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Application of source-receptor models to determine source areas of biological components (pollen and butterflies)

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Abstract

The 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 chemical compounds measured at a sampling point, and thus be able to target actions to reduce pollutants. However, until now, few studies have applied these types of models to describe the source areas of biological organisms. In Catalonia there are very complete records of pollen (data from the Xarxa Aerobiològica de Catalunya, Aerobiology Network of Catalonia) and butterflies (data from the Catalan Butterfly Monitoring Scheme), a biological material that is also liable to be transported long distances and whose areas of origin could be interesting to know. This work presents the results of the use of the Seibert et al. model applied to the study of the source regions of: (1) certain pollen of an allergic nature, observed in Catalonia and the Canary Islands, and (2) the migratory butterfly Vanessa cardui, observed in Catalonia. Based on the results obtained we can corroborate the suitability of these models to determine the area of origin of several species, both chemical and biological, therefore expanding the possibilities of applying the original model to the wider field of Aerobiology.

Key words: trajectory statistics, long-distance transport, pollen, butterflies, Aerobiology

1 Introduction

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 oceans. Despite the complexity of the interactions among different scales, to make it simpler we can distinguish between small-scale transport (in which a significant portion of the substance will settle near the sources, for example within a horizontal distance of 100 km) and large-scale transport. The first one occurs in the boundary layer under the prevailing influence of local circulations, 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.

Among the most common tools used to study transport are the analysis of synoptic maps, remote sensing, the treatment of meteorological variables such as pressure and geopotential, the use of Eulerian models such as SKIRON and NAAPS, the Lagrangian models such as those based on trajectory calculations (Hysplit, Flextra, etc.), and statistical models such as the source-receptor type applied in the present work. These models, based on the statistical analysis of atmospheric trajectories, do not explicitly take into account the atmospheric diffusion, chemical transformations or removal processes by dry and/or wet deposition.

Usually, source-receptor models have been used to study the transport of chemical compounds in the atmo-

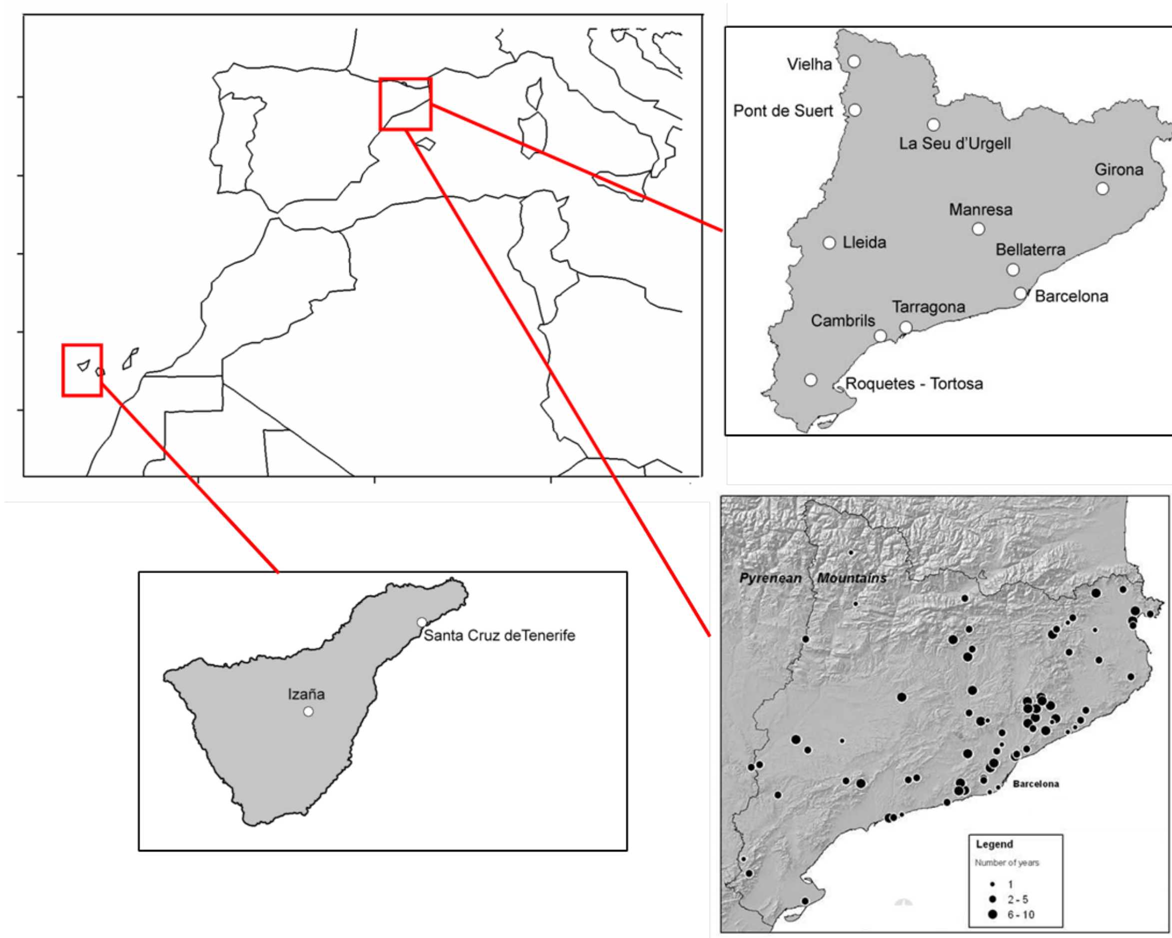

Figure 1. Sampling stations: upper right, those of pollen in Catalonia; lower right, those of *Vanessa cardui* butterfly in Catalonia; bottom left, those of pollen in Tenerife.

sphere, for instance the transport of mineral dust (Bonasoni et al., 2004), ozone (Seibert et al., 1994), acidifying components (Stohl, 1996) and other pollutants (Charron et al., 1998). But the atmosphere also contains biological material such as microorganisms, mold spores, diaspora of plants (pollen and seeds of small size), and small animals like insects and arachnids that spend part of their life cycle in the atmosphere (Johnson, 1969). This material may be injected at high altitudes (>1000 m) and be transported long distances (Chapman et al., 2002; Kellogg and Griffin, 2006) by the same mechanisms that move gases and chemical particles. Therefore, the atmospheric behavior of biological material is liable to be treated with the same methods as those used with chemical compounds. 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, 2008; Sofiev et al., 2006; Skjoth et al., 2007; Siljamo et al., 2008). Similarly, back-trajectories were used to explain long-distance movements of butterflies (French, 1969; Stefanescu et al., 2007; Dantart et al., 2009; Schaffers, 2009). However, until now very few works have used source-receptor models to describe the source areas of biological organisms. This work 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 and butterflies that arrive at the northeast of the Iberian Peninsula and the Canary Islands transported by the wind, thereby extending the application possibilities of the original model to the wider field of Aerobiology.

Specifically, this work presents the results of applying the model to estimate the source areas of: (1) the beech (*Fagus sylvatica* L.) pollen observed in Catalonia (2) the pollen of Chenopodiaceae/Amaranthaceae and Cyperaceae observed in Tenerife, Canary Islands, and (3) the butterfly *Vanessa cardui* observed in Catalonia.

Apart from the great scientific interest that lies in the modeling 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 pests or respiratory allergies.

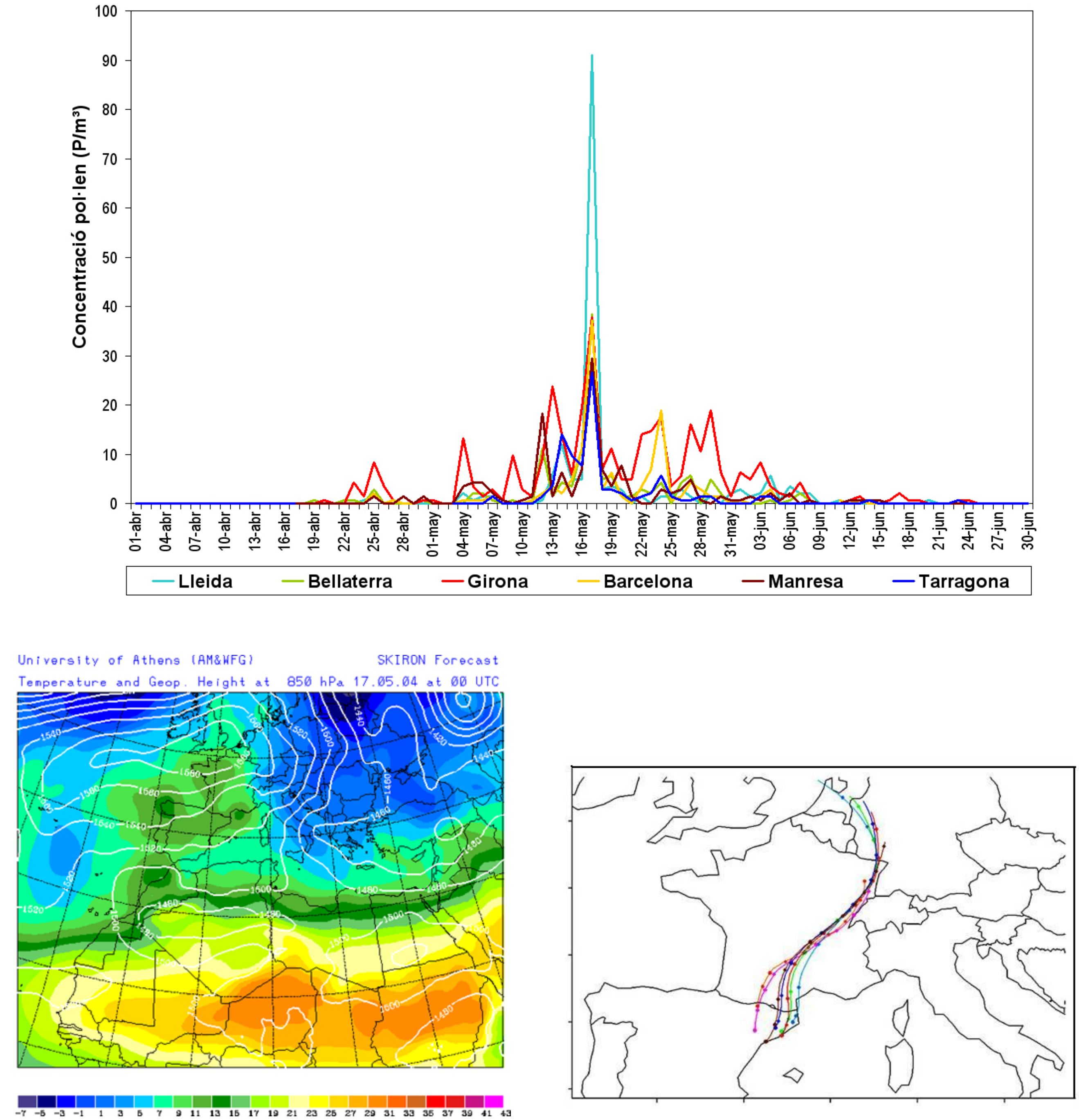

Figure 2. (a) (upper) Pollen dynamics of beech in the period from 1 April to 30 June 2004 (daily average in pollen grains m^{-3}) at the different stations, the peak on 17 May is highlighted; (b) (bottom left) geopotential altitude at 850 hPa at 00 UTC on 17 May 2004; (c) (bottom left) isentropic back-trajectories of 96 hours calculated with Hysplit for 17 May 2004 at 12 UTC with its origin on the aerobiological stations of Catalonia, at 1000 and 3000 m over the sea level.

2 Methodology

2.1 Studied organisms

The beech is a tree that is widespread in central Europe but much more local in Catalonia and the Iberian Peninsula, where it requires rainfall above 1000 mm year^{-1} (Terradas, 1984) and it is found in cool and humid valleys and slopes (Rocha Afonso, 1990), usually between 500 (exceptionally 300) and 2000 m of altitude over the sea level (Bolòs and Vigo, 2005). However, the simultaneous presence of beech 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 Central European, in the stations in Catalonia.

The Chenopodiaceae, Amaranthaceae and Cyperaceae families are cosmopolitan (Mabberley, 1987) and, therefore, they are present in multiple environments worldwide, including dry and desert areas. Within each of these families there are numerous genera and species that are more or less easily distinguishable. In contrast, the pollen of different species is indistinguishable and can only be identified to the family level in the case of Cyperaceae or as belonging to the group Chenopodiaceae/Amaranthaceae in the case of the other two families. In a previous study (Izquierdo, 2008), the analysis of the pollen spectrum of the stations in Tenerife showed the importance of both local/regional contributions and the transport on an extra-regional scale. The relationship between the origin of air masses and the average daily concentrations of each taxon was studied using a statistical analysis of variance, considering the area of origin as a factor. The results related eight taxons with transport on an extra-regional scale. Among them, the groups of Chenopodiaceae/Amaranthaceae and Cyperaceae showed a clear African origin.

Vanessa cardui is a migratory butterfly of the Nymphalidae family that each year, during the spring months, recolonizes Catalonia from North Africa. The observations of *V. cardui* flying at ground level in a defined direction suggested until recent times that their migration depended exclusively on the flying activity of the butterfly, but the work of Stefanescu et al. (2007) demonstrated the connection between the arrival of the butterflies and the presence of a flow of air masses with African origin, which suggests that its displacement benefits from the atmospheric circulation patterns on a synoptic scale.

2.2 Source-receptor model

The source-receptor model is a statistical approximation that combines concentration data from a sampling site with the coordinates of the points crossed by the atmospheric trajectories that arrive at the sampling site. This procedure makes it possible to establish connections between the receptor point and possible source areas.

To do this, the daily 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. A grid with spatial resolution of $1^\circ \times 1^\circ$ is superimposed to the integration domain of the trajectories (Figures 3, 4 and 5). 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:

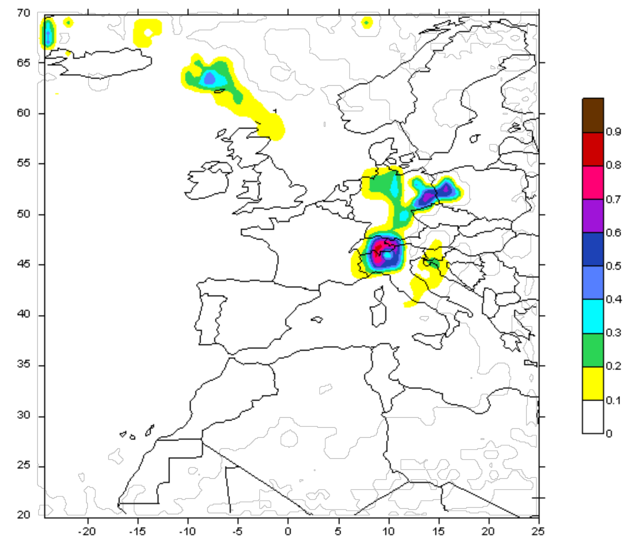

Figure 3. Source areas of beech pollen calculated on the basis of the data from 1 April-30 June during the ten-year period of the sampling 1997-2006. Concentration in pollen grains m^{-3} (p m^{-3}).

$$\log C_{ij} = \frac{\sum_l n_{ijl} \log C_l}{\sum_l n_{ijl}} \quad (1)$$

where C_{ij} 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 isentropic trajectories have been calculated, using a time step of 60 minutes, with the model HYSPLIT-4 (Hybrid Single-Particle Lagrangian Integrated Trajectory Model; Draxler and Hess, 1997) of NOAA (National Oceanic and Atmospheric Administration; http://www.arl.noaa.gov/ready/hysplit4.html) at 1500 meters above sea level (m a.s.l.) from the meteorological data of the U.S. National Climate Data Center (period 1997-2007) and the NCEP/NCAR Reanalysis (period 1983-1996). 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 of the transport 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

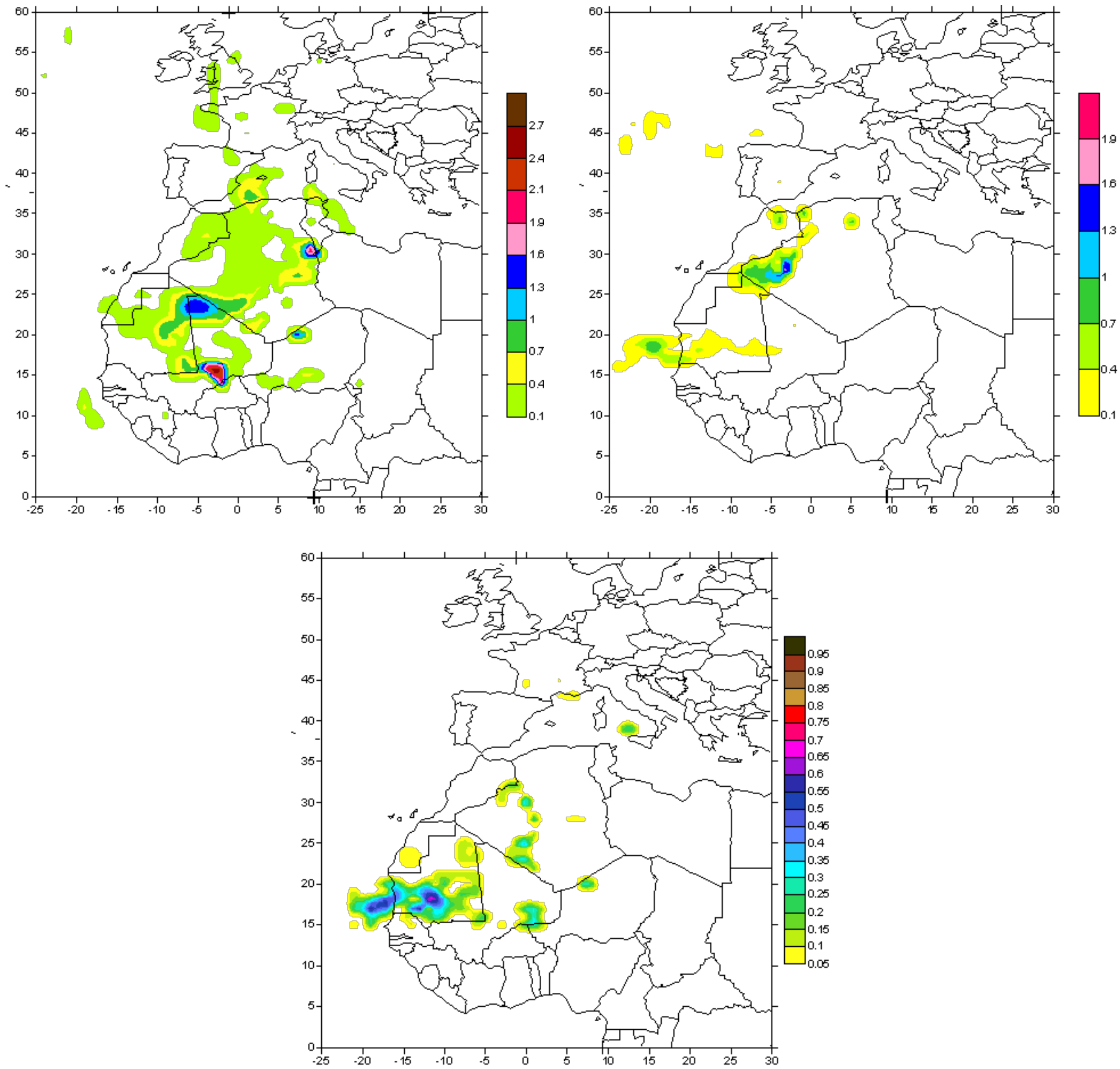

Figure 4. Source areas of the Chenopodiaceae/Amaranthaceae pollen for (a) (upper left) SCO, calculated on the basis of the data from the sampling period 1 January 2006 - 31 December 2007, and (b) (upper right) IZO calculated on the basis of the data from the sampling period 11 June - 11 November 2006 and 23 April - 4 November 2007; and (c) (bottom) Cyperaceae SCO, calculated on the basis of the data from the sampling period 1 October - 31 December 2005, 2006 and 2007. Concentration (p m^{-3}).

between the cell and the eight surrounding cells. Finally, a filter to exclude cells with less than 5 trajectory segments (time steps) has been applied. The concentration map obtained reflects the contribution of each cell to the concentration in the receiving point. In all three cases where the model was applied, the sampled periods have been long enough to be statistically representative.

2.3 Measurement of pollen levels in the atmosphere

The aerobiological sampling in Catalonia and Tenerife was performed using the standard sampling method agreed on by the European aerobiological networks (Hirst method; Hirst, 1952), and following the analysis methodologies used in the Spanish networks (Galán et al., 2007) that provide daily average concentrations of pollen grains per cubic meter (p m^{-3}). The presence of beech pollen in Catalonia was studied by reviewing all available data for the period 1983-2007 at the stations of Barcelona, Bellaterra, Cambrils, Girona, Lleida, Manresa, Pont de Suert, Roquetes, Seu d'Urgell, Tarragona and Vielha (Figure 1). These data showed that despite the limited distribution of the plant in the study area, its pollen is present at certain times, simultaneously, over the whole territory. Back-trajectories

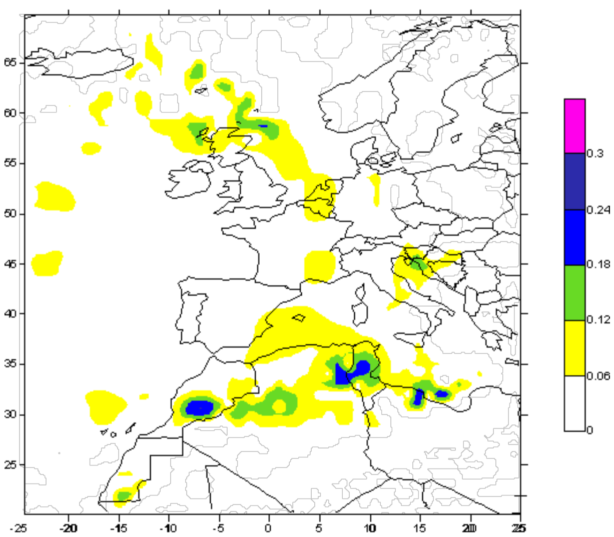

Figure 5. Source areas of *Vanessa cardui*, calculated on the basis of the data from 1 March - 27 June during the ten-years sampling period 1997-2006. Abundance (individuals in 100 m of counting transect).

during the flowering period of beech (April 1-June 30) were calculated for a ten-year period (1997-2006), 720 trajectories and 69,120 time steps, at 1500 meters of altitude in a geographical point representative of the region (41.8°N, 1.5°W), and the average value of the concentration at stations was used.

The arrival of pollen of Chenopodiaceae/Amaranthaceae and Cyperaceae in Tenerife was studied from the daily average concentrations recorded at the stations in Santa Cruz de Tenerife (SCO to 52 m s.n.m.) and Izaña (IZO, at 2367 m s.n.m.) (Figure 1). The sampling period at SCO was continuous during the years 2006-2007, but at IZO it was limited to the period from 11 June to 11 November 2006 and 23 April to 4 November 2007 due to the adverse meteorological conditions during the rest of the year. A back-trajectory at 1500 m for SCO (730 trajectories and 70,080 time steps) and 2500 m for IZO (349 trajectories and 33,504 time steps) was calculated for each sampling day. In the case of Cyperaceae the application of the source-receptor method was only possible in SCO and by using a specific period (1 October to 31 December 2005-2007, 276 trajectories and 26,496 time steps).

2.4 Measurement of the amount of butterflies in the air

The arrival of *Vanessa cardui* in Catalonia was studied from data collected by the Catalan Butterfly Monitoring Scheme (CBMS; www.catalanbms.org/). Observations between 1 March and 27 June (17 weeks) during the period 1997-2006 were used, collected at 79 sampling stations distributed throughout Catalonia (Figure 1). The weekly average abundance of *V. cardui* was estimated from weekly counts made at each of the stations. For the 6 years when the population levels of *V. cardui* were significant enough (2000-2004, 2006), a daily back-trajectory was calculated (a total of 714 trajectories and 68,544 time steps) at 1500 m that, associated with the corresponding value of abundance, was used for the source-receptor model calculations.

3 Results

3.1 Beech pollen in Catalonia

A previous study (Belmonte et al., 2008) for a very important episode during the period from 15 to 19 May 2004, showed that, both for the back-trajectories and the pollen hourly data, the beech pollen came from central Europe in all the stations studied in Catalonia (from Vielha to Tarragona). This fact demonstrated the existence of extra-regional influence in the dynamics of the pollen sampled in Catalonia. Figure 2 shows the concentration of pollen in the spring of 2004, and the meteorological synoptic situation and back-trajectories for this episode.

The application of the source-receptor model to the data of the period 1997 to 2006 pointed to the central-European zone, constituted by northern Italy, Switzerland and the south-west of Germany, as a probable source area of the beech pollen recorded in Catalonia (Figure 3).

3.2 Chenopodiaceae/Amaranthaceae and Cyperaceae pollen in Tenerife

According to the concentration maps obtained by the source-receptor model, the pollen of Chenopodiaceae/Amaranthaceae that arrives at Tenerife has the Sahara and Sahel regions as probable source areas (Figure 4a and 4b). In contrast, the source area of Cyperaceae pollen recorded at SCO is probably the Sahel zone (Figure 4c). When studying concrete episodes with significant peaks, a coincidence is observed between the day of the peak and the arrival of air masses coming from the Sahara or the Sahel, respectively, which strengthens the hypothesis of the possible long-distance transport of pollen from the African continent.

3.3 *Vanessa cardui* in Catalonia

Figure 5 shows the probable source areas of the *Vanessa cardui* populations that arrive at Catalonia during the spring, highlighting one area in Morocco, another in Tunisia and a third in the Tripolitan region of Libya. The coincidence between the arrival of migratory waves of *V. cardui* and African winds from the identified areas provide an indirect evidence that the origin of the butterflies is in these source areas (Stefanescu et al., 2007).

4 Conclusions

This work proves that the source-receptor model used is suitable to indicate the source areas of the pollen recorded in Catalonia and the Canary Islands, and of the species of butterfly *Vanessa cardui* observed in Catalonia. The model shows as source area of the beech pollen a zone that comprises northern Italy, Switzerland and southern Germany, where there are large forests of beech (Magri et al., 2006). Moreover, the model indicates that the Cyperaceae pollen found in Tenerife probably comes from the Sahel, while the Chenopodiaceae/Amaranthaceae pollen comes from the Sahara. These families are present in the territory (African Flowering Plants Database, 2009). Paleopalinologic studies of the pollen in the marine sediments off the coast of Africa have also reported the transport of Chenopodiaceae/Amaranthaceae from the area of the Sahara (Hooghiemstra et al., 2006) and the transport of Cyperaceae from Sahara-Sahel (Romero et al., 2003). Although these observations show the presence of pollen in the past, in which the distribution of plants might have been different from the current distribution, some recent works about the pollen contents in West Africa, such as the study of Calleja et al. (1993), coincide with the results of the sediment, confirming the transport of these kinds of pollen from Africa. Regarding the *V. cardui* butterfly, the model proposes three source areas in North Africa (the area of the Anti Atlas in Morocco, the area between Algeria and Tunisia, and the Tripoli strip in Libya). During an expedition to Morocco in March 2009 several areas of massive emergence of *V. cardui* (with large concentrations of larvae, pupae and newly born adults) were found in the Souss valley. These observations represent a strong validation of the model proposed by Stefanescu et al. (2007).

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