Rainfall for days 51-60	,289	,108	-,310	-,036	-,359
Maximum temperature for days 61-70 (2-11 March)	**-,719***	**-,929****	**-,714***	**-,946****	**-,878****
Minimum temperature for days 61-70	**-,790***	**-,857****	**-,710***	**-,833***	-,671
Rainfall for days 61-70	,263	,190	,286	,024	-,012
Maximum temperature for days 71-80 (12-21 March)	**-,790***	-,452	**-,735***	-,357	-,422
Minimum temperature for days 71-80	,168	-,286	,095	-,310	-,411
Rainfall for days 71-80	**,715***	,252	,464	-,024	,012
Maximum temperature for days 81-90 (22 -31 March)	-,299	-,595	-,452	-,421	-,454
Minimum temperature for days 81-90	-,412	-,410	-,411	-,422	-,411
Rainfall for days 81-90	,021	,011	,022	,011	,022

Table 5.7c: Equations to forecast the SPS of *Pistacia* and R_Square values.

Station	SPS of *Pistacia*	R_Square
BCN	$129.80 - 8.12\ T_{min31Jan}$	0.744
BTU	$132.40 - 2.70\ T_{max2Mar}$	0.878
GIC	$145.72 - 5.43\ T_{min1Jan} - 2.22\ T_{max12Mar}$	0.967
MAN	$132.32 - 2.33\ T_{max2Mar} - 1.33\ T_{min2Mar}$	0.968
TAU	$128.83 - 2.74\ T_{max2Mar}$	0.676

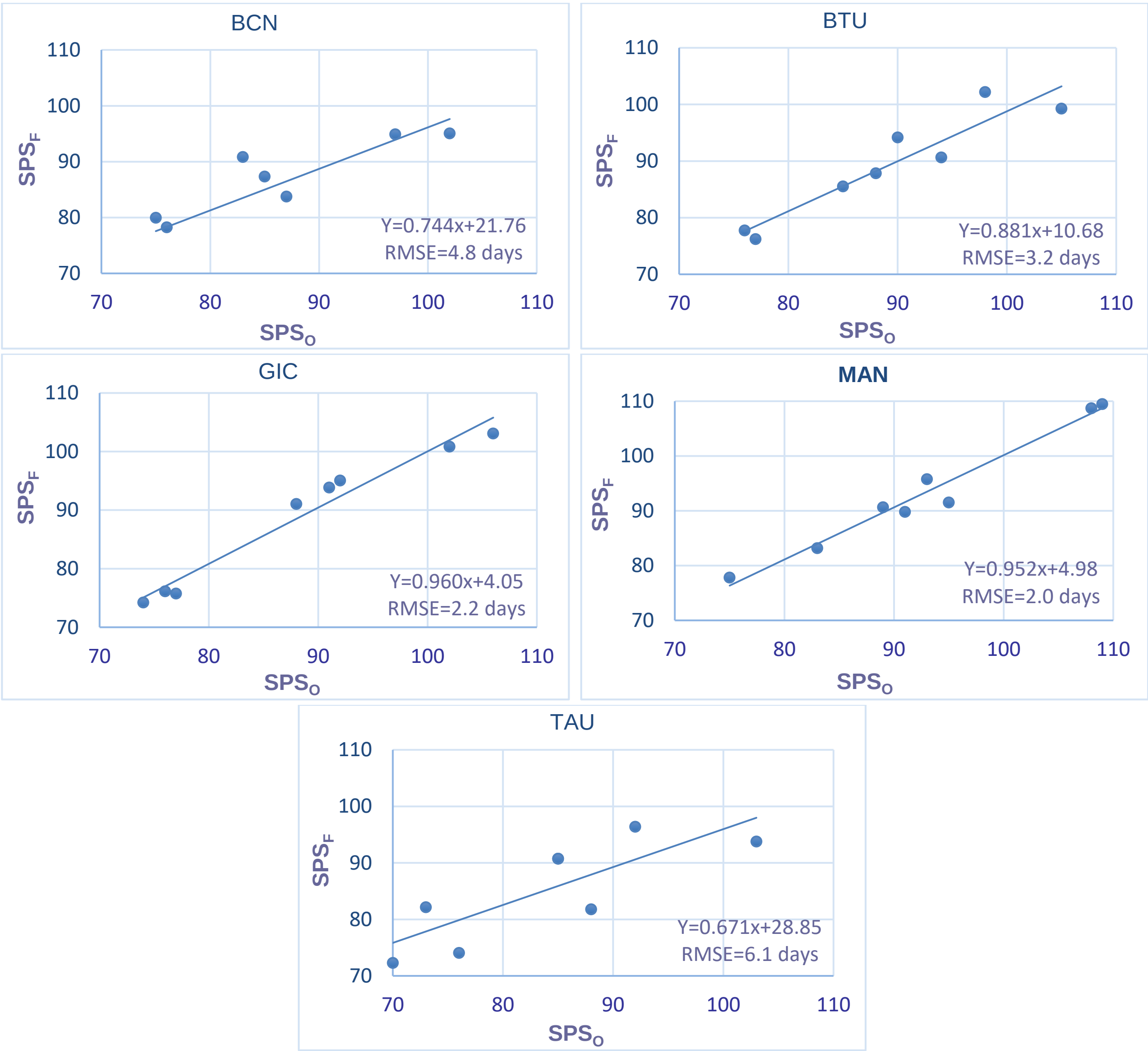


Figure 5.3c: Linear regression between forecast and observed SPS values of *Pistacia*.

Table 5.8c: Accuracy of the model predicting the SPS of *Pistacia* for the year 2013.

Pistacia			
Station	SPS_F (day)	SPS_O (day)	$SPS_F - SPS_O$ (days)
BCN	85	88	-3
BTU	95	91	-4
GIC	97	91	+6
MAN	108	102	+6
TAU	83	73	+10

Table 5.6d: Spearman's rank correlation coefficient between the SPS of *Plantago* and meteorological variables.
(*) Correlation is significant at the 0.05 level. (**) Correlation is significant at the 0.01 level.

Plantago					
Independent variables	BCN	BTU	GIC	MAN	TAU
Maximum temperature for days 1-10 (1-10 January)	-,659	-,238	-,216	-,048	-,548
Minimum temperature for days 1-10	**-,755***	-,204	-,275	,000	-,228
Rainfall for days 1-10 from	,626	-,036	,275	,098	,277
Maximum temperature for days 11-20 (11-20 January)	-,407	,167	-,012	,595	-,310
Minimum temperature for days 11-20	-,647	,548	-,252	,299	-,500
Rainfall for days 11-20	,430	-,084	,000	-,146	,024
Maximum temperature for days 21-30 (21-30 January)	-,287	,214	,108	-,024	-,595
Minimum temperature for days 21-30	-,311	-,024	-,323	-,143	-,667
Rainfall for days 21-30	,086	-,143	**-,765***	,132	,240
Maximum temperature for days 31-40 (31 January-9 February)	**-,934****	-,548	-,627	-,048	**-,814***
Minimum temperature for days 31-40	**-,886****	-,119	-,223	-,048	-,429
Rainfall for days 31-40	**,873****	**,731***	,695	,342	,381
Maximum temperature for days 41-50 (10-19 February)	**-,790***	-,491	-,539	-,455	-,287
Minimum temperature for days 41-50	**-,814****	-,180	-,527	-,299	-,476
Rainfall for days 41-50	-,048	,357	,175	,357	,095
Maximum temperature for days 51-60 (20 February-1 March)	-,048	,595	,563	,571	-,214
Minimum temperature for days 51-60	,060	,690	,551	,690	-,286
Rainfall for days 51-60	-,157	,024	-,180	,240	-,119
Maximum temperature for days 61-70 (2-11 March)	**-,886****	-,429	-,479	**-,575***	-,667
Minimum temperature for days 61-70	-,623	-,167	-,431	**-,711***	-,643
Rainfall for days 61-70	,419	-,167	,443	,214	,096
Maximum temperature for days 71-80 (12-21 March)	-,407	-,119	,024	-,548	**-,976****
Minimum temperature for days 71-80	-,252	**-,826***	**-,826***	-,286	-,619
Rainfall for days 71-80	,024	,024	-,371	,415	,419
Maximum temperature for days 81-90 (22-31 March)	-,659	**-,833***	-,599	-,448	-,327
Minimum temperature for days 81-90	-,311	-,347	,108	-,095	-,321
Rainfall for days 81-90	,011	,548	,204	,400	,021

Table 5.7d: Equations to forecast the SPS of *Plantago* and R_Square values.

Station	SPS of *Plantago*	R_Square
BCN	$160.37 - 5.27\, T_{max31Jan}$	0.892
BTU	$149.91 - 1.71\, T_{max22Mar} - 2.60\, T_{min12Mar}$	0.936
GIC	$127.40\ - 3.86\, T_{min12Mar}$	0.758
MAN	$127.28 - 3.28\, T_{min2Mar}$	0.537
TAU	$147.57 - 3.18\, T_{max12Mar}$	0.864

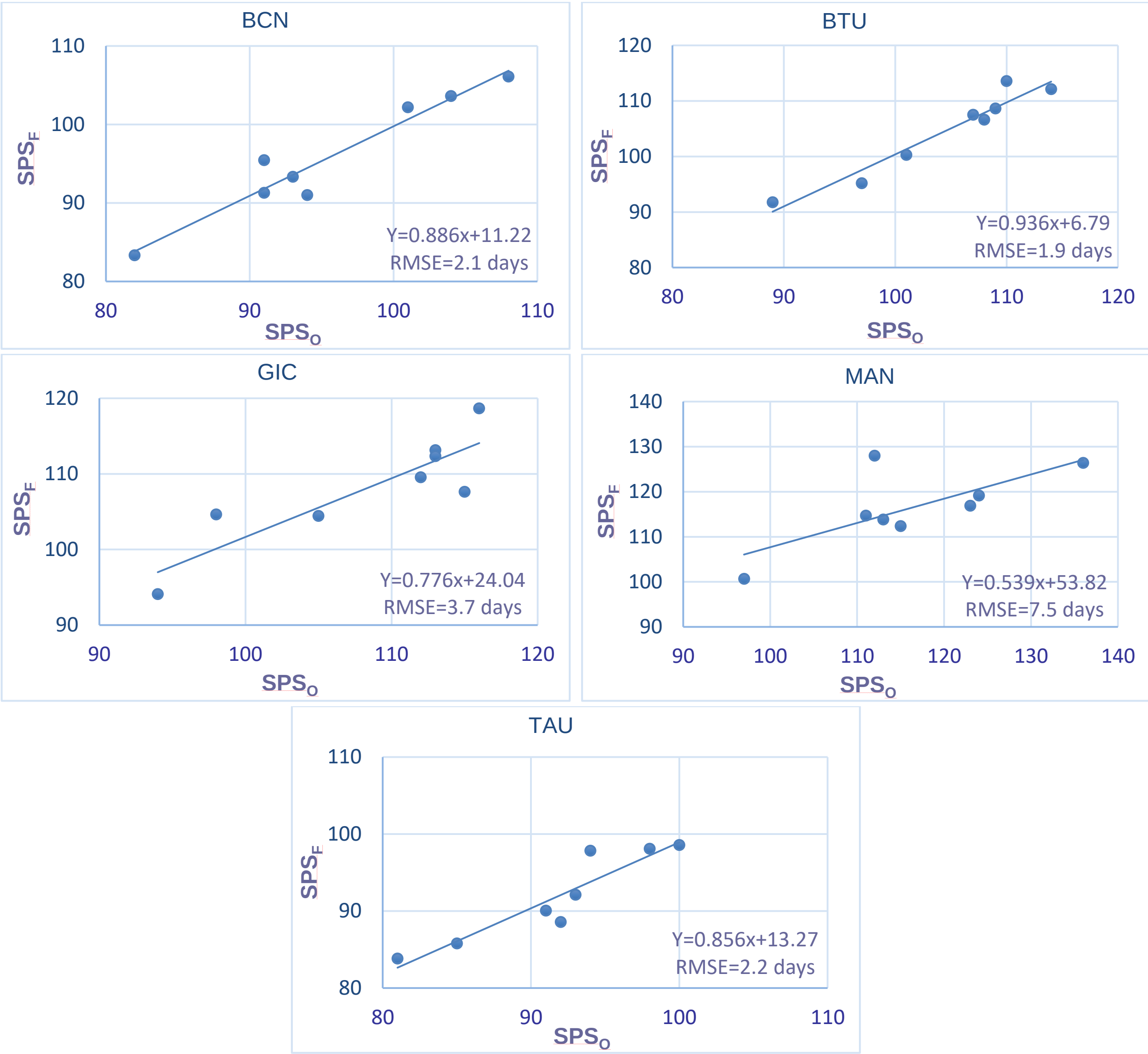


Figure 5.3d: Linear regression between forecast and observed SPS values of *Plantago*.

Table 5.8d: Accuracy of the model predicting the SPS of *Plantago* for the year 2013.

Plantago			
Station	SPS_F (day)	SPS_O (day)	$SPS_F - SPS_O$ (days)
BCN	99	103	-4
BTU	110	102	+8
GIC	115	112	+3
MAN	125	122	+3
TAU	91	93	-2

Table 5.6e: Spearman's rank correlation coefficient between the SPS of *Platanus* and meteorological variables.
(*) Correlation is significant at the 0.05 level. (**) Correlation is significant at the 0.01 level.

Platanus					
Independent variables	BCN	BTU	GIC	MAN	TAU
Maximum temperature for days 1-10 (1-10 January)	-,262	-,500	-,262	-,327	-,647
Minimum temperature for days 1-10	-,571	-,575	-,429	-,446	-,343
Rainfall for days 1-10	,024	,216	,143	,235	,412
Maximum temperature for days 11-20 (11-20 January)	-,214	-,238	-,707	-,048	-,419
Minimum temperature for days 11-20	-,595	-,476	-,238	-,315	-,647
Rainfall for days 11-20	,195	-,325	,122	-,247	-,084
Maximum temperature for days 21-30 (21-30 January)	**-,810** **	-,667	-,476	-,675	-,455
Minimum temperature for days 21-30	**-,738***	-,429	,167	-,434	-,575
Rainfall for days 21-30	,390	,048	,036	,176	,060
Maximum temperature for days 31-40 (31 January-9 February)	-,595	**-,762***	-,515	-,639	**-,729***
Minimum temperature for days 31-40	**-,833***	**-,714***	-,635	-,615	-,431
Rainfall for days 31-40	,263	,347	,024	,358	,407
Maximum temperature for days 41-50 (10-19 February)	-,167	-,551	-,357	**-,764***	-,482
Minimum temperature for days 41-50	-,595	-,431	-,119	-,673	-,647
Rainfall for days 41-50	-,190	-,262	-,407	-,277	-,275
Maximum temperature for days 51-60 (20 February- 1 March)	-,571	-,500	**-,714***	-,494	-,515
Minimum temperature for days 51-60	-,571	-,429	-,571	-,386	-,563
Rainfall for days 51-60	,275	,263	-,095	,085	-,335
Maximum temperature for days 61-70 (2-11 March)	**-,810***	**-,833***	-,595	**-,927** **	**-,826***
Minimum temperature for days 61-70	-,619	**-,976** **	**-,714***	**-,904** **	**-,826***
Rainfall for days 61-70	,503	,643	,643	-,120	,506
Maximum temperature fordays 71-80 (12-21 March)	-,690	-,411	-,455	-,411	-,433
Minimum temperature for days 71-80	-,571	-,400	-,408	-,433	-,422
Rainfall for days 71-80	,000	,012	,003	,002	,022
Maximum temperature for days 81-90 (22 -31 March)	-,422	-,344	-,366	-,455	-,388
Minimum temperature for days 81-90	-,322	-,411	-,322	-,433	-,422
Rainfall for days 81-90	,023	,036	,074	,052	,123

Table 5.7e: Equations to forecast the SPS of *Platanus* and R_Square values.

Station	SPS of *Platanus*	R_Square
BCN	$112.26 - 3.37\ T_{max21Jan}$	0.699
BTU	$89.19 - 2.81\ T_{min2Mar}$	0.884
GIC	$111.66 - 1.98\ T_{max20Feb}$	0.653
MAN	$120.12 - 2.32\ T_{max2Mar}$	0.854
TAU	$107.21 - 1.90\ T_{max2Mar}$	0.739

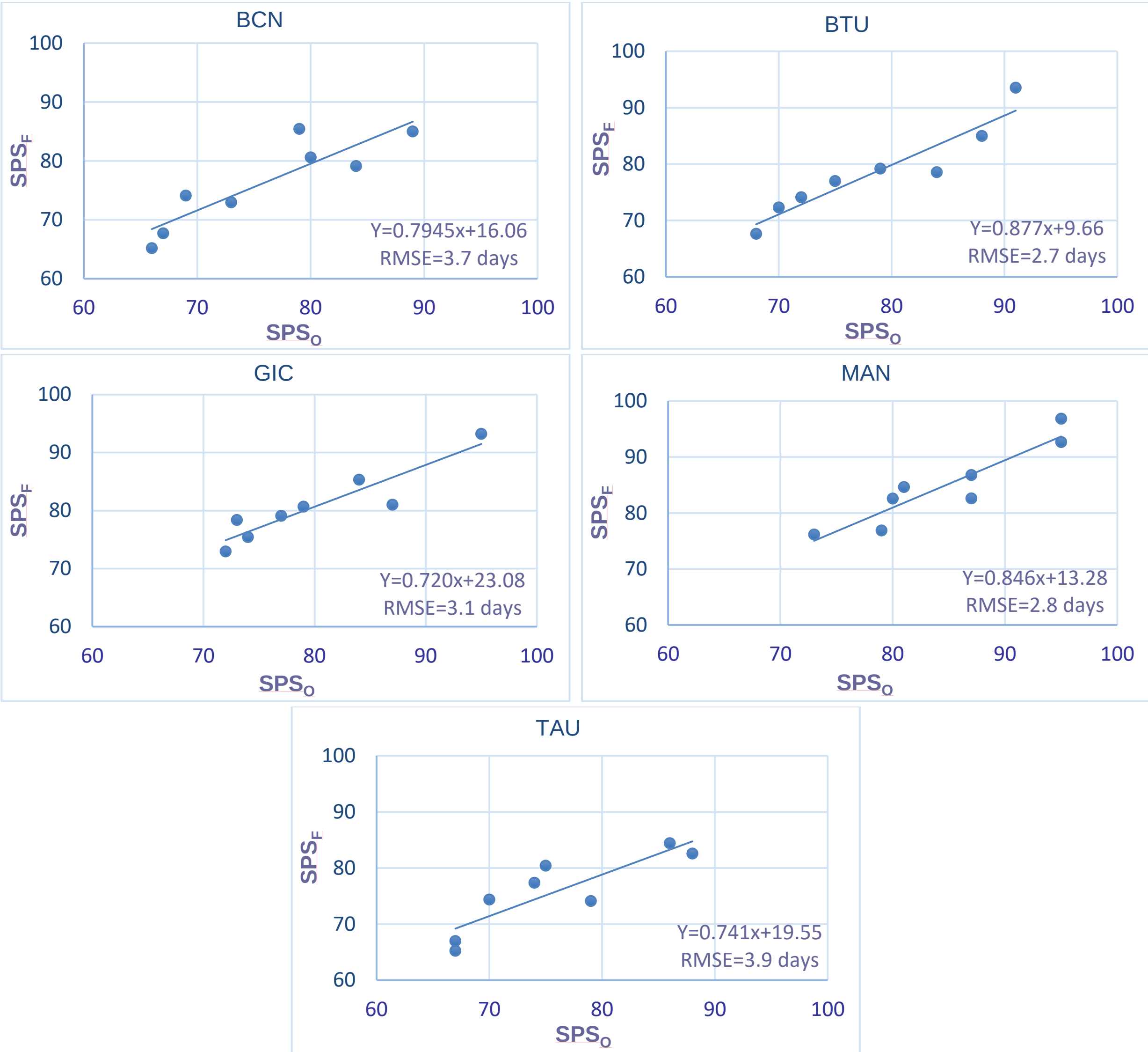


Figure 5.3e: Linear regression between forecast and observed SPS values of *Platanus*.

Table 5.8e: Accuracy of the model predicting the SPS of *Platanus* for the year 2013.

Platanus			
Station	SPS_F (day)	SPS_O (day)	$SPS_F - SPS_O$ (days)
BCN	77	82	-5
BTU	78	84	-6
GIC	81	84	-3
MAN	91	92	-1
TAU	75	75	0

Table 5.6f: Spearman's rank correlation coefficient between the SPS of *Quercus* deciduous type and meteorological variables.
(*) Correlation is significant at the 0.05 level. (**) Correlation is significant at the 0.01 level.

Quercus deciduous type					
Independent variables	BCN	BTU	GIC	MAN	TAU
Maximum temperature for days 1-10 (1-10 January)	-,048	-,524	-,119	-,084	,143
Minimum temperature for days 1-10	-,021	**-,755***	-,690	-,635	-,108
Rainfall for days 1-10	-,148	,204	-,333	-,061	-,325
Maximum temperature for days 11-20 (11-20 January)	,036	-,262	-,120	,299	,357
Minimum temperature for days 11-20	-,434	-,476	-,357	-,127	-,167
Rainfall for days 11-20	,111	-,313	-,537	-,454	-,095
Maximum temperature for days 21-30 (21-30 January)	**-,747***	-,619	-,667	-,515	-,524
Minimum temperature for days 21-30	**-,771***	-,333	-,381	-,371	-,690
Rainfall for days 21-30	,395	-,024	-,287	,169	,036
Maximum temperature for days 31-40 (31 January-9 February)	-,530	**-,881****	-,587	-,599	-,551
Minimum temperature for days 31-40	-,663	-,524	-,299	-,252	-,381
Rainfall for days 31-40	,170	,491	,405	,417	,333
Maximum temperature for days 41-50 (10-19 February)	,048	-,443	-,190	-,476	,120
Minimum temperature for days 41	-,422	-,299	-,119	-,386	,048
Rainfall for days 41-50	-,096	-,286	-,036	,060	,310
Maximum temperature for days 51-60 (20 February-1 March)	-,422	-,524	-,143	-,084	,262
Minimum temperature for days 51-60	-,446	-,476	-,190	-,072	,214
Rainfall for days 51-60	,267	,168	-,071	-,060	,238
Maximum temperature for days 61-70 (2-11 March)	-,446	**-,762***	-,476	**-,741***	-,214
Minimum temperature for days 61-70	**-,711***	**-,905****	**-,786***	-,659	-,524
Rainfall for days 61-70	,048	,381	,214	,204	-,012
Maximum temperature for days 71-80 (12-21 Mar)	-,627	-,667	-,371	-,587	-,548
Minimum temperature for days 71-80	**-,711***	-,012	**-,717***	**-,719***	**-,762***
Rainfall for days 71-80	-,072	,287	-,119	,344	-,024
Maximum temperature for days 81-90 (22-31 Mar)	-,422	-,344	-,366	-,455	-,388
Minimum temperature for days 81-90	-,322	-,411	-,322	-,433	-,422
Rainfall for days 81-90	,023	,036	,074	,052	,123

Table 5.7f: Equations to forecast the SPS of *Quercus* deciduous type R_Square values.

Station	SPS of *Quercus* deciduous type	R_Square
BCN	$107.85 - 3.49\ T_{min21Jan}$	0.777
BTU	$126.59 - 1.89\ T_{min2Mar} - 1.91\ T_{max31Jan}$	0.978
GIC	$108.52 - 2.28\ T_{min2Mar}$	0.719
MAN	$127.05 - 2.08\ T_{max2Mar}$	0.641
TAU	$110.56 - 2.61\ T_{min12Mar}$	0.424

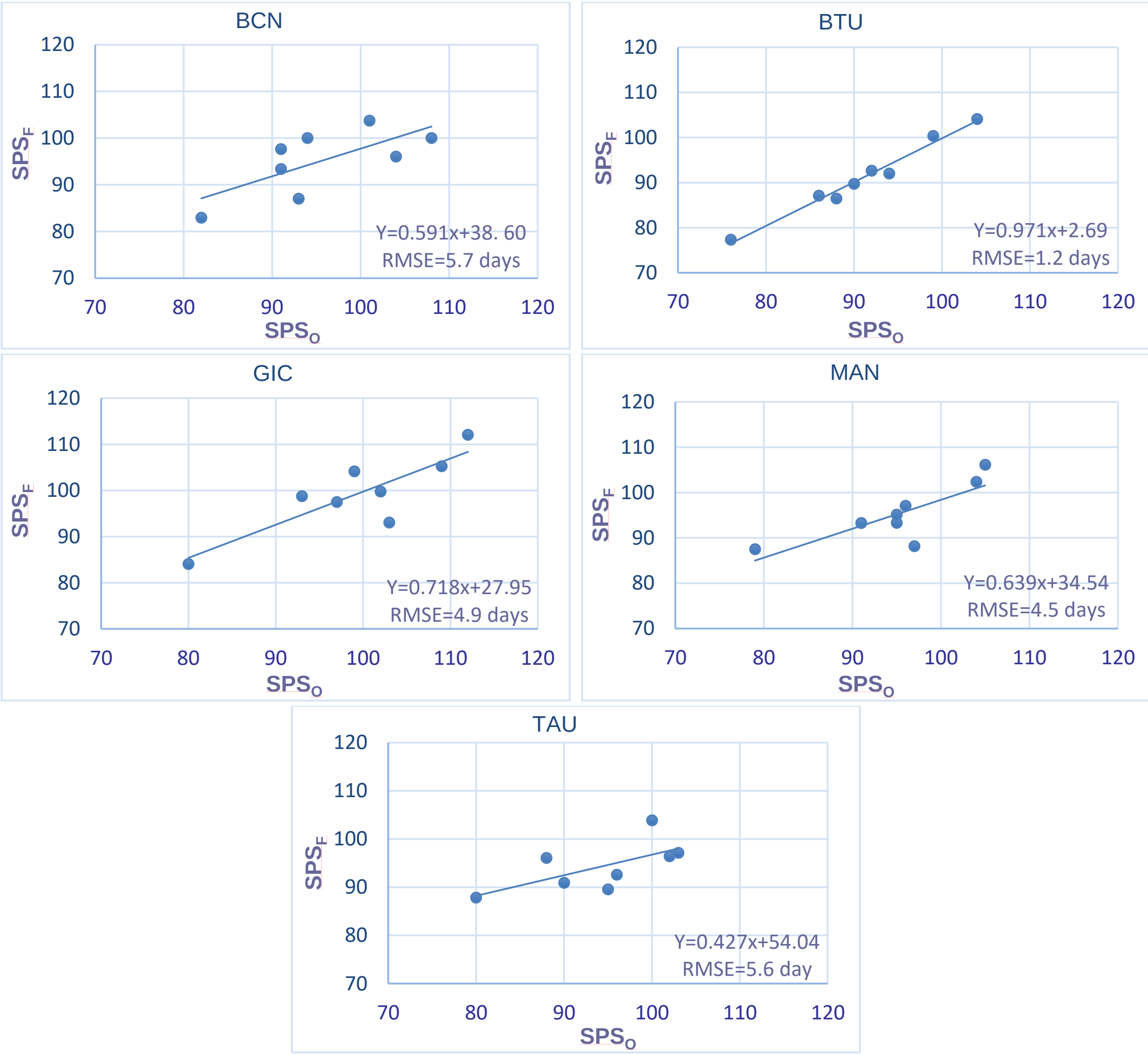


Figure 5.3f: Linear regression between forecast and observed SPS values of *Quercus* deciduous type.

Table 5.8f: Accuracy of the model predicting the SPS of *Quercus* deciduous type for the year 2013.

Quercus deciduous type			
Station	SPS_F (day)	SPS_O (day)	$SPS_F - SPS_O$ (days)
BCN	94	100	-6
BTU	86	96	-10
GIC	95	108	-13
MAN	94	104	-10
TAU	99	102	-3

5.5. Discussion

The meteorological data used in the current study were daily temperature (maximum and minimum) and daily rainfall obtained from the Meteorological Service of Catalonia at 6 meteorological stations. Although different criteria are used for defining the Start of the main Pollen Season (SPS), here we have considered the SPS when 2.5% of the cumulative annual catch has been reached and the end of the main pollen season when 97.5% has been reached. This method has been used by many authors (e.g., Pathirane 1975; Lejoly-Gabriel 1978).

Taking into account that temperatures before the pollination season have a great influence in the SPS, Tables 5.9 show the average maximum, minimum and mean temperatures for three months, January, February and March, and the SPS for each station during the years included in the study. The lowest average mean temperature recorded in 2005 can explain the late SPS for all the taxa in all the stations, except for *Olea* and *Plantago*. For these two taxa, the late SPS occurred in 2010, because they are dependent on the maximum temperature, and the maximum temperature during 2010 was lower than that recorded during the other years in the 6 stations. On the other hand, the highest average mean temperature recorded in 2001 can explain the earlier SPS for all the taxa in all the stations. These results, which are consistent with the results obtained by other researchers (Zulima González-Parrado et al., 2014) had shown that there is a negative correlation between temperature and the SPS of the pollen taxa included in this study. In other words, relatively high temperatures lead to earlier SPS, while relatively low temperatures delay the SPS.

In order to have a quick look about the different climatology in the 6 stations, Table 5.10 shows averaged values of maximum, minimum and mean temperature for the three months before the pollination season (January, February and March) for all the years included in the study. BCN and TAU are relatively warmer than the other cities. These two stations are located in urban areas on the coast and have the same phytoclimate (Allué, 1990). On the other hand, LLE and MAN recorded the lowest mean temperatures.

The two methods have been tested in the control year, 2013. Table 5.11 shows mean values of maximum, minimum and mean temperatures and total rainfall for three months before the pollination season (January, February, and March) for 2013. Table 5.12 shows mean values of maximum, minimum and mean temperatures (ºC) and total rainfall (mm) averaged for the three months before the pollination season (January, February, and March) for 2013.

The forecasting models have been tested computing the discrepancy between the predicted and the observed values by means of the root mean square error (RMSE). Table 5.13 and

Table 5.14 show the RMSE, and systematic and random errors in the forecasting of SPS using the method of Summing Temperatures and the method of Multiple Regression, respectively.

5.5.1. The method of Summing Temperatures

Olea is the taxon that needs to accumulate more temperature, which agree with the fact that *Olea* is the taxon that pollinates later, on the first half of May. The initial date for the sum is the first of February for all the stations. The differences in the thermal threshold could be attributed to bio-geographical characteristics; a lower altitude of Barcelona, Girona and Tarragona, resulted in a higher threshold temperature (Črepinšek et al., 2006). The sum of daily mean temperature had less interregional variation. The lower sum temperature obtained in BCN is due to early flowering of *Olea*. Aguilera et al. (2014) pointed out that for the olive trees showing the rapid floral development, the lower heat requirements are due to better adaptation to warmer regions. The threshold temperatures obtained in this work do not differ too many from those provided in previous studies (Galán et al., 2005; Martins et al., 2012; Orlandi et al., 2006; Achmakh et al., 2015). The threshold temperatures for the olive tree reported by these authors ranged between 5°C and 12.5°C, values a little bit high than those obtained here. This fact can be considered to depend mainly on the methodology used to statistically evaluate the best threshold temperatures.

Pinus is the taxon that needs to accumulate less temperature, due to the SPP for *Pinus* is in the middle of March, the taxon that pollinates earlier. The initial date of the sum is the first of January, except in BCN where that date is delayed until the 21st of January. It should be also notice that the accumulated temperature in BCN is much lower than in the other stations, and present the highest value of the thermal threshold among all the stations. It is difficult to compare the predictive ability of our method to those of other researchers, because there are very few studies dealing with conifer pollination specifically. Regarding the accuracy of the model tested with the year 2013 (Table 5.5b) the forecasted SPS in GIC differs from the observed one in 22 days. This is the worst forecasted value of all but it is consistent with the highest value of the standard deviations of the SPS for *Pinus* in GIC (Table 5.3).

Regarding the RMSE (Table 5.13), the best forecasts have been obtained for *Platanus* in all the stations except at GIC. For this taxon the systematic errors are lower than for the other taxa. This result is consistent with the fact that the standard deviations of the SPS of *Platanus* are the lowest in all the stations (Table 5.3).

5.5.2. The method of Multiple Regression

The preliminary work of the multiple regression method included the correlation analysis between the SPS (dependent variable) and meteorological factors (independent variables) that have a great influence on the pollination season of *Olea*, *Pinus*, *Pistacia*, *Plantago*, *Platanus* and *Quercus* deciduous type (Tables 5.6). This analysis showed that the temperature on days that precede the pollination process influences on the timing of these taxa. This reinforces the results found by many researchers that the increase in temperature in the spring does influence the heading times of flowers and the SPS (Emberlin et al., 1993 a, 1999). For all the taxa and all the stations the correlations are negative with temperature and positive with rainfall; meaning that if the temperature is higher, the main pollen season starts earlier and the opposite, if the temperature gets lower, the main pollen season tends to start later. On the other hand, a positive significant correlation with the rainfall means that if rainfall is bounteous in the months before the pollination period the main pollen season will be later.

After the correlation, the multiple regression analysis has been used to forecast the SPS of *Olea*, *Pinus, Pistacia Plantago*, *Platanus* and *Quercus* deciduous type. The method gives an equation that allows calculating the forecast value of the SPS and its associated errors (Valencia-Barrera et al., 2002). Regarding these equations (Tables 5.7), only the SPS of *Olea* in BCN has to be calculated considering the rainfall in the beginning of April, just one month before the SPS. For *Pistacia*, *Plantago*, *Platanus*, and *Quercus* deciduous type, the best variable to forecast the SPS was the temperature during the first half of March, except in BCN where the best variable was the temperature during January and February. For *Olea* and *Pinus*, the best variable was the temperature during the first half of February, except in MAN where the best variable was the temperature in March, like for the other taxa.

The R_Square values in the multiple regression models range from 0.424 for *Quercus* deciduous type in TAR to 0.978 for *Quercus* deciduous type in BTU (Tables 5.7). This value helps to understand how much of the dependent variable is explained by the model.

5.5.3. The RMSE and the comparison between the two methods.

In order to compare the differences between the two methods, the models were evaluated using systematic and unsystematic root mean square errors, in order to assess the intrinsic error of the model and the random one. The results show a highly variable depending on the pollen taxa and the sampling station (Table 5.13 and Table 5.14).

Regarding to the RMSE associated at the method of Summing Temperatures (Table 5.13) the intrinsic error of the model is higher than the random error for *Olea*, *Pinus* and *Pistacia*, while for Platanus and *Quercus* deciduous type the intrinsic errors are lower than the random ones.

The RMSE obtained with the method of Multiple Regression (Table 5.14) are in general lower than those obtained with the method of Summing Temperatures. The RMSE of the forecasted value of SPS for *Pinus* in GIC and *Plantago* in MAN are the highest of all. The high value of the RMSE for *Plantago* in MAN is in concordance with the low value of R_square: 0.537 (Table 5.7d), while the R_square value for *Pinus* in GIC (0.788) is not as low as we would expect (Table 5.7c). Conversely, the RMSE for *Quercus* deciduous type in BTU is the lowest of all, being the systematic part of the error lower than the random one, and the R_square value (0.978) the highest of all (Table 5.7d)

5.6. Conclusions

This research proves that it is possible to construct successfully models to forecast the Start of the Main Pollen Season for *Olea*, *Pinus*, *Pistacia*, *Plantago*, *Platanus* and *Quercus* deciduous type.

The method of Summing Temperatures will have to sum daily mean temperature from the initial date, above the thermal threshold. When approaching the necessary sum and taking into account the temperatures expected and predicted by the meteorological service, the method will allow informing physicians and allergologists a few days before the arrival of the first pollen grains.

Regarding the method of Multiple Regression, the coefficients in the equations are always negative for the temperatures, meaning that an increase in temperature leads to an earlier SPS. Moreover, rainfall does not seem to have a great influence on the SPS, as it was seen in Chapter 2.

The errors in the forecasting methods could be also due to the difference between the temperature measured at the meteorological stations and that to which the plant is actually submitted.

Finally, it can be concluded that the research has made a notable contribution predicting the Start of the Main Pollen Seasons for some taxa in Catalonia. These methodologies could be improved extending the database over the years, adding the new yearly pollen and meteorological data.

Tables 5.9: Maximum, minimum and mean temperatures averaged for three months before the pollination season (January, February, and March) and the SPS of 6 pollen taxa for the years included in the study.

	BCN								
	Maximum temperature	Minimum temperature	Mean temperature	*Olea*	*Pinus*	*Pistacia*	*Plantago*	*Platanus*	*Quercus* dec t.
2001	16,5	8,6	**12,6**	105	45	75	82	67	80
2005	12,7	4,7	**8,7**	129	85	102	101	89	105
2006	13,8	5,9	9,9	124	79	87	91	80	100
2007	17,0	7,3	12,2	129	63	76	91	69	97
2008	14,7	5,4	10,0	115	59	75	93	66	80
2009	13,6	6,1	9,9	130	68	83	104	73	93
2010	**12,0**	5,1	**8,6**	131	83	97	108	84	100
2011	14,0	6,6	10,3	124	71	85	94	79	95

	BTU								
	Maximum temperature	Minimum temperature	Mean temperature	*Olea*	*Pinus*	*Pistacia*	*Plantago*	*Platanus*	*Quercus* dec t.
2001	17,2	5,0	**11,0**	104	55	77	89	68	76
2005	14,0	1,2	**7,6**	129	91	105	107	91	104
2006	14,9	3,5	9,0	128	83	85	97	84	94
2007	16,0	4,1	10,0	129	68	76	110	70	88
2008	16,1	4,1	10,0	123	69	88	109	72	86
2009	14,9	3,9	9,4	132	73	94	108	75	92
2010	**13,2**	3,0	8,1	143	87	98	114	88	99
2011	15,0	3,4	9,2	124	77	90	101	79	90

	GIC								
	Maximum temperature	Minimum temperature	Mean temperature	*Olea*	*Pinus*	*Pistacia*	*Plantago*	*Platanus*	*Quercus* dec t.
2001	**17,7**	5,8	**11,8**	105	55	77	89	68	76
2005	16,5	-1,6	**7,5**	129	91	105	107	91	104
2006	15,5	4,3	9,9	129	83	85	97	84	94
2007	16,3	4,6	10,5	130	68	76	110	70	88
2008	16,4	3,8	10,0	117	69	88	109	72	86
2009	15,2	2,9	9,0	134	73	94	108	75	92
2010	**13,3**	2,9	8,1	144	87	98	114	88	99
2011	15,1	1,6	8,3	126	77	90	101	79	90

Tables 5.9 (cont): Maximum, minimum and mean temperatures averaged for three months before the pollination season (January, February, and March) and the SPS of 6 pollen taxa for the years included in the study.

	LLE								
	Maximum temperature	Minimum temperature	Mean temperature	*Olea*	*Pinus*	*Pistacia*	*Plantago*	*Platanus*	*Quercus* dec t.
2001	16.1	3.0	**9,5**	114	69	73	92	74	78
2005	12.2	0.0	**6,0**	130	96	111	120	93	106
2006	13.0	2.2	7,5	129	94	96	102	84	97
2007	14.2	2.1	8,1	129	90	73	115	74	103
2008	15.2	3.0	9,0	124	86	78	119	74	79
2009	14.1	2.3	8,2	136	76	86	95	78	95
2010	**13.1**	2.1	7,6	144	95	107	115	91	101
2011	14.0	1.1	7,6	129	79	91	98	84	96

	MAN								
	Maximum temperature	Minimum temperature	Mean temperature	*Olea*	*Pinus*	*Pistacia*	*Plantago*	*Platanus*	*Quercus* dec t.
2001	15,5	3,8	**9,7**	109	64	75	97	73	79
2005	12,9	-0,7	**6,1**	131	95	109	112	95	105
2006	13,2	2,1	7,7	129	87	91	111	87	95
2007	15,1	2,8	9,0	141	71	83	115	79	97
2008	15,2	2,9	9,0	134	74	89	123	80	91
2009	13,7	3.0	8,3	136	74	95	113	81	95
2010	**12,2**	2,2	7,7	147	94	108	136	95	104
2011	14,4	2,1	8,3	134	78	93	124	87	96

	TAU								
	Maximum temperature	Minimum temperature	Mean temperature	*Olea*	*Pinus*	*Pistacia*	*Plantago*	*Platanus*	*Quercus* dec t.
2001	**17.0**	6,1	**11,6**	107	45	70	81	67	80
2005	14,2	2,4	**8,3**	131	85	103	98	88	102
2006	14,7	4,7	9,7	128	74	88	94	79	95
2007	17,1	5,3	11,2	128	63	76	92	67	103
2008	16,9	5,4	11,2	125	60	73	85	70	90
2009	15.0	4,3	9,7	131	67	85	91	74	88
2010	**13,3**	3,8	8,6	144	85	92	100	86	100
2011	15,4	4.0	9,7	126	66	85	93	75	96

Table 5.10: Mean values of maximum, minimum and mean temperature (ºC) for the three months before the pollination season (January, February and March) in 6 stations for all the years included in the study.

	January			February			March			Average		
	T.max	T.min	T.mean	T.max	T.min	T.mean	T.max	T.min	T.mean	T.max	T.min	T.mean
BCN	11,4	5,3	8,4	12,6	5,5	9,0	18,9	7,9	13,4	14,3	6,2	**10,2**
BTU	13,6	2,6	8,1	14,7	2,9	8,8	17,7	5,3	11,5	15,3	3,6	9,4
GIC	14,0	2,2	8,1	13,3	2,7	8,0	17,6	5,2	11,4	15,0	3,4	9,2
LLE	9,9	0,6	5,5	13,7	0,8	7,3	18,4	4,5	11,5	14,0	2,1	**8,0**
MAN	11,0	1,0	6,0	13,4	1,5	7,5	17,7	4,5	11,1	14,0	2,0	**8,0**
TAU	14,0	3,2	8,6	14,9	3,8	9,4	18,0	5,4	11,7	15,6	4,1	**10,0**

Table 5.11: Mean values of maximum, minimum and mean temperatures and total rainfall for three months before the pollination season (January, February, and March) for the control year 2013.

	January				February				March			
	T.max	T.min	T.mean	Rain	T.max	T.min	T.mean	Rain	T.max	T.min	T.mean	Rain
BCN	13,2	5,0	9,1	34	12,2	4,0	8,1	25	18,0	8,2	13,0	143
BTU	13,0	3,1	8,0	22	12,0	2,1	7,0	28	16,1	8,1	12,1	111
GIC	14,1	-1,0	6,7	13	13,4	0,0	6,7	37	14,1	4,2	9,2	28
LLE	10,4	0,0	5,0	36	13,3	1,2	7,3	29	16,1	4,3	10,2	74
MAN	10,0	-1,1	4,5	33	11,0	-1,1	5,0	14	14,0	4,0	9,0	120
TAU	15,1	3,0	9,0	16	13,2	4,3	8,2	51	17,1	7,1	12,0	100

Table 5.12: Mean values of maximum, minimum and mean temperatures (ºC) and total rainfall (mm) averaged for the three months before the pollination season (January, February, and March) in 6 stations for the control year 2013.

	Average			
	T.max	T.min	T.mean	Rain
BCN	14,5	5,7	9,8	202
BTU	13,7	4,4	9,3	161
GIC	13,9	1,0	7,5	78
LLE	13,2	1,8	7,5	139
MAN	11,7	0,7	6,2	187
TAU	15,1	4,8	10,0	167

Table 5.13: Root mean squared error (RMSE) and systematic and random errors in the forecasting of SPS using the method of Summing Temperatures.

	Summing Temperatures																	
	Olea			*Pinus*			*Pistacia*			*Plantago*			*Platanus*			*Quercus* deciduous type		
	RMSE	System	Random	RMSE	System	Random	RMSE	System	Random	RMSE	System	Random	RMSE	System	Random	RMSE	System	Random
BCN	5,29	3,81	3,67	3,72	2,09	3,07	7,92	7,27	3,13	2,80	1,52	2,33	1,96	2,11	3,18	2,45	1,65	1,81
BTU	6,49	5,62	3,25	4,65	3,05	3,51	3,42	2,14	2,66	6,30	2,33	5,85	2,20	1,57	1,54	3,06	1,95	2,35
GIC	6,72	6,50	1,70	6,98	5,02	4,84	5,08	3,67	3,52	4,24	2,31	3,56	7,55	3,68	6,60	3,34	1,91	2,74
LLE	9,81	9,27	3,19	6,63	4,99	4,37	5,92	4,97	3,21	5,49	4,05	3,72	2,61	1,51	2,13	3,76	2,73	2,59
MAN	7,51	6,14	4,13	4,73	3,47	3,21	4,80	3,90	2,79	6,07	4,74	3,79	3,67	1,52	3,35	4,43	2,10	3,91
TAU	5,60	5,98	2,35	5,21	3,47	3,88	3,14	2,03	2,39	2,24	1,68	1,47	3,14	1,86	2,53	2,86	1,62	2,35

Table 5.14: Root mean squared error (RMSE) and systematic and random errors in the forecasting of SPS using the method of Multiple Regression.

	Multiple Regression																	
	Olea			*Pinus*			*Pistacia*			*Plantago*			*Platanus*			*Quercus* deciduous type		
	RMSE	System	Random	RMSE	System	Random	RMSE	System	Random	RMSE	System	Random	RMSE	System	Random	RMSE	System	Random
BCN	2,30	0,53	2,24	5,65	2,54	5,05	4,81	2,43	4,15	2,12	0,94	1,90	3,69	1,67	3,28	5,67	3,23	4,67
BTU	4,52	1,85	4,12	3,05	1,04	2,87	3,23	1,11	3,03	1,94	0,50	1,88	2,72	0,98	2,53	1,20	0,24	1,18
GIC	5,69	3,11	4,76	7,95	3,90	6,93	2,18	0,67	2,08	3,74	1,75	3,31	3,16	2,19	2,28	4,93	2,63	4,17
MAN	5,96	4,30	4,13	4,84	2,25	4,29	2,02	0,71	1,89	7,45	4,96	5,56	2,80	1,15	2,55	4,52	2,74	3,60
TAU	4,93	2,61	4,18	5,91	3,42	4,55	6,14	3,56	5,00	2,21	2,21	0,85	3,86	1,96	3,32	5,58	4,21	3,65

6. LONG-RANGE TRANSPORT

6.1. Introduction

6.2. Data and Methodology

6.2.1. Pollen data

6.2.2. Source-receptor model

6.2.3. *Betula* simultaneous peaks

6.3. Results and discussion

6.3.1. Source-receptor model

6.3.2. *Betula* simultaneous peaks

6.4. Conclusion

6.1. Introduction

The residence time of substances that, by natural or anthropogenic causes, are introduced into the atmosphere can be very variable, but it is generally long enough (more than one day) for them to be transported away from sources of emission and settle thousands of km away over land and/or oceans. Despite the complexity of the interactions among different scales, to make it simpler, we can distinguish between local transport (in which a significant portion of the substance will settle near the source, for example within a horizontal distance of a few hundred kilometres) and long-range transport (LRT, thousands of km). The first one occurs in the boundary layer under the prevailing influence of local circulations, such as breezes and topographic features. LRT occurs in the free troposphere and is managed by global circulation patterns and synoptic scale systems. Airborne pollen is a biological material that is liable to be transported long distances and whose areas of origin could be interesting to explore.

The size of pollen grains varies from 5 to 200 microns in diameter (Nilsson and Praglowski, 1992) and is, therefore, about 5 to 50 times higher (in linear dimensions) than the particle size of the conventional atmospheric aerosol. However, in despite the much larger size, the grains of many pollen types (anemophile pollen) have a similar behaviour in its atmospheric dispersion than the anthropogenic PM10 (particulate matter with diameter less than 10 μm). This similarity is due to the aerodynamic shape and low density of pollen, which drastically reduces its gravitational deposition and makes it more susceptible to the atmospheric transport (Sofiev et al., 2006). The LRT of pollen is essentially episodic, which means that an inverse mode treatment can be applied, that is, from the sampling site backwards in time, to define the possible source regions responsible for each episode, or through the application of source-receptor models to delimit the most probable source areas for each given pollen type. Recently, some authors have used back-trajectories and transport models to explain the movement of the pollen at a large scale (Belmonte *et al*., 2000, 2008a, 2008b; Izquierdo *et al*., 2015b; Sofiev *et al.*, 2006; Skjoth *et al.*, 2007; Siljamo *et al*., 2008; García Mozo *et al*. 2017).

Source-receptor models allow the establishment of relationships between a receptor point (sampling point) and the probable source areas (regions of emission) through the association of concentration values at the receptor point with the corresponding atmospheric back-trajectories, and, together with other techniques, to interpret transport phenomena on a synoptic scale. These models are generally used in air pollution studies to determine the areas of origin of mineral dust (Bonasoni *et al*., 2004), ozone (Seibert *et al*., 1994), acidifying components (Stohl, 1996) and other pollutants (Charron *et al*., 1998) measured at a sampling point, and thus be able to target actions to reduce emissions. However, few studies have applied these models to describe the source areas of biological organisms that may be injected at high altitudes (>1000 m) and be transported to long distances (Chapman *et al*., 2002; Kellogg and Griffin, 2006) by the same mechanisms that move gases and chemical particles. However, it is possible to treat the behaviour in the atmosphere of biological material with the same methods as those used with chemical compounds.

On the other hand, birch (*Betula*) pollen is one of the important causes of respiratory allergy in Northern and Central Europe. In Catalonia, the allergy to birch is not frequent, with the exception of the northern mountain areas, but it is occurring and the intensity of the derived health problems can be increased by LRT outbreaks. Birch trees are abundant in Central, North and East of Europe, but are scarce in the Mediterranean territories, especially in Spain were they only grow in the northern regions under certain environmental conditions of height. The airborne birch pollen patterns in Catalonia show abrupt high concentrations in areas with usually low local influence (Izquierdo *et al.*, 2017).

In previous works, France and Central Europe have been established as potential source areas of *Betula* pollen that arrives to NE Iberian Peninsula (IP). Moreover, the effect of the orographic barrier of the Pyrenees has also been evaluated in the *Betula* pollen LRT (Izquierdo *et al*., 2017). But up to now, the differentiated potential contribution of the two main sources, Pyrenees and Central Europe, to the LRT over Catalonia has not been evaluated. The use of modelling is a good tool to study and understand the atmospheric mechanisms that cause *Betula* pollen peaks. To this end, we have studied the provenance of the air masses leading to main pollen peaks produced simultaneously in, at least 4 of the 6 monitoring stations considered. For the dates of the peaks, the individual back-trajectories have been computed to characterize the direction of the flow associated to the peaks.

This chapter presents the results of the use of the source-receptor model of Seibert *et al*. (1994) applied to the study of the source areas of pollen that arrive to the Northeast of the IP transported by the wind. Specifically, this work presents the results of applying the model to estimate the source areas of six pollen taxa that are susceptible to reach Catalonia from distant regions: *Ambrosia, Betula*, *Corylus*, *Fagus*, *Fraxinus*, and *Olea*. Apart from the great scientific interest that lies in the modelling of the source areas to understand the life cycles of the species, the use of these models has utility to botanists, allergists, and environmental quality managers in the study and treatment of problems such as respiratory allergies.

The main objective of the second part of this chapter is to differentiate the *Betula* pollen transport from Pyrenees and from Central Europe. It will be done by means of: i) to isolate the simultaneous peaks, based on the 95th percentile, produced in at least 4 of the 6 aerobiological stations; ii) to determine the provenance region of the associated air-masses based on the back-trajectories; iii) to classify the peaks in two groups depending on its simultaneity with peaks in the Vielha Pyrenees

Station; iv) to quantify the potential contribution of the regional pollen transport from Pyrenees and the LRT from France and Central Europe to the total *Betula* pollen collected at the Catalan stations.

6.2. Data and Methodology

6.2.1. Pollen data

We have focused on those pollen types that are not abundant in the territory but present an episodically behaviour with high punctual values of concentration: *Ambrosia, Betula*, *Corylus*, *Fagus*, *Fraxinus* and *Olea*. The geographical distribution of these taxa corresponds predominantly to Central and Northern Europe, with the exception of *Olea*, abundant in southern IP and Northern Africa.

Betula trees are abundant in central, Northern and Eastern Europe, but are scarce in the Mediterranean territories, especially in Spain, where the northern regions constitute the southern border of the distribution area (de Bolòs and Vigo, 2005). *Betula* airborne pollen has been selected here to study its LRT over Catalonia because its episodic outbreaks introduce large amounts of highly allergenic pollen during the birch pollen season in Northern Europe and Pyrenees. *Betula* pollen is distributed by wind and impacts human health by causing seasonal hay fever, pollen-related asthma, and other allergic diseases, being one of the most important causes of respiratory allergy in North and Central Europe (Emberlin *et al*., 1993, 1997).

Ambrosia (ragweed) is another of the taxa chosen to understand the airborne pollen pattern and provenance, in order to contribute to a better management of it and prevent the expansion of a possible new bioinvader that can also become a health problem due to its highly allergenic pollen. The Annual Pollen Integral appear to be clearly influenced by the pollen concentrations in the peak dates, and these are linked to LRT from regions where *Ambrosia* is widely widespread, such as eastern France, Northern Italy and Hungary and Serbia. The episodes of pollen transport are increasing in number in the recent years. Although airborne *Ambrosia* pollen type is not showing any clear increasing trend, local populations of the plant could be having an influence on the pollen records, since the genus is clearly expanding in the territory at considerably high spread rates. *Ambrosia* populations have to be surveyed both for public health reasons and as a new bioinvader (Fernández-Llamazares *et al*., 2012).

Corylus is a genus of bushes sometimes considered small trees from the Betulaceae family represented in the study area by the only species *C. avellana*. They are plants growing in fresh deciduous forests with wet soil conditions, up to 1900 masl (de Bolòs & Vigo, 2005; Rocha Afonso, 1990). They are appreciated by their fruits (the hazelnuts) and this makes them to be cultivated. In

Catalonia, hazels are abundantly grown in the province of Tarragona and with a lesser extent in the vicinity of the city of Girona. *Corylus* pollen is one of the 12 most important aeroallergens in Europe, where the genus is represented by three species. The genus is abundant in Europe, and pollen concentrations considerably high are found in Central Europe, especially in the Alpine region in France, Switzerland and Austria (Skojth et al 2013). Cor a 1, the major allergen from *Corylus* is cross reactive with Bet v 1, from *Betula* (de Weger et al, 2013).

Fagus is a tree that is widespread in Central Europe but much more local in Catalonia and the IP, where it requires rainfall above 1000 mm year^{-1} (Terradas, 1984) and it is found in cool and humid valleys and slopes, usually between 500 (exceptionally 300) and 2000 m above sea level (de Bolòs and Vigo, 2005). However, the simultaneous presence of *Fagus* pollen (although often sporadically) has been observed at several of the aerobiological stations studied in Catalonia. The aim of this work is to locate the regions of origin of the pollen of this tree, typically Pyrenees, France and Central European, reaching the aerobiological stations in Catalonia.

Fraxinus is a genus of trees from the Oleaceae family represented in the study area by two species: F. angustifolia and F. excelsior. They are plants growing in deciduous forests with wet soil conditions and/or close to rivers and banksides, the first one in the lowlands, up to 1000 masl, and the second one in heights up to 1800 m a.s.l. (de Bolòs and Vigo, 2005, Andrés, 2012). In some occasions, they are used in the cities as ornamental plants (Belmonte J, personal communication). In central Europe the genus is very abundant and pollen concentrations are considerably high (de Weger *et a*l, 2013). *Fraxinus* pollen is allergenic, and its major allergen is a homolog of the *Olea* major allergen (de Weger *et al*, 2013).

Olea is one of the most abundant airborne pollen types in southern Europe and one of the most important causes of respiratory allergies in the Mediterranean areas. The olive tree is extensively cultivated in the Mediterranean Basin for the collection of its fruit and conversion into oil. Previous works describe African intrusion episodes as potential contributors to *Olea* pollen levels in two different cities of southern Spain (García-Mozo *et al*., 2017) in spite of its high local presence. Izquierdo *et al*. 2011 detected *Olea* pollen in the atmosphere of Tenerife (Canary Islands) coming from South Spain.

6.2.2. Source-receptor model

The identification of the probable sources of atmospheric pollutants is very frequently resolved with the use of Trajectory Statistical analysis Methods (TSMs). Several studies (Wotawa and Kröger, 1999; Stohl, 1996; Begum *et al*. 2005; Schefinger and Kaiser, 2007) have concluded that TSMs are computationally fast procedures that deliver first hints on potential source areas. Between TSMs, involving air pollution data, the Seibert's methodology based on concentration fields

(Seibert *et a*l. 1994) is one of the most used in the transport interpretation of inert air pollutants. For example, Apadula *et al*. (2003) used these approaches to the localization of source and sinks of carbon dioxide in high mountain areas in Europe; Hoh and Hites (2004) to pesticides in USA; Salvador *et al*. (2004) to the PM10 in Spain, and Xie and Berkowitz (2007) to hydrocarbons in Texas.

Between TSMs, source-receptor methodologies (SRM) are one of the most used. SRM are statistical approximations that combine concentration data from a sampling site with the coordinates of the points crossed by the atmospheric trajectories that arrive to the sampling site. This procedure makes it possible to establish connections between the receptor point and possible source areas. To do this, the 12-hourly (00 and 12 UTC) back-trajectories for a given altitude during the period corresponding to the sampling time must be calculated previously. Back-trajectories are then associated to a concentration value of the element of interest in the receptor site. To the domain of integration of the trajectories, has been superimposed a grid on which a set of cells with spatial resolution 1º x 1º latitude and longitude is defined. There are different methodologies to determine the probable source areas. In this work the method of Seibert (Seibert *et al*., 1994), has been used, which calculates a logarithmic average concentration for each cell on the basis of the residence time of the trajectories in the different cells:

$$logC_{i,j} = \frac{\sum_l n_{ijl} logC_l}{\sum_l n_{ijl}}$$

where $C_{i,j}$ is the concentration in the cell (i,j), l is the index of the trajectory, C_l is the concentration in the receiving site corresponding to the trajectory l and n_{ijl} is the number of time steps of the l trajectory in the cell (i,j).

In this work two trajectories by day (00 and 12 UTC) have been calculated using a time step of 60 minutes, with the model HYSPLIT - 4 (Hybrid Single-Particle Lagrangian Integrated Trajectory Model; Draxler, 2011) of NOAA (National Oceanic and Atmospheric Administration) at 1500 meters above sea level (m a.s.l.) from the GDAS meteorological data of the U.S. National Climate Data Center. The altitude of 1500 m, which roughly corresponds to the standard pressure level of 850 hPa, has been selected because it is the most representative in the lower troposphere, as it is at the border between the surface winds regime and those of the free troposphere. To minimize the uncertainty of the trajectories a smoothing method has been applied, so that the value of each cell has been replaced by the average value between the cell and the eight surrounding cells. Finally, a filter to exclude cells with less than 30 trajectory segments (time steps) has been applied. The concentration map obtained reflects the contribution of each cell to the concentration in the receiving point. The sampled periods in which the model has been applied are long enough to be statistically representative.

Average relative horizontal position errors for three-dimensional trajectories were estimated to be less than 20% for travel times longer than 24 h in the free troposphere. Upper bounds for average absolute horizontal and vertical errors after 120 h travel time were 400 km and 1,300 m, respectively (Stohl and Seibert, 1998).

The source-receptor model has been applied to the pollen data record of the aerobiological stations of Barcelona (BCN), Bellaterra (BTU) and Lleida (LLE) during the 10-year period 2005 - 2015 using the Main Pollination Season (MPS) of each taxon. As has been already defined in previous chapters, the MPS corresponds to the period which begins on the date (Start) when the sum of the mean daily pollen concentrations reaches 2.5% of the Annual Pollen Integral (APIn or annual sum) and ends (End) on the date when the sum reaches 97.5%. As the period of the MPS varies slightly from one to another year, a mean value for the Start and End has been used here for each taxon.

6.2.3. *Betula* simultaneous peaks

Daily *Betula* pollen concentrations recorded at the 6 Catalan stations: Barcelona (BCN), Bellaterra (BTU), Girona (GIC), Lleida (LLE), Manresa (MAN) and Tarragona (TAU) during the birch flowering season for the 10-year period 2005-2014 has been featured in this study. On the other hand, daily pollen concentrations recorded at the Vielha (VIE) aerobiological station (in the Pyrenees, 42°42′N 0°47′E, 980 m a.s.l. and oriented to the north; see Figure 6.1) during the same period have also been used. The data of VIE have been used to characterize the transport of *Betula* pollen that arrives to the Catalan stations, and to try to quantify the potential contribution of the *Betula* pollen transported from the Pyrenees and from central and Northern Europe to the Catalan stations.

A threshold value is used to select *Betula* pollen peaks: daily pollen concentrations higher than 95th percentile of each year. The hypothesis that we propose here is that differences between pollen dynamics in VIE and the other six stations could be related to different atmospheric transport patterns. Therefore, *Betula* pollen simultaneous peaks were sorted into two groups in order to identify the different atmospheric transport patterns: (1) simultaneous pollen peaks at the six sampling stations and non-simultaneous with VIE peaks; (2) simultaneous pollen peaks observed at the six stations and simultaneous with a VIE peak.

Four back-trajectories (18, 12, 06, 00 UTC) 48-h length at 1500 m a.s.l. by day, have been computed for each day of the simultaneous peaks. The trajectories have been computed arriving GIC, the aerobiological station which presents the highest values of *Betula*. We have considered that the peaks are simultaneous when are registered, at least, in 4 of the 6 aerobiological stations. Absence of precipitation (daily precipitation less than 1 mm) in the days of the peaks has been previously checked. The peaks have been then categorised as simultaneous and non-simultaneous with VIE. Based on this we have made a first estimation of the amounts that annually contribute the Pyrenees region (regional transport) and France and central Europe (LRT) to the *Betula* pollen collected in Catalonia. The discussion is completed analysing if the date of the maximum annual VIE pollen value is previous, coincident, or subsequent to each one of the pollen peaks.

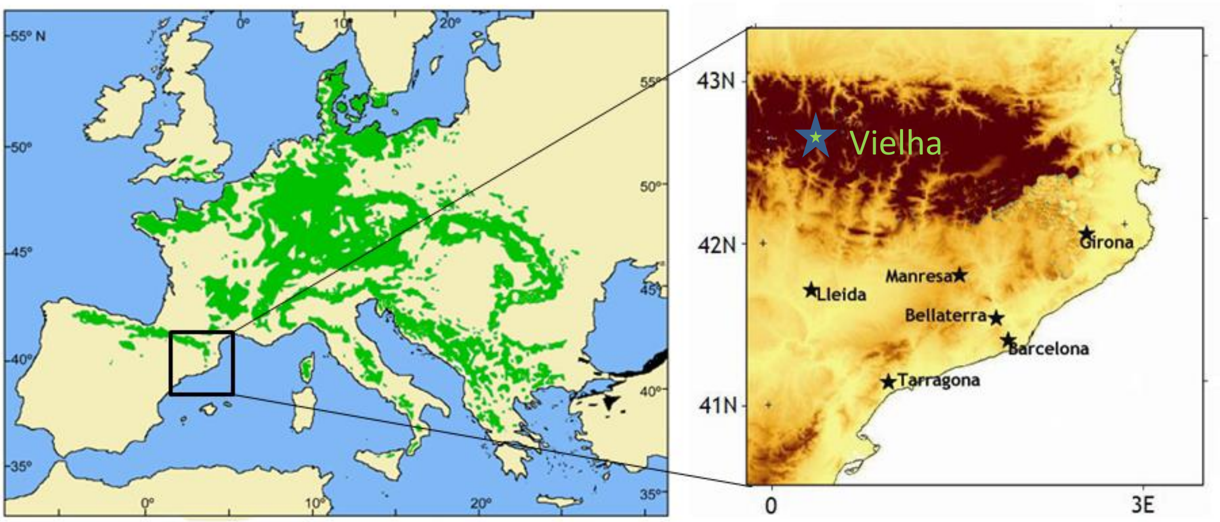


Figure 6.1: Location of the 6 aerobiological stations and Vielha

6.3. Results and discussion

6.3.1. Source-receptor model

The application of the source-receptor model to the 10-year period 2005-2014 showed that the probable source regions for the pollen arrivals of *Betula, Fraxinus* and *Fagus* to the Catalan stations are located in central and southern France, and the Pyrenees (Figures 6.2). These regions are covered by extensive forests of these three species. For *Betula* pollen, no important differences are found between the three stations, being BCN and BTU more similar between them, due to their proximity. For *Fraxinus*, the similarities are maintained between BCN and BTU, while LLE do not show any relevant source-region. A previous study (Belmonte *et a*l., 2008b) for a very important episode with high values of *Fagus* during the period from 15 to 19 May 2004, showed that, both for the back-trajectories and the pollen hourly data, the *Fagus* pollen came from Central Europe in all the stations studied in Catalonia (the stations analysed in this episode were BCN, BTU, LLE, TAU, MAN, GIR and Vielha). This fact demonstrated the existence of extra-regional influence in the dynamics of the pollen sampled in Catalonia.

The source regions for *Ambrosia* seem to be in the IP (Figures 6.2). This is not in accordance with a previous study from Fenández-Llamazares *et al*. (2012) who analysed the provenance of 64 peaks corresponding to the period 1997-2009 by computing back-trajectories and the application of a SRM. They obtained predominantly north eastern (41%) and northern (36%) provenance, from the Lyon region, in France, and Hungary-Serbia. This disagreement could be due to the more recent dates of the period analysed in our work and the fact that *Ambrosia* is highly widespread in each of the mentioned regions and could be that its geographical distribution region has moved to more southern areas. Another argument to take into account is the low values registered in the Catalan stations in our analysed period. The highest value is 4.9 pollen/m^3, registered in the LLE station.

Regarding the pollen of *Olea*, the source regions for BCN and BTU are different from those obtained for LLE, in which the southern areas appear more prominent. Olive crops are mainly located in southern Spain and Northern Africa. In Catalonia, there is also a local influence, but due to the proximity, its transport from southern Spain and Northern Africa is probably the main responsible of the detected peaks.

As we pointed out in Chapter 4, *Corylus* is one of the taxa that showed to be influenced in its long-range and regional transport by the atmospheric modes of the Northern Hemisphere teleconnection patterns. However, must be taken into account that among the six taxa we selected in this chapter, *Corylus* is the one in which its tree has a greater presence close to the sampling stations. The SRM locates the major sources in France for BCN, Northwestern France for BTU and eastern Pyrenees, North and West of the IP and South and Center of France for LLE, although always the regional and local sources are also present. This result is in agreement with the increase in LRT of *Corylus* and *Fagus* from western and central Europe, detected in Chapter 4, during the negative phase of annual NAO and AO. In the same way, agrees with the transport from Mediterranean regions of *Corylus* and *Fagus* and the regional transport of *Corylus* from western IP, linked to the positive phases of NAO, AO and WeMO.

6.3.2. *Betula* simultaneous peaks

The number of simultaneous peaks at the Catalan stations (concentrations >95th percentile in at least 4 of the stations) obtained in the 10-year period is 28. The corresponding dates are shown in Table 6.1, in which it is also described the regions crossed by the back-trajectories, as well as the simultaneity or not with a peak in the VIE station. In Table 6.1 are grouped the episodes coincident with a peak in VIE (SV) and those non coincident (NV). Back trajectories show that in all the cases the main flow is from the north (Figures 6.3 and 6.4). When the provenance region is Pyrenees, an estimate of the residence time of the back-trajectories in the region has been done based on the number of 6-h time steps over Pyrenees.

In 13 of the 28 cases there is simultaneity with the VIE station (SV). In general, with two exceptions, the back-trajectories show that when there is SV, the residence time of the back-trajectories in the Pyrenees region is high, and it corresponds to slow flow with long travel along the Pyrenees region, from west to east. When we analyse the date of the most important annual peak in VIE, that we attribute to the local flowering, we observe that in 10 of the 13 cases there was coincidence with the local VIE flowering (last column, Table 6.1). In these 10 detected cases, the back-trajectories showed a long residence time (between 12 and 48 hours) in Pyrenees region. The other three cases corresponded to peaks in which, for one of them, the pollination VIE peak was previous, and two for which the pollination VIE peak was later.

In reference to the 15 cases of non-simultaneity with VIE (NV), in none of them there was any coincidence with the pollination peak in the VIE station. In 10 of the cases the pollination in VIE was previous to the dates of the peak and in 5 of the cases it was later. In these 5 cases in which the pollination in Pyrenees was produced later, the back trajectories showed a quick passage through the Pyrenees, with the exception of 12/04/2014 in which the back-trajectories came from Pyrenees but also from the North of the IP. Therefore, it could be considered that in these 5 cases, the *Betula* accounted in the Catalan stations corresponded to LRT from France and Central Europe. In the 10 cases in which the pollination in Pyrenees was previous to the peaks, the back-trajectories show a residence time in Pyrenees shorter than in the cases of simultaneity with VIE, between 0 and 18 hours (with 2 exceptions), thus with a lower Pyrenees load in the air-masses. Thereupon, in these 10 cases, the main transport can be also considered from France and central Europe, but probably with some mixture of pollen coming from Pyrenees.

For the above, we consider those episodes having simultaneity with VIE (SV) as regional transport from Pyrenees and those being non-simultaneous with VIE as long-range transport (LRT) form. Table 6.2 shows the pollen concentrations (pollen/m^3) corresponding to the peaks for each station. Because the criterion was simultaneity in at least four of the six stations, the asterisk indicates those values lower than the 95th percentile. The sum of the amounts, separately for VS and NV, has been done for each station in the 10-year period and the percentage related to the total amounts are also specified. From this, it follows that the station that received the largest amount of *Betula* coming from distant sources (sum of amounts of SV and NV) is TAU with 52%, followed by BCN (44%) and BTU (40%) and the one that received the least amount is LLE (30%). This is consistent with the fact that TAU, BCN and BTU are the stations with the lowest local *Betula* contribution due to the lower presence of the tree in their territory. On the other hand, the difference between the percentage contribution of the regional transport (SV) and LRT (NV) in these stations is the highest (20% for TAU, 15% for BTU and 13% for BCN), being higher NV, indicating this that the LRT from European sources have a major influence. On the contrary, LLE and GIC showed the lowest differences probably because they are the closest stations to the Pyrenees. It is also remarkable to note that LLE is the only station in which the Pyrenees influence was greater than the LRT.

Our results represent that, for the total period and the six stations, near 40% of the collected pollen corresponded to foreign transport. From this, about 15% corresponded to regional transport from Pyrenees and 25 % to LRT, mainly from France and Central Europe.

On the other hand, if we consider the contribution of the complete outbreaks to the pollen collected in the aerobiological stations, the episodes of foreign transport should contemplate also the pollen of the 24 hours before and after the peak dates. Then, considering these amounts, the contribution of the LRT outbreaks represents 58% of the total pollen collected at the Catalan stations in the 10-year period. From this percentage, 38% corresponds to NV and attributed to transport from France and Central Europe, and 20% to SV attributed to regional transport from Pyrenees.

Table 6.1: Dates of the simultaneous peaks in, at least, 4 of the stations. The column Provenance describes the regions crossed by the back trajectories and the estimated residence time in Pyrenees. There is also indicated if there was simultaneity with a pollen peak in VIE and if the pollination in VIE was previous, coincident or later to the dates of the simultaneous peaks.

Date	Provenance (back-traj)	VIE simultaneity	VIE pollination
13/04/2005	Pyrenees (12 h), Central France, Germany	no	later
26/04/2006	Pyrenees (24 h), S and SW France	no	previous
27/04/2006	Pyrenees (6 h), Central and W France, Atlantic	no	previous
15/04/2007	Italy; Greece, Med	no	later
18/04/2007	E and SE France	no	later
19/04/2007	Pyrenees (12 h), Central and N France	no	later
02/05/2009	E France, Switzerland, Germany	no	previous
05/05/2009	N France, England	no	previous
27/04/2011	Pyrenees (6 h), Central France, Central and N Germany	no	previous
12/05/2012	Pyrenees (18 h), S France, Central IP	no	previous
13/05/2012	Pyrenees (18 h), S and SW France, IP, Portugal	no	previous
14/05/2012	Pyrenees (18 h), S SW and Central France	no	previous
06/05/2013	Pyrenees (18 h), S SW and Central France	no	previous
12/04/2014	Pyrenees (24 h), S France, N IP	no	later
18/04/2014	Pyrenees (42 h), S and Central France, Germany	no	previous

Date	Provenance (back-traj)	VIE simultaneity	VIE pollination
18/04/2005	Pyrenees (12 h), Cantabria, Galicia, S France	yes	later
22/04/2005	Pyrenees (24 h) , Cantabria, Galicia	yes	later
25/04/2008	Pyrenees (18 h), S and SW France, Atlantic	yes	coincident
26/04/2008	Pyrenees (18 h), S, SW and W France, Atlantic	yes	coincident
27/04/2008	Pyrenees (48 h), Med	yes	coincident
24/04/2009	Pyrenees (48 h), S and W France)	yes	coincident
26/04/2010	Pyrenees (36 h), S and SW France, Atlantic	yes	coincident
27/04/2010	Pyrenees (12 h), S and SW France, Atlantic	yes	coincident
28/04/2010	Pyrenees (18 h), Central France	yes	coincident
29/04/2010	Pyrenees (36 h), S and Central France	yes	coincident
09/04/2011	Pyrenees (36 h), S and SW France	yes	coincident
24/04/2013	Med, N Italy	yes	previous
16/04/2014	Atlantic from Greenland	yes	coincident

Table 6.2: Daily concentrations (pollen/m^3) at the six stations corresponding to the simultaneous peaks (in asterisk, the values less than the 95th percentile). The total amounts and the percentage with respect to the total sum for the 10-year period are also indicated. Blanks are missing data.

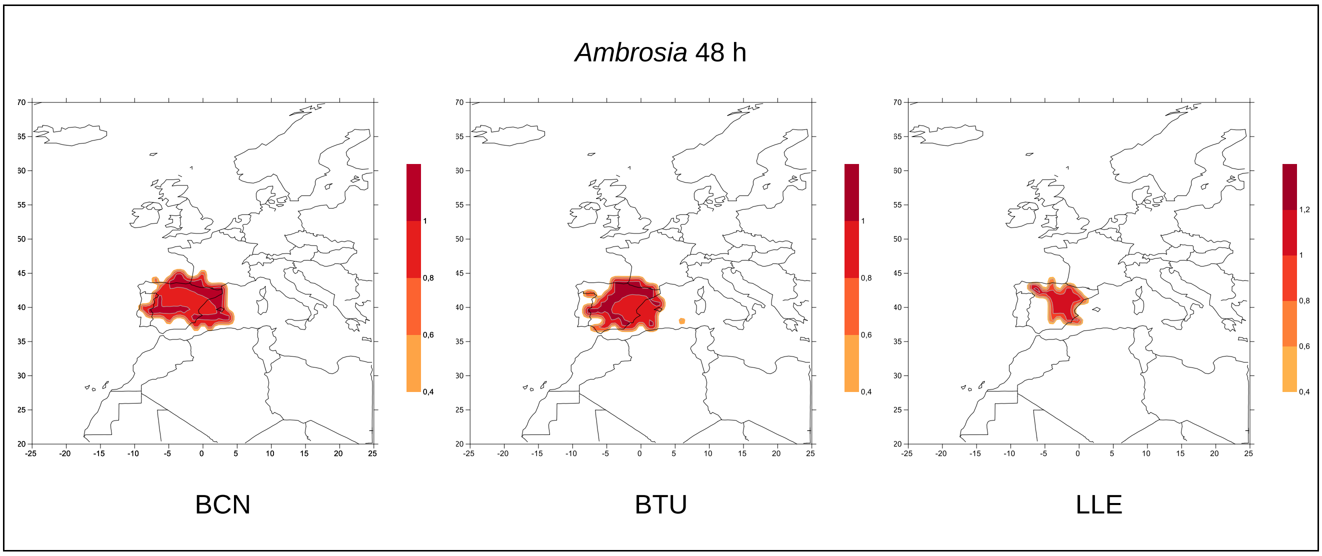
VIE non-simultaneity	BCN	BTU	LLE	GIC	MAN	TAU
13/04/2005	39,2	17,5	11,2	99,4	15,4	27,3
26/04/2006	60,9	34,3	20,3	20,3	52,5	39,9
27/04/2006	23,1	41,3	7	20,3	32,9	44,1
15/04/2007	19,6	74,2	0*	109,9	81,2	53,2
18/04/2007	42,7	16,8	3,5	38,5	1,4*	79,8
19/04/2007	165,2	77,7	8,4	93,1	1,4*	158,2
02/05/2009	17,5	9,1	2,8	23,8	6,3*	26,6
05/05/2009	18,9	9,1	0,7*	6,3*	12,6	22,4
27/04/2011	6,3*	4,2	2,8	1,4*	3,5	5,6
12/05/2012	12,6	14,7	0,7*	9,1	4,9	0*
13/05/2012	5,6	4,2	3,5		4,9	4,2
14/05/2012	10,5	2,1*	3,5	2,1*	4,9	7
06/05/2013	11,2	11,9	9,8	48,3	9,1*	
12/04/2014	54,6	39,2	3,5	81,2	4,9*	31,5
18/04/2014	10,5	21,7	8,4	55,3	25,2	2,8*
Total	**498,4**	**378**	**86,1**	**609,01**	**261,1**	**502,61**
Percentage (%)	**28,4**	**27,6**	**13,5**	**19,2**	**24,8**	**36,1**

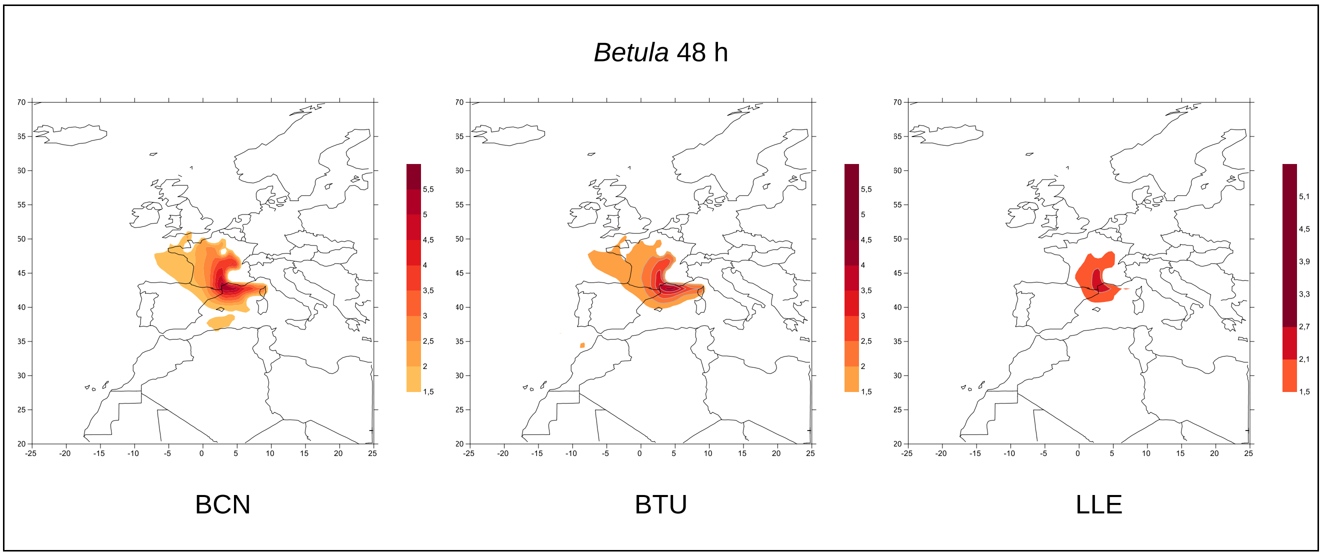
VIE simultaneity	BCN	BTU	LLE	GIC	MAN	TAU
18/04/2005	10,5	3,5	0,7*	9,8	0*	2,8*
22/04/2005	22,4	9,8	0*	23,8	9,8	0*
25/04/2008	8,4	9,8	0*	37,1	3,5	2,1
26/04/2008	11,9	21	0*	33,6	11,2	7
27/04/2008	7,7	4,9	0*	10,5*	6,3	4,2
24/04/2009	65,1	41,3	7	32,2	12,6	64,4
26/04/2010	14	4,9*	4,9*	41,3	10,5	13,3
27/04/2010	34,3	14,7	16,8	80,5	18,2	39,9
28/04/2010	25,2	14	42	63,7	30,1	30,1
29/04/2010	21	6,3	14,7	22,4	11,2	24,5
09/04/2011	9,8	24,5	4,2	14,7	0*	0,7*
24/04/2013	25,9	3,5*	9,8	19,6*	21,7	9,1
16/04/2014	12,6	14,7*	6,3	48,3*	17,5	16,8
Total	**268,8**	**172,9**	**106,4**	**437,5**	**152,6**	**214,9**
Percentage (%)	**15,4**	**12,6**	**16,9**	**13,8**	**14,4**	**15,6**

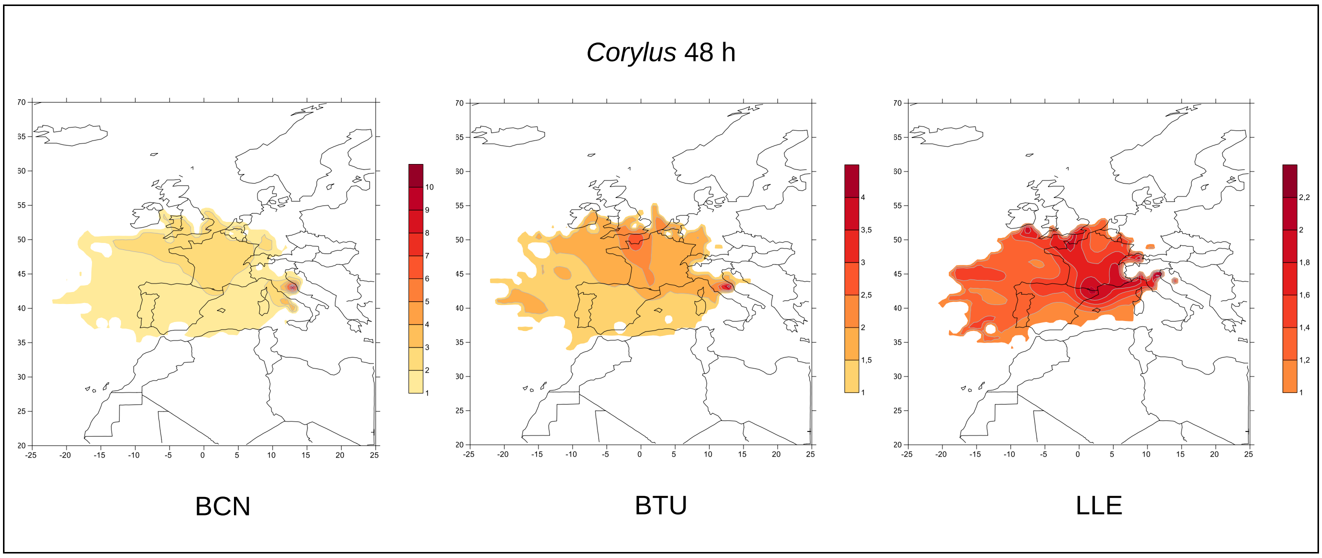
6.4. Conclusions

A source-receptor model has been applied to determine the potential source regions of six pollen types that, not being very abundant in the territory, episodically present high values and hence are susceptible to come from distant sources: *Ambrosia, Betula*, *Corylus*, *Fagus*, *Fraxinus*, and *Olea.* Using meteorological and aerobiological data obtained for a period of 10 years for tree stations (BCN, BTU and LLE), and taking into account forests distribution, the study points as probable source regions for the pollen arrivals of *Betula, Fraxinus* and *Fagus* central and southern France, and the Pyrenees. The source regions for *Ambrosia* seem to be in the IP, which would mean that probably its geographical distribution has moved to more southern areas due to the highly widespread character of this taxon. The results for *Corylus* show that there is a great local influence. The source regions for *Olea* are situated in southern IP and Northern Africa, although this result is only clear for LLE.

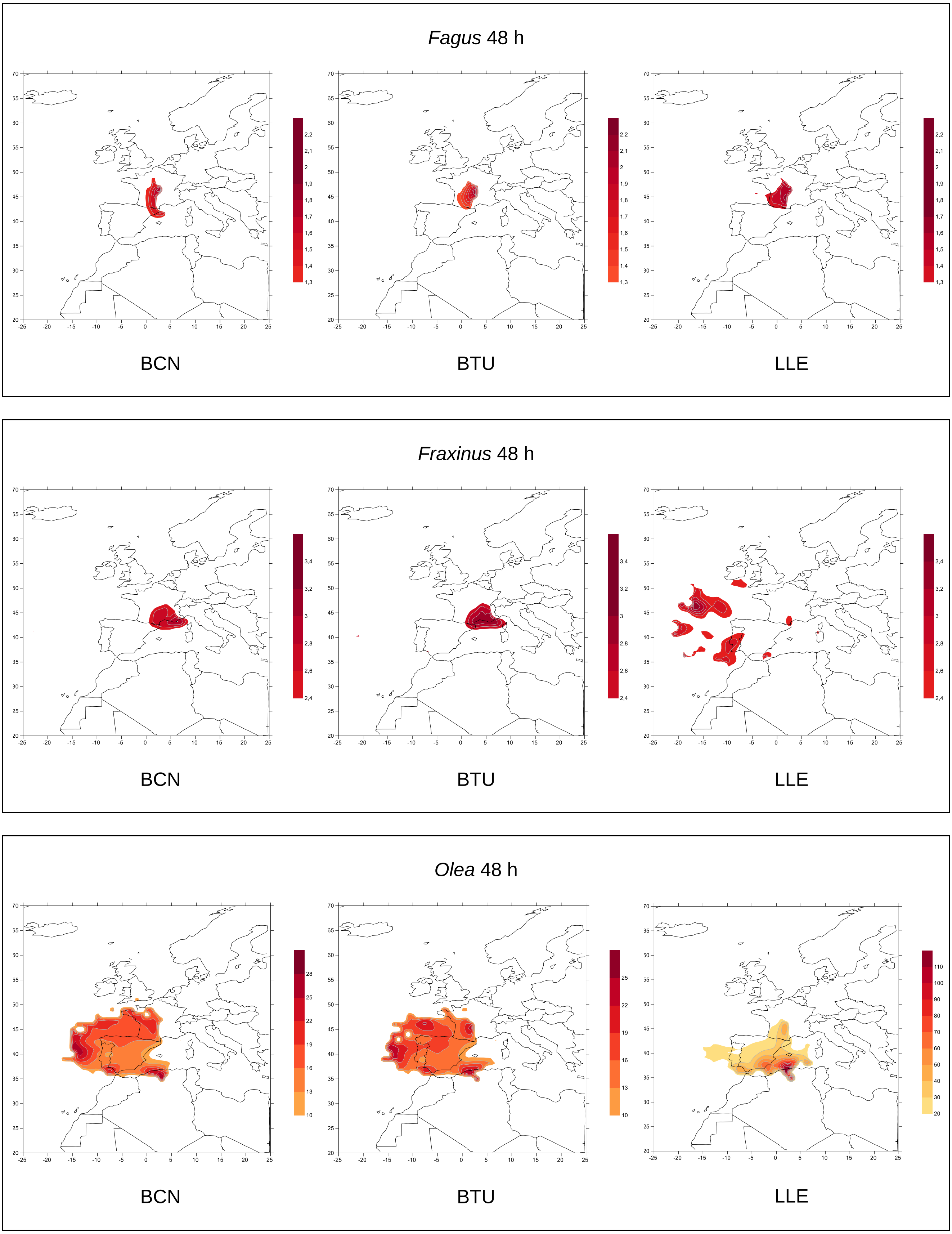
The atmospheric transport for *Betula* pollen has been studied in order to assess the contribution due to arrivals from distant sources. Further, to differentiate between the arrivals of foreign regional pollen from that coming from France and Central Europe, the provenance of the air masses leading to pollen peaks of have been also analysed. For the dates of the peaks, the individual back-trajectories have been computed to characterize the direction of the flow associated to the peaks. A classification in two groups depending on its simultaneity with peaks in the Vielha Pyrenees Station has been made. This has allowed quantifying the potential contribution of the regional pollen transport from Pyrenees and the LRT from France and Central Europe to the total *Betula* pollen collected at the Catalan stations. For the total period and the six stations, near 40% of the collected pollen corresponded to foreign transport. From this, about 15% corresponded to regional transport from Pyrenees and 25 % to LRT, mainly from France and Central Europe. Considering the contribution of the complete outbreaks and not only the peak days, these contributions arise to 58%, with a 38% corresponding to transport from France and Central Europe, and 20% to regional transport from Pyrenees.



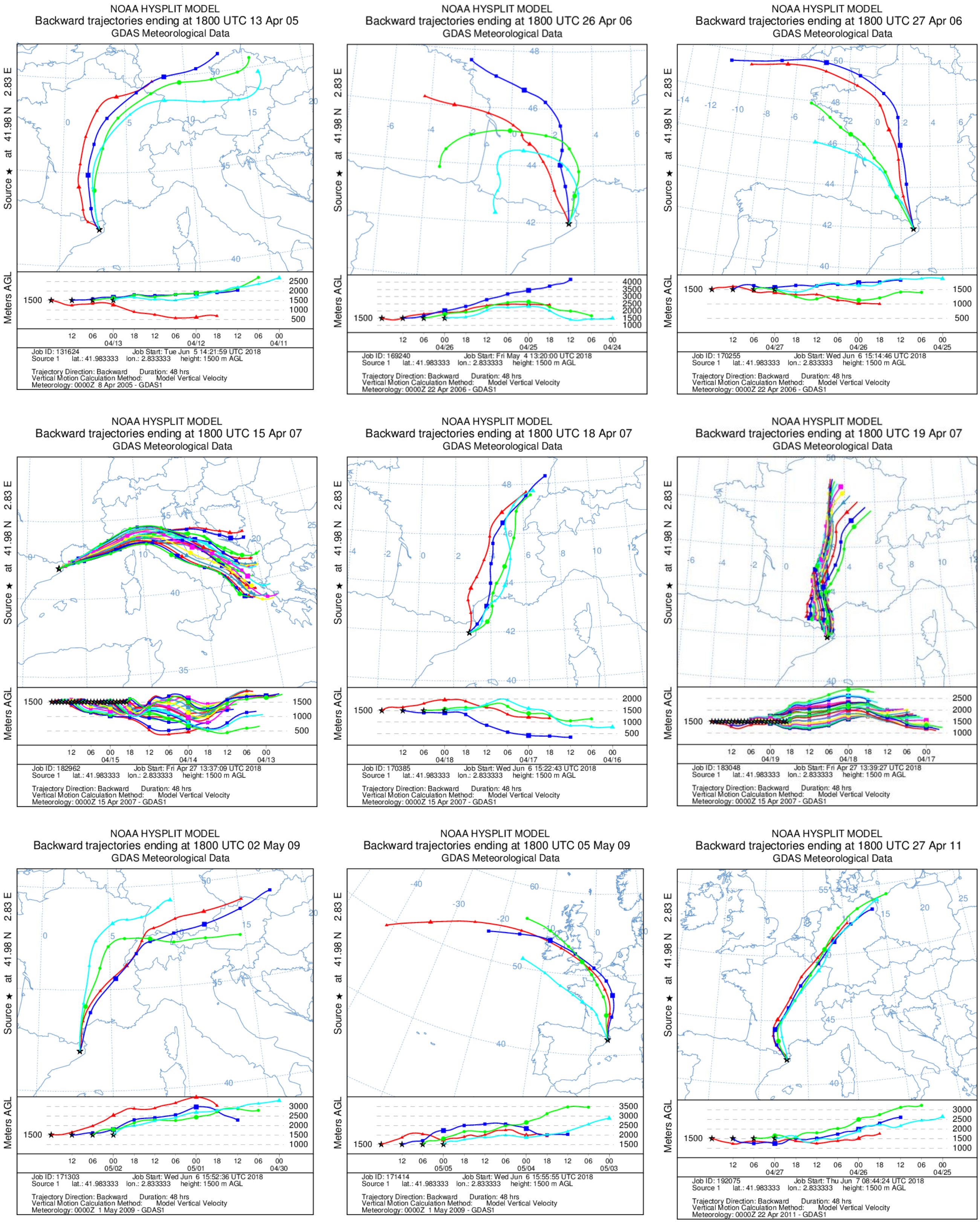




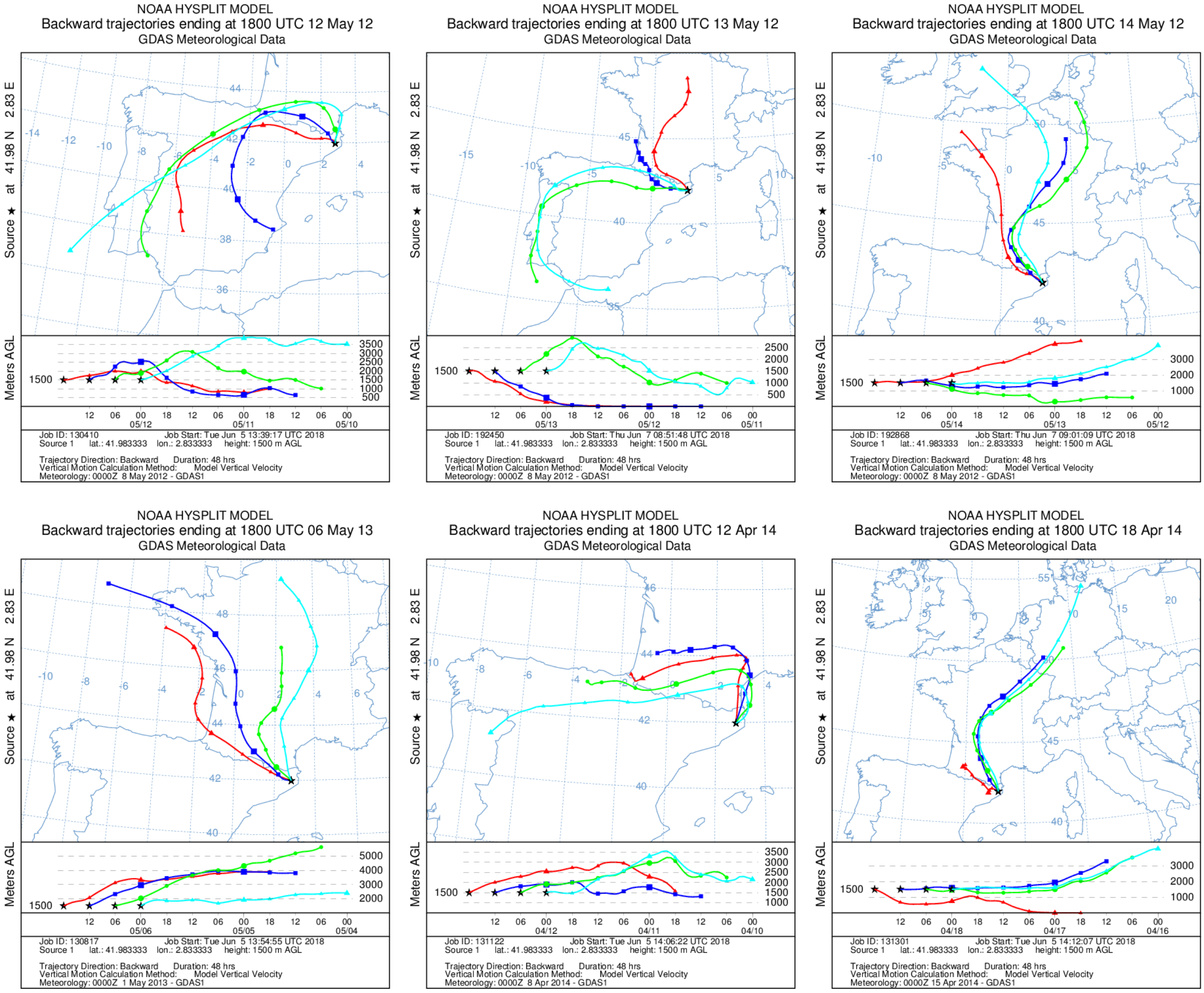
Figures 6.2: Source regions. Concentration fields for *Ambrosia, Betula and Corylus*.



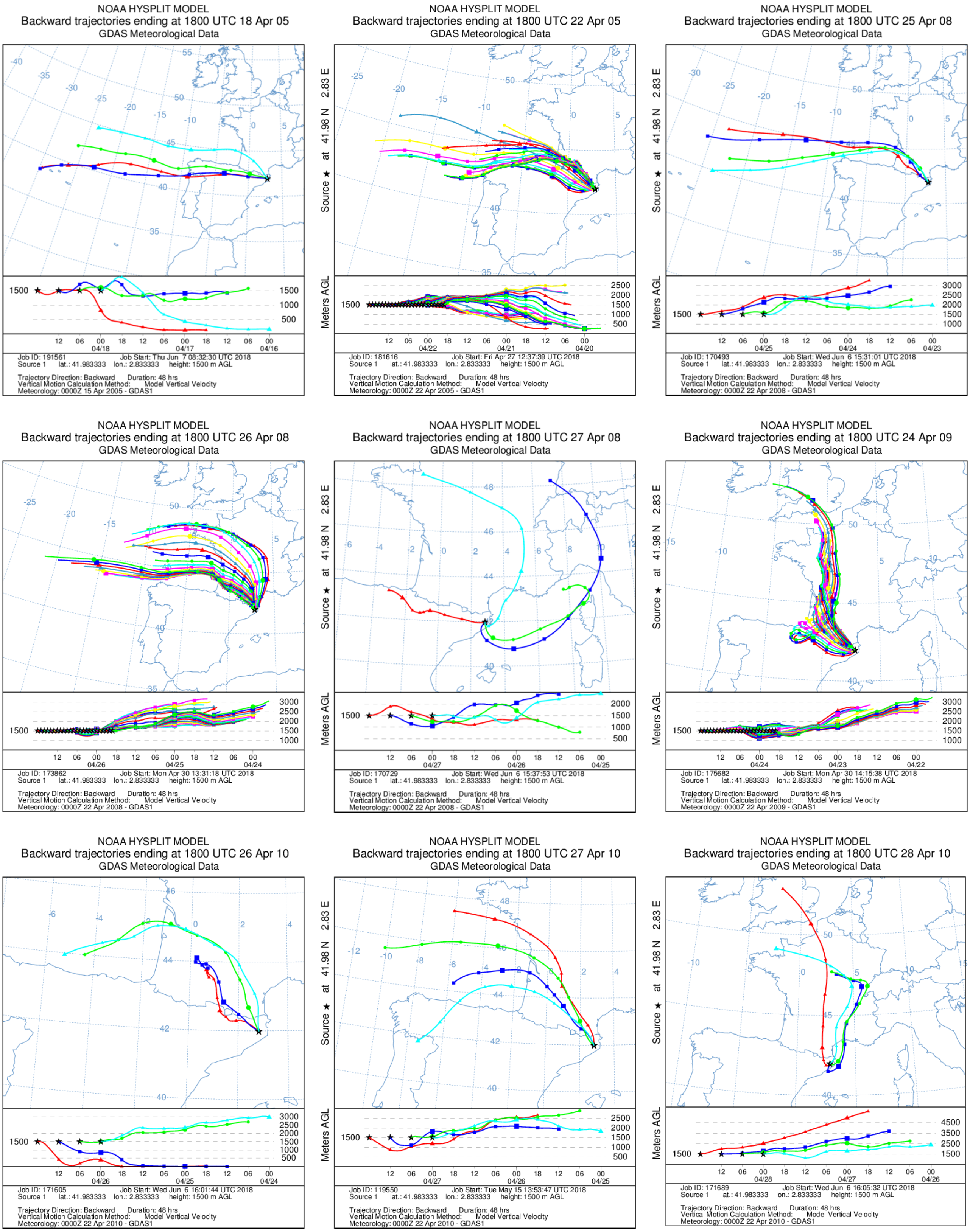
Figures 6.2 (cont): Source regions. Concentration fields for *Fagus*, *Fraxinus* and *Olea*



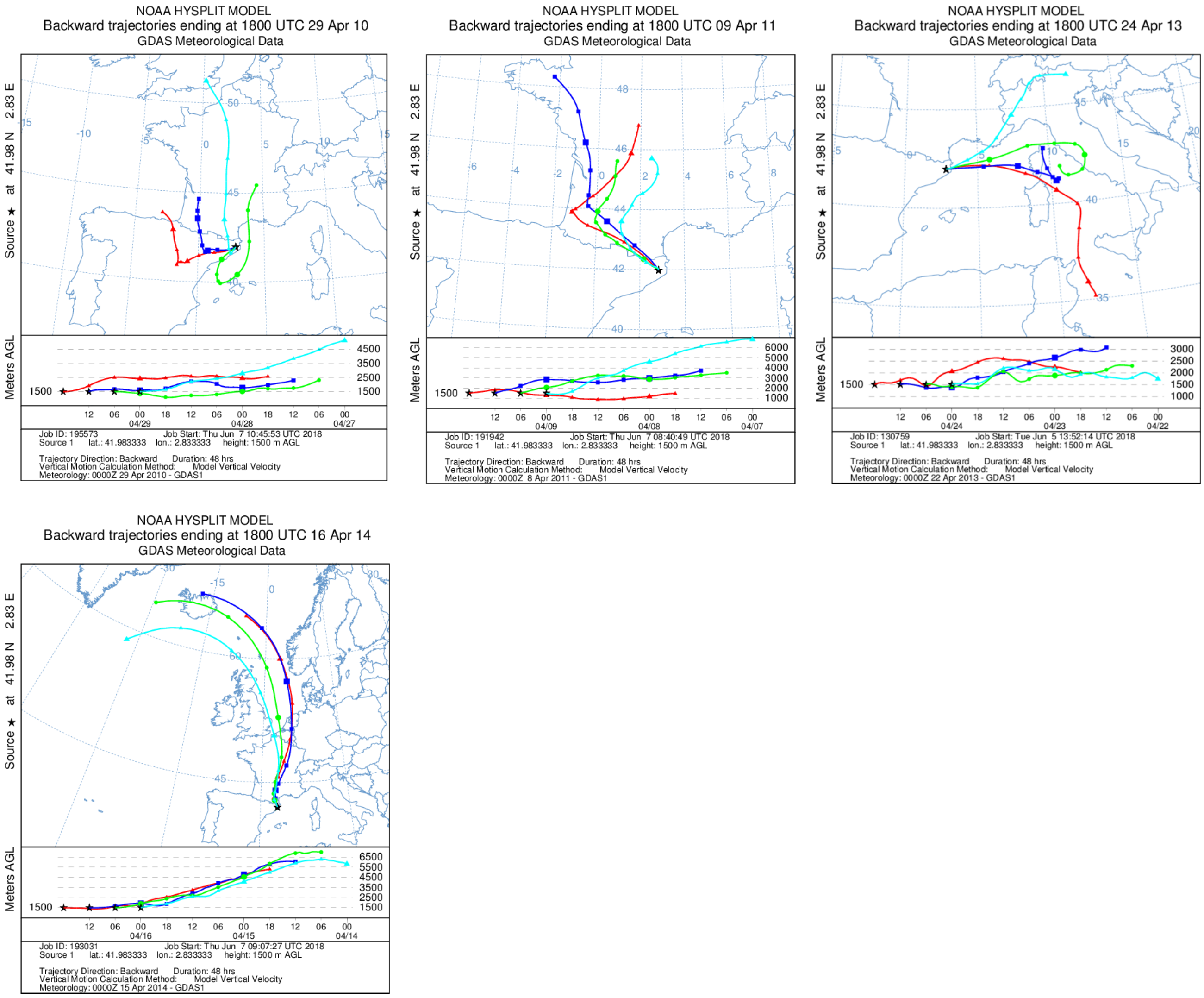
Figures 6.3: 48-h back-trajectories beginning at 18, 12, 06 and 00 (1500 m height) for the dates of the peaks non-simultaneous with a VIE peak



Figures 6.3 (cont): 48-h back-trajectories beginning at 18, 12, 06 and 00 (1500 m height) for the dates of the peaks non-simultaneous with a VIE peak



Figures 6.4: 48-h back-trajectories beginning at 18, 12, 06 and 00 (1500 m height) for the dates of the peaks simultaneous with a VIE peak



Figures 6.4 (cont): 48-h back-trajectories beginning at 18, 12, 06 and 00 (1500 m height) for the dates of the peaks simultaneous with a VIE peak

7. GENERAL CONCLUSIONS

The attempt of the presented research project was to investigate the influence of meteorological variables and climate variability on the airborne pollen levels in Catalonia. The forecast of the Start of the Main Pollen Season and the analysis of the Long-range transport of pollen were also considered. Airborne pollen series recorded by the Aerobiological Network of Catalonia (XAC) at six stations in Catalonia for 22 pollen taxa during two decades (1994-2014) were used for this research.

Each chapter separately constitutes a specific study with its own entity, although all of them are focused as a contribution to a more general study that is the one that gives title to this thesis:

STUDY OF THE METEOROLOGICAL MECHANISMS CONTROLLING LEVELS
AND TRANSPORT PROCESSES OF AIRBORNE POLLEN IN THE ATMOSPHERE

In **Chapter 2** and **Chapter 4** we have focussed in the influence of climatology on the airborne pollen levels through the analysis of the impact of meteorological variables (mainly precipitation and temperatures) and climatic indices at monthly, seasonal and annual level.

Climate variability associated with the Northern Hemisphere Teleconnection patterns (North Atlantic Oscillation, Arctic Oscillation and Western Mediterranean Oscillation) affects both annual pollen production and the timing of the Main Pollen Season (MPS).

Generally an increase of pollen production for most of pollen taxa studied linked to an increase of precipitation was detected in Catalonia during the negative phase of climatic indices.

Temperature was the most influencing meteorological variable on pollen production and on the timing of the MPS. Warm winters seem to advance the Start of the MPS and extend its Length while the End of the MPS is not influenced by winter weather. Conversely, changes in annual temperatures, especially minimum and mean values explained the advances or delays of the End of the MPS. For most of the studied pollen taxa, positive phases of the three climatic indices were related to an advance and enlargement of the MPS.

The observed correlations suggest the possibility of predicting the onset and severity of pollination season through the atmospheric modes of the climatic indices.

In **Chapter 3** we have focussed in the influence of the wind (speed and direction) on the pollen concentrations of 12 pollen taxa which sources are situated near the station (local transport) and have a major representation in the atmosphere. Here we have excluded those of them arriving at Catalonia due to a long-range transport mechanism (we will focus on them in Chapter 6).

Positive correlations between wind and pollen concentration were observed when the wind blows towards the station from the direction of the source location, and negative correlation resulted when the wind blows in a direction from the city towards the source of pollen or coming from the sea. The cleaning and dispersion effect over the pollen concentrations has been observed over the coastal stations (BCN, BTU and TAU) mainly due to the wind induced by the sea breeze effect (SW and SE) and over the inland stations (LLE and MAN) when westerly frontal synoptic situations are presented.

This study could also be useful not only to identify and locate airborne pollen sources but to detect changes in the geographical distribution of vegetation near the sampling stations.

Taking into account that temperature and precipitation are the main variables controlling the Start of the main Pollen Season (SPS) in **Chapter 5** we have explored two methods to forecast the SPS for 6 pollen taxa having a well-defined pollination season in Catalonia.

Two traditional forecasting models were used to predict the SPS. The first is based in the cumulated sum of mean daily temperatures (Summing Temperatures) and the second is based on a Multiple Regression analysis with maximum and minimum temperatures and precipitation. The root mean square error (RMSE) has been used to measure the quality of the models and also their predictability power. Results showed a high variability which depends on the pollen taxa and the sampling station. The RMSE ranged from 0.7 days for *Pistacia* in Manresa by the Multiple Regression model, up to 10 days for other taxa and stations. *Platanus* was the taxon showing the best results for all the stations. The RMSE obtained with the method of Multiple Regression were in general lower than those obtained with the method of Summing Temperatures.

Taking into account the interannual variability of temperature and precipitation, these statistical methodologies could be improved extending the database to more recent years, adding the new pollen and meteorological data.

Finally, in **Chapter 6** we present the results of applying the source-receptor model to estimate the source areas of 6 pollen taxa that are not abundant in the territory but susceptible to reach Catalonia transported by the wind from distant regions (long-range transport) presenting episodically high punctual values of concentration.

Source regions for the pollen arrivals of *Betula, Fraxinus* and *Fagus* to the Catalan stations are located in central and southern France, and the Pyrenees, while *Ambrosia* and *Olea* peaks of pollen concentrations comes from the Iberian Peninsula. The results for *Corylus* show that there is a great local influence.

Apart from the great scientific interest that lies in the modelling of the source areas to understand the life cycles of the species, the use of these models has utility to botanists, allergists, and environmental quality managers in the study and treatment of problems such as respiratory allergies.

As a general conclusion, results showed that airborne pollen levels and its dynamics were influenced by meteorological conditions. Improving knowledge about the influence of meteorology on the pollen dynamics is essential to improve modelling and obtain better forecast of the start and the severity of the pollen season. Most of the results obtained in this study corroborate results shown by other researchers; although, there are some limitations due to the time resolution of the data (monthly and yearly) used in our work. Therefore, more research is needed for better comprehend the interaction between meteorology and airborne pollen levels and its dynamics. For a future research, the results regarding correlations between temperature and pollen concentrations may improve by splitting the annual period in two sections, one since the beginning of the pollination until the peak date and the other from this moment to the end of the pollination. This will be the case for most taxa pollinating between spring and summer. Regarding the results about regional and long-range transport, a natural continuation of this work will consist in the use of daily pollen counts for specific episodes and the application of a nested model at high resolution, such as the Weather Research Forecast mesoscale model (WRF). This would allow tracing the paths followed by the air masses with more precision and a better determination of the source regions.

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