

Source areas and long-range transport of pollen from continental land to Tenerife (Canary Islands)

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Received: 21 May 2009 / Revised: 11 February 2010 / Accepted: 13 February 2010
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Abstract The Canary Islands, due to their geographical position, constitute an adequate site for the study of long-range pollen transport from the surrounding land masses. In this study, we analyzed airborne pollen counts at two sites: Santa Cruz de Tenerife (SCO), at sea level corresponding to the marine boundary layer (MBL), and Izaña at 2,367 m.a.s.l. corresponding to the free troposphere (FT), for the years 2006 and 2007. We used three approaches to describe pollen transport: (1) a classification of provenances with an ANOVA test to describe pollen count differences between sectors; (2) a study of special events of high pollen concentrations, taking into consideration the corresponding meteorological synoptic pattern responsible for transport and back trajectories; and (3) a source–receptor model applied to a

selection of the pollen taxa to show pollen source areas. Our results indicate several extra-regional pollen transport episodes to Tenerife. The main provenances were: (1) the Mediterranean region, especially the southern Iberian Peninsula and Morocco, through the trade winds in the MBL. These episodes were characterized by the presence of pollen from trees (*Casuarina*, *Olea*, *Quercus* perennial and deciduous types) mixed with pollen from herbs (*Artemisia*, Chenopodiaceae/Amaranthaceae and Poaceae wild type). (2) The Saharan sector, through transport at the MBL level carrying pollen principally from herbs (Chenopodiaceae-Amaranthaceae, Cyperaceae and Poaceae wild type) and, in one case, *Casuarina* pollen, uplifted to the free troposphere. And (3) the Sahel, characterized by low pollen concentrations of Arecaceae, Chenopodiaceae-Amaranthaceae, Cyperaceae and Poaceae wild type in sporadic episodes. This research shows that sporadic events of long-range pollen transport need to be taken into consideration in Tenerife as possible responsible agents in respiratory allergy episodes. In particular, it is estimated that 89–97% of annual counts of the highly allergenic *Olea* originates from extra-regional sources in southern Iberia and northern Africa.

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Keywords Pollen · Aerobiology · Back trajectory ·
Source receptor model · Long range transport · Allergy

Introduction

Pollen records from aerobiological monitoring sites have traditionally been interpreted as if the pollen originated from the local environment. Consequently, pollen forecasting tools have been designed by taking into account only local meteorological variables and phenological observations from the neighbourhood. This view is recently changing to

acknowledge much broader bioaerosol movements, based on increasing evidences of pollen and spore transport over much greater distances, implying continental (Belmonte et al. 2000; Sofiev et al. 2006; Siljamo et al. 2007, 2008; Belmonte et al. 2008a; Skj  th et al. 2009) or intercontinental scales (Prospero et al. 2005; Kellogg and Griffin 2006).

Despite their large size (5–50 times greater than aerosols; Nilsson and Praglowski 1992), the behavior of many pollen taxa in the atmosphere is similar to that of conventional atmospheric aerosols due to the low density of anemophilous pollen grains, which reduces their gravitational deposition, along with other features such as aerodynamic contours and low ornamentation. The residence time of pollen grains in the atmosphere, 2–3 days, and their deposition velocity, estimated at about 1 cm/s (Sofiev et al. 2006), are comparable to those of atmospheric aerosol species, and implies that about one-half of the emitted mass will be transported to distances $>10^3$ km (Aylor 2002).

This long-range transport of bioaerosols gives cause for concern because of its potential to distribute pathogens and allergens that can affect the human health or human interests such as agriculture and farming (Belmonte et al. 2000; Griffin et al. 2001; Taylor 2002; Brown and Hovm  ller 2002; Shinn et al. 2003; Garrison et al. 2003; Wu et al. 2004; Kellogg et al. 2004; Griffin 2007; Polymenakou et al. 2008). This transport can also have an impact on the structure of ecosystems, since pollen is responsible for gene flow (Ellstrand 1992; Ennos 1994; Burczyk et al. 2004), and it contributes to determining the spatial distribution of plant species (Ellstrand 1992; Smouse et al. 2001; Sharma and Khanduri 2007; Schmidt-Lebuhn et al. 2007). Therefore, the study of pollen gene dispersal is instrumental in the interpretation of the biogeographic range of some plants and for plant conservation issues.

Extra-regional transport of pollen at distances greater than a few hundreds of kilometers has recently been studied by several authors; some of those studies are briefly reviewed here. Van Campo and Qu  t (1982) identified several pollen types that had been transported from North Africa to Montpellier (France) together with mineral desert dust. Similarly, Franzen and Hjelmroos (1988) observed pollen transport from Germany, Holland and England to the Swedish coast, and Franzen (1989) and Franzen et al. (1994) documented the arrival of pollen grains from the Mediterranean in Fennoscandia. Also, *Cannabis sativa* (marihuana) pollen originating in Morocco was detected in Malaga, South Spain (Cabezudo et al. 1997) and *Cannabis*, *Cupressus*, *Pinus*, *Platanus* and *Sambucus* pollen were observed in Cordoba (South Spain) exclusively during dust African events (Cari  anos et al. 2004). Transport of pollen to western Europe has also been reported. This is exemplified by the arrival in Denmark of *Betula* pollen coming from Poland and Germany (Skj  th

et al. 2007), and pollen from Russia coming to Finland (Siljamo et al. 2008). Also, *Ambrosia* pollen originating in the Czech Republic, Slovakia, Hungary and Ukraine was found in Poland and Italy (Cecchi et al. 2006; Stach et al. 2007; Kasprzyk 2008). Transport from northern latitudes has been described in Spain: *Ambrosia* pollen coming from France was recorded in Catalonia (north-eastern Spain; Belmonte et al. 2000) and *Fagus sylvatica* (beech) pollen reaching Catalonia was traced back to central Europe (Belmonte et al. 2008a). In North America, the arrival of *Juniperus ashei* pollen released in southern Oklahoma and Texas to Tulsa has been reported (Rogers and Levetin 1998). In South America, extra-regional pollen of *Celtis* coming from the northeast, and of *Nothofagus* from the southwest, has been found to contribute to Mar de Plata City (Argentina) pollen records (Gassmann and P  rez 2006). In northwest India, bioaerosols collected during dust storms sporadically contained pollen from Himalayan species (Yadav et al. 2007). The presence of pollen grains from trees forming forests at much lower latitudes has been evidenced in the Arctic environment (Bourgeois 2000; Rousseau et al. 2003, 2006, 2008). Extra-regional pollen transport has also been found in the Antarctic (Wynn-Williams 1991) and Australia (Hart et al. 2007).

A strong association of biological particles with desert dust has recently been suggested (Kellogg and Griffin 2006). Dust clouds generated by storm activity over arid land can result in viruses, fungi spores and pollen associated with mineral particles being raised to altitudes higher than 2 km, which are then transported for thousands of kilometers at a planetary scale. For example, viable microorganisms and fungi spores from Africa were sampled in Barbados after being transported by African dust plumes (Prospero et al. 2005). Intercontinental mineral dust transport has been the subject of much attention during recent decades (Guerzoni and Chester 1996; Goudie and Middleton 2001; Prospero et al. 1996; Zhang et al. 1997), but further research is needed on the biological component associated with the dust.

African dust is mobilized and transported through specific meteorological conditions involving convective vertical movements and zonal wind patterns. The African wind system is characterized by a strong seasonal component related to the annual oscillation of the Intertropical Convergence Zone (ITCZ): in summer (May–November), trade winds carry Saharan dust to the Caribbean and North America, whereas in winter (December–April), dust flow is shifted to South America. Throughout the year, episodic pulses of dust from North Africa arrive in Europe associated with the movement of storms tracks from the Atlantic to the Mediterranean at the latitude of the Iberian Peninsula (Moulin et al. 1997; Escudero et al. 2006).

The island of Tenerife (Canary Islands) constitutes an ideal location to study air mass transport from Africa because of its

geographical position in the northern edge of the African dust belt. The chemical and mineralogical properties of dust reaching Tenerife have been thoroughly described (Coudé-Gaussen et al. 1987; Bergametti et al. 1989; Viana et al. 2002, 2006; Díaz et al. 2006; Alonso-Pérez et al. 2007; Rodríguez et al. 2007) but no studies regarding pollen transport have been undertaken in the Canary Islands until now.

The lower troposphere of Tenerife can be divided clearly into two layers, each affected by different air mass circulation. The lowest humid and relatively cold troposphere, or marine boundary layer (MBL), is affected by the north-easterly trade winds. Through this circulation pattern, Tenerife receives the influence of Mediterranean or south European air masses. The very dry free troposphere at Tenerife is separated from the MBL by the trade wind inversion layer (TIL) at an altitude that oscillates between 500 and 1,600 m above sea level (m.a.s.l.; Torres et al. 2001; Rodríguez 1999; Alonso-Pérez et al. 2007). The free troposphere (FT) is characterized by subsiding NW air masses, except in summertime, when this normal flow is alternated with dust-laden Saharan air mass outbreaks.

In this study, we analyzed airborne pollen counts at two sites, one corresponding to the MBL (Santa Cruz de Tenerife Observatory, SCO, at 52 m.a.s.l.), the other to the FT (Izaña Observatory, IZO, at 2,367 m.a.s.l.). The aim of the study was to describe episodes of long-range pollen transport to Tenerife and to identify the provenance areas at these two altitudes for some pollen taxa. Some debate exists as to the distance needed to be considered as long-range transport because this definition depends on the subject of study, with lighter biological structures being able to be transported much further distances (Nathan et al. 2003). In the case of our pollen study, we consider that extra-regional trajectories (from outside the Canary Islands) correspond to long-range transport, since they are always larger than 500 km.

We used three approaches to describe pollen transport: (1) a classification of provenances with an analysis of variance (ANOVA test) to describe pollen count differences between sectors; (2) a study of special events of high pollen concentrations, taking into consideration the corresponding meteorological synoptic pattern responsible for the transport and back trajectories; and (3) a source–receptor model applied to a selection of pollen taxa to show their source areas.

Material and methods

Study area

The island of Tenerife (Canary archipelago) is located 350 km west of the Western Saharan coast and 1,300 km south-west of the Iberian Peninsula. Its meteorology is highly influenced by the North Atlantic anticyclone, which varies in strength and

position throughout the year, and by the quasi-permanent action of the trade winds that circulate along the eastern side of the anticyclone approaching the island from the north-east. The predominance of trade winds in the MBL plays a key role in the atmospheric dynamics of Tenerife (Font 1956; Cuevas 1996; Viana et al. 2002; Rodríguez et al. 2004).

Sampling was performed at two sites: Santa Cruz de Tenerife (SCO; 16°14'51" W; 28°28'21" N; 52 m.a.s.l.) as representative of the MBL, and Izaña Atmospheric Observatory (IZO; 16°29'58" W; 28°18'32" N; 2367 m.a.s.l.) as representative of the FT. Both sampling stations are managed by the Izaña Atmospheric Research Center of the Agencia Estatal de Meteorología (AEMET). Santa Cruz de Tenerife is a city of 220,000 inhabitants located in the northeast of Tenerife by the Atlantic Ocean and close to the Macizo de Anaga ridge. The climate is mild (mean annual temperature: 21.2°C) and dry (214 mm mean annual rainfall). IZO station is located in the central mountain chain of Tenerife 15 km north-east of the Teide volcano (3,718 m.a.s.l.). The climate is cold (mean annual temperature: 9.8°C) and more humid than the lowland (440 mm mean annual precipitation).

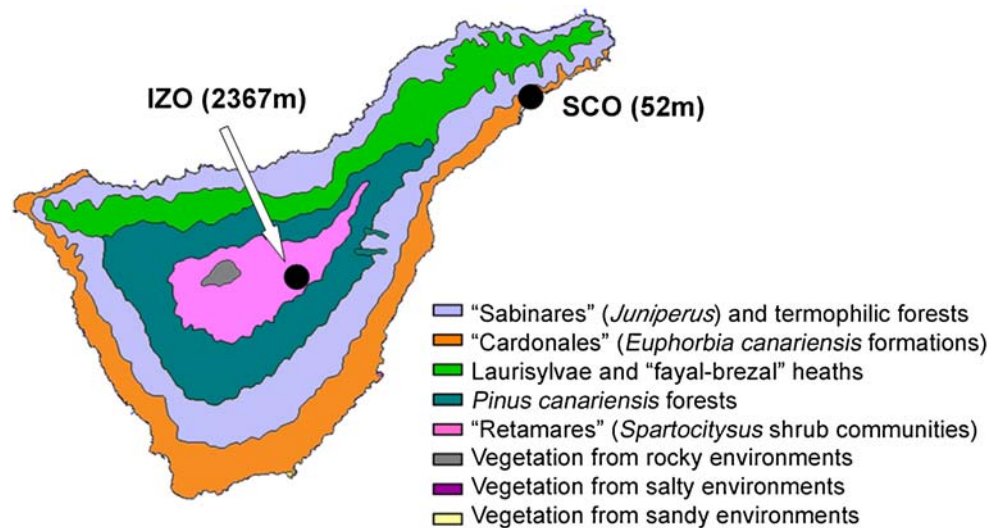
Vegetation

The vegetation of Tenerife is arranged mostly in concentric belts around the Teide peak, with the exception of a forested and humid area (laurel forest) present only at the North side of the island where rainfall and mists are frequent due to the trade winds. Following Rivas Martínez (1987) and Arco Aguilar et al. (2006), the vegetation of Tenerife can be summarized thus: vegetation from rocky environments (above 3,000 m.a.s.l.), “Retamares” (dominated by the endemic broom *Spartocytisus supranubius*), *Pinus canariensis* forests, Laurisylvae and “fayal-breza” heaths at the more humid northern area (with *Laurus*, *Persea*, *Ocotea*, *Ilex*, *Myrica*, *Ilex*, *Erica*...), “Sabinars” (*Juniperus*) and thermophile forests and “Cardonales” (sub-desert scrub formations with *Euphorbia canariensis* and *E. balsamifera* as dominating species) as well as vegetation from saline and sandy environments in these very special areas (Fig. 1). Other vegetation types that have to be considered are the ornamental plants introduced in the urban and urbanized areas and the ruderal and nitrophilic plant communities growing close to human settlements. Each vegetation type mentioned has a particular list of species besides those that are cited as representative, most of which will constitute the atmospheric pollen spectra.

Pollen data record

Pollen data were recorded at the two monitoring stations using samplers (Lanzoni VPPS 2000; Bologna, Italy) based on the Hirst method (Hirst 1952), the standard method

Fig. 1 Tenerife vegetation map (Belmonte et al. 2008b)



approved by European aerobiological networks. Pollen counting followed the method of the Spanish Aerobiology Network (Red Española de Aerobiología, REA; Galán Soldevilla et al. 2007). The Hirst method performs a sequential and non interrupted sampling that has been proven useful in long-range transport research (Gassmann and Pérez 2006; Belmonte et al. 2008a; Siljamo et al. 2008; Skjøth et al. 2009; Šikoparija et al. 2009).

Sampling was undertaken during the years 2006–2007. The sampling period at SCO was continuous during both years, whereas at IZO, samples were only collected from 11 June to 11 November 2006 and from 23 April to 4 November in 2007 because of adverse meteorology in the rest of the year.

Criteria to determine extra-regional transport

As a first approach we applied an ANOVA analysis to pollen counts distinguishing for provenance areas as this would give a hint of preferential geographical regions providing the pollen (Fig. 2).

The temporal series of pollen counts were then analysed. Most taxa showed low background concentrations for most of the time (hypothesized as coming from the local environment), which were broken by outstanding peak events. An example of pollen daily variation showing peak events is given for Poaceae in Fig. 3. Once identified, the meteorological situation for peak events was analyzed in depth with the help of synoptic meteorological maps and meteorological and dust models. This provided information to unveil any coherent air mass movements from specific source areas.

Classification of provenances

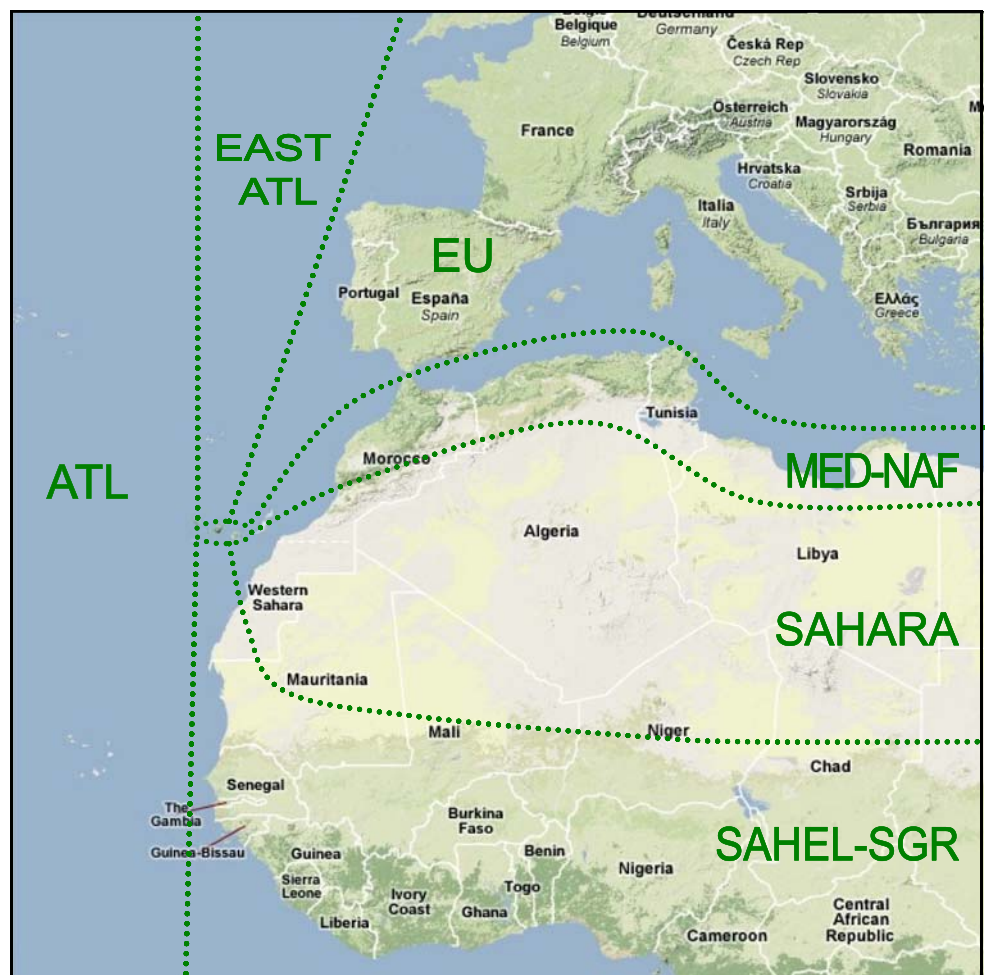
The provenance of the air-masses was identified with HYSPLIT (hybrid single-particle Lagrangian integrated

trajectory) 4.0 dispersion model back-trajectories from the Air Resources Laboratory (ARL, available at <http://www.arl.noaa.gov/ready/hysplit4.html>, Draxler and Rolph 2003), using the GDAS (Global Data Assimilation System) meteorological dataset from the NCEP (National Center for Environmental Prediction) and the vertical velocity model. The starting point was set at 12:00 UTC from the coordinates of each monitoring site and run backwards for 144 h. Back-trajectories were calculated daily near the surface at both sampling stations and at a higher level (altitudes of 100 and 1,500 m.a.s.l. at SCO and 2,500 and 3,000 m.a.s.l. at IZO). For classifying provenances, only back trajectories at height, indicating synoptic movements (1,500 m and 3,000 at SCO and IZO, respectively) were considered.

According to the area crossed by the back trajectories, provenances of the air masses reaching the two Tenerife stations were classified into one of six predefined source geographic sectors (Fig. 2): (1) Sahel, Sudanese and Guinean Regions (SAHEL-SGR), (2) Sahara Desert (SAHARA), (3) Mediterranean-North Africa (MED-NAF), (4) Europe (EU), (5) Eastern Atlantic (EAST ATL) and (6) Atlantic (ATL). A seventh category was added because several trajectories were observed to cross south Europe, the Mediterranean and North Africa, combining categories 3 and 4 (EU+MED-NAF). The abovementioned sectors of the African continent (1–3) were established according to the latitudinal distribution of vegetation belts in northwest Africa reported in White (1983).

To test for differences in mean pollen counts of the studied taxa between the different provenances, we applied an ANOVA analysis to the normalized pollen data (logarithm of pollen concentrations). For pairwise post-hoc comparisons, the Tukey test was applied; significance was set at $P < 0.05$ level.

Fig. 2 Definition of sectors of back trajectory provenance. Map base from Basarsoft and Geocentre consulting, PPWK, Tele Atlas, MapLink/Tele Atlas, Europe Technologies 2008, available at <http://maps.google.es>



Peak events

Daily pollen dynamics were screened to identify peak events by means of a Student *t*-test: for each taxon, concentrations at day *d* were compared to those of the previous day (*d*−1) with a one-tailed *t*-test. The null hypothesis states that the concentration differences in two consecutive days are not significantly different from zero (at $P < 0.05$). Peak days were those that showed significant differences in consecutive days. For the significant peak events, we calculated the corresponding 4-day ensemble back trajectories at 500 m.a.s.l for SCO (within the MBL) and 2,500 m.a.s.l for IZO (in the FT). The starting point was set at 00:00 UTC from the coordinates of each monitoring site. The interpretation of the back trajectories was complemented with meteorological synoptic maps. Because dust and biological components are jointly uplifted to the atmosphere by the same convective air motions (Kellogg and Griffin 2006), and because dust images can help visualise the areas where both components were uprooted, dust forecast models such as DREAM (<http://www.bsc.es/projects/earthscience/DREAM>) and SKIRON

(<http://forecast.uoa.gr/>), and satellite information such as MODIS (<http://rapidfire.sci.gsfc.nasa.gov/>) and TOMS AI Index, (<http://toms.gsfc.nasa.gov/>) were scrutinized for the peak periods. Four outstanding peak events were identified and are described in detail below.

Source–receptor model

Pollen taxa that presented significant differences between provenances (based on ANOVA analysis) and that showed significant peak patterns (based on *t*-tests) were selected for further exploration of source areas by applying a source–receptor model. The selected taxa were: *Artemisia*, Chenopodiaceae/Amaranthaceae and Poaceae wild type at SCO and IZO, and Arecaceae, Cyperaceae and *Olea* only at SCO, due to lack of data at IZO.

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) have tried to validate various TSMs, mostly through direct comparison with known sources. More

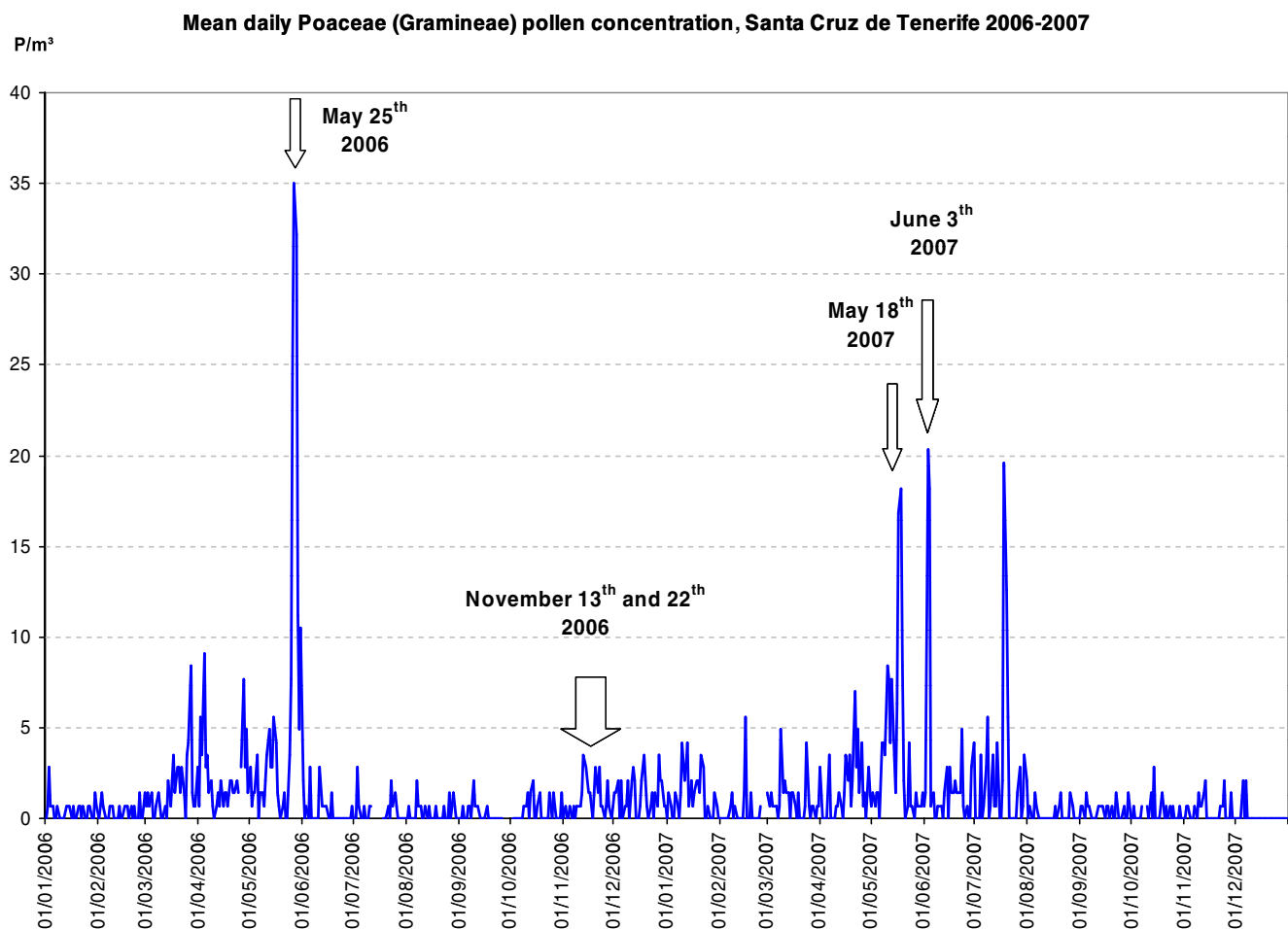


Fig. 3 Sequence of mean daily pollen concentrations of Poaceae wild type pollen at Santa Cruz de Tenerife (SCO), from 1 January 2006 to 31 December 2007. Arrows Studied peak events

recently, a more quantitative approach (Scheffinger and Kaiser 2007) was applied to three TSMs using virtual and real sources as well as comparison with EMEP emission inventory. All these studies concluded that methods of trajectory statistics are computationally fast procedures that deliver first hints on potential source areas. These studies also agree that TSMs provide a helpful tool for estimating the spatial distribution of emissions of air pollutants from measurements. Between TSMs, methods involving air pollution data—Seibert's methodology based on concentration fields (Seibert et al. 1994) being one of the most used—together with methods based on conditional probability fields (Potential Source Contribution Function, PSCF) are used. Both are still very much in use in the interpretation of transport of inert air pollutants; for example, Apadula et al. (2003) used these approaches to localize sources and sinks of carbon dioxide in high mountain areas in Europe; Polissar et al. (2001) applied the PSCF to the atmospheric aerosol at Barrow; Hoh and Hites (2004) to pesticides in US, Salvador et al. (2004) to the PM₁₀ in Spain, and Xie and Berkowitz (2007) to hydrocarbons in Texas. More recently, Wang et al.

(2009), implemented a GIS-based software that combines statistical analysis of air mass back trajectories with long-term air pollution measurements to identify potential sources. While most TSMs applications have dealt with chemical components in the atmosphere, much less work has been done on the biological aerial component, although the methodology is equally applicable. In a recent study, Belmonte et al. (2008a) described the source area of *Fagus* pollen reaching Catalonia using a Seibert source–receptor model.

Source–receptor methodologies establish relationships between a receptor point and the probable source areas. Daily 96-h back-trajectories were computed for the full sampling period and each back trajectory was associated to the corresponding daily pollen abundance. The back-trajectories considered were from 1,500 m.a.s.l. at SCO and 2,500 m.a.s.l. at IZO, with segment end points of 60-min time steps. A grid, in our case composed of 2,601 cells of 1°×1° latitude and longitude, was then superimposed on the integration region of the trajectories in order to map the contributing areas for selected pollen taxa.

The Seibert methodology (Seibert et al. 1994), where a logarithmic mean pollen concentration is computed for each grid cell based on the residence time of the trajectories in the cells, was applied:

$$\log C_{ij} = \frac{\sum_l n_{ijl} \log C_l}{\sum_l n_{ijl}}$$

where C_{ij} is the pollen concentration in the (i,j) cell, l is the index of the trajectory, n_{ijl} is the number of time steps of the trajectory l in the cell (i,j), and C_l is the pollen concentration measured at the receptor point corresponding to the trajectory l . To minimise the uncertainty of the trajectories, a smoothing was applied and the value of each cell was replaced by the average between the cell and the eight neighbouring cells. A final filter excluded cells with less than five end points. The abundance field map obtained in this manner reflects the contribution of each cell to the pollen abundance at the receptor point.

Source–receptor sensitivity analysis

We initially applied both Seibert's methodology and the PSCF to our pollen data. A sensitivity analysis was performed with different factors, such as the averaging in the smoothing procedure, the number of total time steps considered in the back trajectories (48, 72, 96, 120 and 144), the weighting function used to minimize the effect of the cells with low number of time steps, and the exceedance

criterion values (average, percentile 80, percentile 90, and percentile 95). Although the models were sensitive to all these factors, the source areas obtained did not vary significantly.

Results

ANOVA analysis

Seventy pollen types were identified at SCO during 2006–2007 (710 days of measurements). Only six pollen types presented significant differences between provenances by ANOVA: Arecaceae (palms), *Casuarina*, Cyperaceae (sedges), Chenopodiaceae/Amaranthaceae, Moraceae and *Salix* (willows; Table 1). It can be seen that the SAHEL-SGR was the predominant provenance for Arecaceae and Cyperaceae pollen; the North African origin, especially the MED-NAF provenance, prevailed for *Casuarina* and Chenopodiaceae/Amaranthaceae. Moraceae and *Salix* showed no clear pattern, but in both cases EU was the predominant provenance.

Forty-six pollen types were identified at IZO during the study periods in 2006–2007 (341 days of measures). Six pollen types showed ANOVA significant differences between provenances: *Artemisia*, Boraginaceae, Chenopodiaceae/Amaranthaceae, Ericaceae, *Pinus* and *Quercus* deciduous type (Table 1). MED-NAF was the predominant provenance for *Artemisia*, Boraginaceae, and Chenopodiaceae/

Table 1 Mean daily airborne pollen concentration (p/m^3) for each provenance at both studied stations for the taxa that showed significant differences with an ANOVA analysis ($P < 0.05$). Lower case letters indicate post-hoc Tukey test differences between provenances: numbers

with the same letter are not statistically different, while numbers with different letters are significantly different at $P < 0.05$. SCO Santa Cruz de Tenerife, IZO Izaña Atmospheric Observatory

	SAHEL-SGR	SAHARA	MED-NAF	EU	EU+MED-NAF	ATL	EAST ATL
SCO							
Arecaceae	5.72 a	3.03 ab	1.85 b	1.33 b	1.44 b	1.90 b	2.03 b
<i>Casuarina</i>	0.00 ab	0.13 ab	0.21 a	0.03 b	0.08 ab	0.03 b	0.06 b
Chenopodiaceae/ Amaranthaceae	0.47 abc	1.56 bc	1.78 b	0.37 bc	1.05 bc	0.36 c	0.44 c
Cyperaceae	0.58 a	0.09 bc	0.13 b	0.04 bc	0.08 bc	0.01 c	0.00 c
Moraceae	0.12 ab	0.21 b	0.30 ab	0.86 a	0.30 b	0.28 b	0.42 a
<i>Salix</i>	0.00 ab	0.08 ab	0.00 ab	0.09 a	0.03 ab	0.01 b	0.01 b
IZO							
<i>Artemisia</i>	0.06 b	0.08 b	1.20 a	0.11 b	0.08 b	0.17 b	0.19 a
Boraginaceae	0.04 ab	0.00 b	0.09 a	0.04 ab	0.00 ab	0.01 b	0.00 ab
Chenopodiaceae/ Amaranthaceae	0.78 a	0.39 ab	0.81 a	0.21 ab	0.25 ab	0.20 b	0.47 ab
Ericaceae	0.02 b	0.02 b	0.23 b	0.04 b	0.95 a	0.08 b	0.00 b
<i>Pinus</i>	0.26 ab	0.22 b	0.88 ab	0.63 ab	3.54 a	1.45 ab	0.19 ab
<i>Quercus</i> deciduous type	0.00 ab	0.03 ab	0.11 ab	0.00 ab	0.16 a	0.005 b	0.00 ab

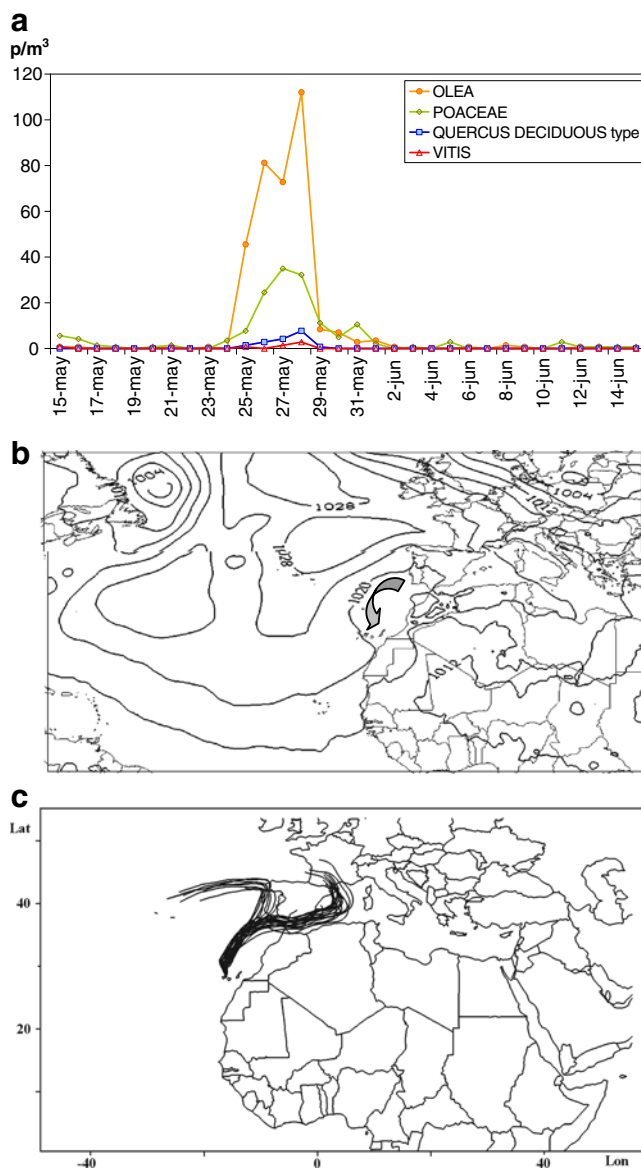


Fig. 4a–c Episode from 25 to 29 May 2006 at SCO. **a** Mean daily pollen concentration. **b** Synoptic weather map showing sea level pressure (hPa) from ECMWF on 28 May 2006. *Arrow* Movement of air mass. **c** Four-day ensemble back trajectories calculated at 500 m.a.s.l. altitude at 00:00 UTC from 28 May 2006

Amaranthaceae, but the SAHEL-SGR provenance was also important for the two last pollen types. EU+MED-NAF was the most important origin for Ericaceae, *Pinus* and *Quercus* deciduous type.

Study cases

Episode on 25–29 May 2006 at SCO

From 25 to 29 May 2006, a significant increase in daily airborne pollen concentration (on the basis of *t*-tests) of

Olea (olive trees), *Quercus* deciduous type (deciduous oaks and corks), *Vitis* (grape vine) and Poaceae wild type (grasses) was observed at SCO (Fig. 4a). On 28 May, *Olea* pollen concentration reached 112 pollen grains/m³ (p/m³). No data are presented for IZO because the instrument was not yet operative at these dates.

The synoptic meteorology on 28 May exemplifies the whole episode (Fig. 4b): a low-pressure system situated over the Atlantic coast of Morocco triggered a movement of air masses from North Africa and the Iberian Peninsula to

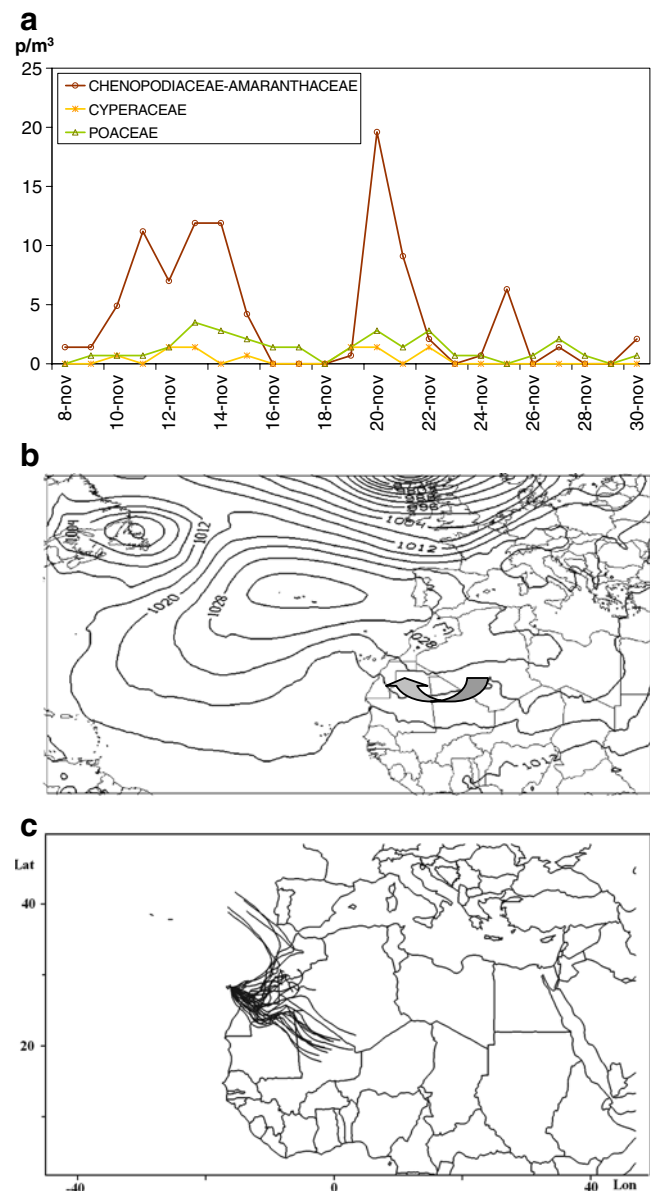


Fig. 5a–c Episodes during November 2006 at SCO. **a** Mean daily pollen concentration. **b** Synoptic weather map showing sea level pressure (hPa) from ECMWF on 20 November 2006. *Arrow* Movement of air mass. **c** Four-day ensemble back trajectories calculated at 500 m.a.s.l. altitude at 00:00 UTC for 20 November 2006

the Canary Islands. This can be seen in the ensemble back trajectories (Fig. 4c). The pollen types identified during this episode (olive, grape vine and deciduous and cork oaks) correspond to typical taxa of the Mediterranean vegetation

(although ubiquitous grasses were also found), a result wholly compatible with long-range transport from the Mediterranean region; more specifically, from southern Spain and northern Morocco and Algeria.

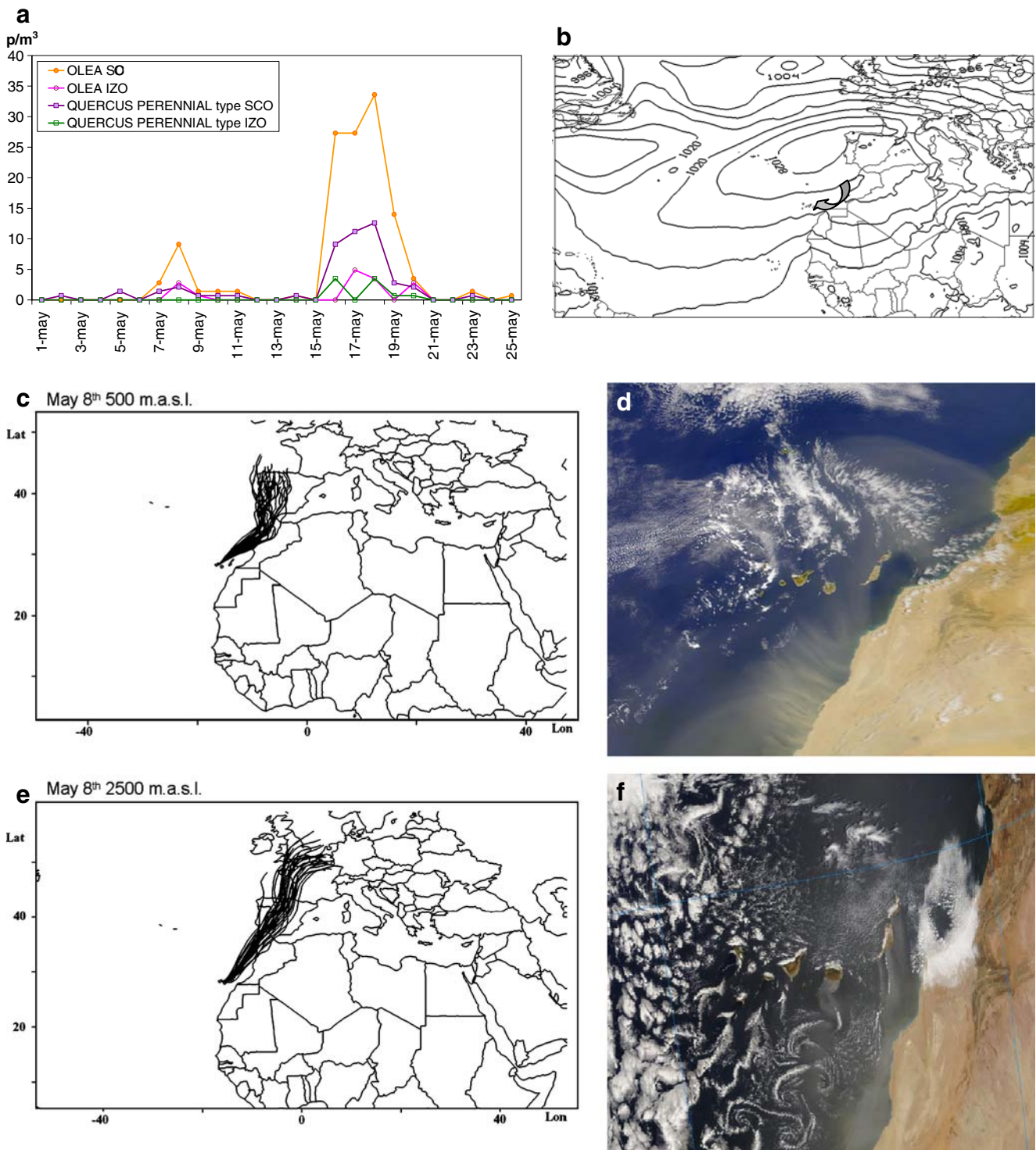


Fig. 6a–f Episodes from 7 to 21 May 2007 at SCO and IZO. **a** Mean daily pollen concentration. **b** Synoptic weather map showing sea level pressure (hPa) from ECMWF on 8 May 2007. **c** Four-day ensemble back trajectories calculated at 500 m.a.s.l.

altitude at 00:00 UTC on 8 May 2007. **d** SeaWiFS image on 8 May 2007. **e** Four-day ensemble back trajectories calculated at 2,500 m.a.s.l. altitude at 00:00 UTC on 8 May 2007. **f** MODIS image on 16 May 2007

Episodes during November 2006 at SCO

In November 2006, two episodes (10–15 and 19–22 November) of pollen peak concentrations of *Chenopodiaceae*/*Amaranthaceae*, accompanied with lower, though significant, peaks of *Cyperaceae* and *Poaceae* wild type, were recorded at

SCO (Fig. 5a). As before, no data are presented for IZO because the sampler was not operating. The atmospheric situation was similar in both episodes. The Canary Islands were between two high-pressure systems: one located to the north of the Archipelago and centered in the island of Madeira, and the other over North Africa (Fig. 5b). High

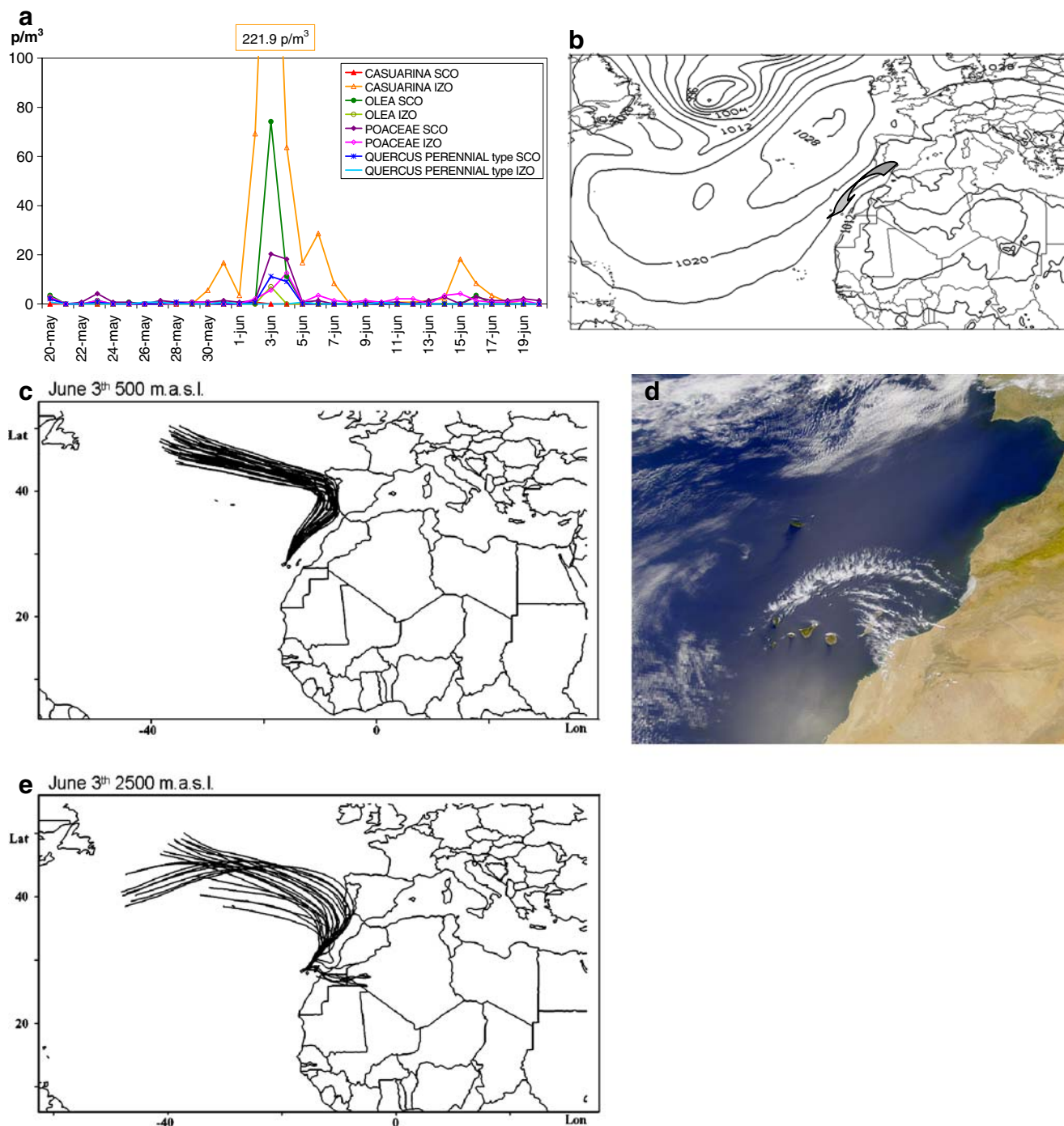


Fig. 7 Episodes on 2–5 June 2007 at SCO and IZO. **a** Mean daily pollen concentration. **b** Synoptic weather map showing sea level pressure (hPa) from ECMWF on 3 June 2007. **c** Four-day ensemble back trajectories calculated at 500 m.a.s.l.

altitude at 00:00 UTC on 3 June 2007. **d** SeaWiFS image on 3 June 2007. **e** Four-day ensemble back trajectories calculated at 2,500 m.a.s.l. altitude at 00:00 UTC on 3 June 2007

pressure over North Africa caused the transport of air masses carrying edaphic dust and pollens from Mauritania and the Western Sahara to the Canary Islands. Four-day ensemble back trajectories for 10–11 November and 20–21 November originated mostly in a broad region around the borders of Algeria-Mali-Mauritania (See Fig. 5c for the episode on 20 November). Vegetation that showed significant pollen peaks in these episodes is present in this area as reported in the African Flowering Plants Database, version 3.1 (Conservatoire et Jardin botaniques de la Ville de Genève and South African National Biodiversity Institute, Pretoria, retrieved May 2009 from <http://www.ville-ge.ch/musinfo/bd/cjb/africa/>).

Episodes during May 2007 at SCO and IZO

In May 2007, two pollen concentration peaks of *Olea* and *Quercus* perennial type were observed at SCO and IZO: the first was on 7–11 May, and the second, with higher concentrations, on 16–20 May. At SCO, the concentration peak was simultaneous for both pollen types on 18 May. Pollen concentrations at SCO were always higher than those at IZO (Fig. 6a).

The meteorological scenario during the first episode was characterized by the presence of a high-pressure system located to the west of the Iberian Peninsula (Fig. 6b). This had a heavy impact on surface winds and caused the trade winds to be replaced by air streams coming from North Africa. This is confirmed by the ensemble back trajectories at 500 and 2,500 m.a.s.l. for 8 May (Fig. 6c,e), and the SeaWiFS images on 8 and 9 May, which show a clear dust intrusion over the North Atlantic impacting over the Canary Islands (Fig. 6d).

Although both the MBL and the FT were affected by this atmospheric situation, transport basically occurred at the lowest levels of the troposphere, producing higher concentrations at SCO. On 9 May (not shown), back trajectories at 500 and 2,500 m.a.s.l. showed a Moroccan origin, which crossed areas of distribution of *Olea* and *Quercus ilex* in northern Morocco (Charco 1999).

In the second episode, besides the western Iberian Peninsula high-pressure system, a low-pressure system was located in the center of the Sahara (not shown), reinforcing the air flow from the African Mediterranean region towards the Canary Islands. The second episode, from 16 to 20 May, corresponded to what we define as a combined transport. Combined transport would occur in two steps. Here, it began with an air movement produced by the depression over the Sahara, which carried a cloud of dust and pollen over the Atlantic, and, from that point, an air flux from the eastern branch of the high situated in the west of the Iberian Peninsula would impinge on the dust cloud, carrying the material to the Canary Islands (Fig. 6f).

Episode on 2–5 June 2007 at SCO and IZO

During the episode from 2 to 5 June 2007, a sudden increment of *Casuarina* daily concentrations at IZO, reaching values up to 221.9 p/m³, was observed. Simultaneously, *Olea* also showed significant increases at IZO (Fig. 7a). At SCO, significant peaks were found for *Olea*, *Quercus* perennial type, Poaceae wild type and *Vitis*. Possible pollen transport to IZO from the lower parts of the island was unlikely since moderate synoptic winds (higher than 20 km/h) were recorded at IZO on 3 and 4 June, inhibiting the valley-to-mountain breeze in the morning. During the night, a catabatic flow assures free-troposphere conditions at IZO. So, the remarkably high peak of *Casuarina* recorded at IZO, much higher than concentrations at SCO (non significant peak), must be due to long-range transport of pollen from higher altitudes. The SeaWiFS image, corresponding to 3 June, shows low stratocumulus in the northern part of the islands and a “dust-shadow” to the south (Fig. 7d). These two facts indicate that the dust cloud moving southwards affected only the high lands of Tenerife (IZO).

The synoptic meteorological situation was characterized by a high-pressure system over the north Atlantic in front of the Iberian Peninsula, and a low-pressure system situated over Sardinia and Corsica (Fig. 7b). In the preceding days, i.e., 1–2 June, several nuclei of low pressure formed also in North Africa. Under this atmospheric situation, ensemble back trajectories (Fig. 7c,e) and the forecast of the DREAM dust model indicated that air masses moved to the Canary Islands from the south of the Iberian Peninsula. A combined transport was also observed in this case, stemming from pattern similar to that previously described (episode 2.3): first, the air mass moved from Morocco and the Western Sahara to the Atlantic under the action of the North African low, and this was then mixed with the air mass coming from Iberian Peninsula to Tenerife. The pollen types identified during this episode are characteristic of Mediterranean vegetation assemblages

Table 2 Percent contribution of long-range transported pollen to total annual counts, calculated from the sum of peak events in each year

Year 2006	SCO	IZO
<i>Olea</i>	89	
<i>Vitis</i>	88	
<i>Quercus</i> deciduous type	86	
Cyperaceae	57	
Poaceae	29	
Chenopodiaceae-Amaranthaceae	27	
Year 2007		
<i>Olea</i>	94	97
<i>Quercus</i> perennial type	44	62
Poaceae	-	33

(Belmonte and Roure 1991), except for *Casuarina*. Hence, MBL pollen transport was from Iberian Peninsula air masses (Fig. 7c), whereas the FT pollen dynamic was characterized by combined transport (Fig. 7e), as confirmed by the important

arrival of *Casuarina* from Western Saharan and southern Morocco mixed with Mediterranean pollen types at IZO.

As seen by these meteorological transport pathways and the nature of the pollen types, the Mediterranean region

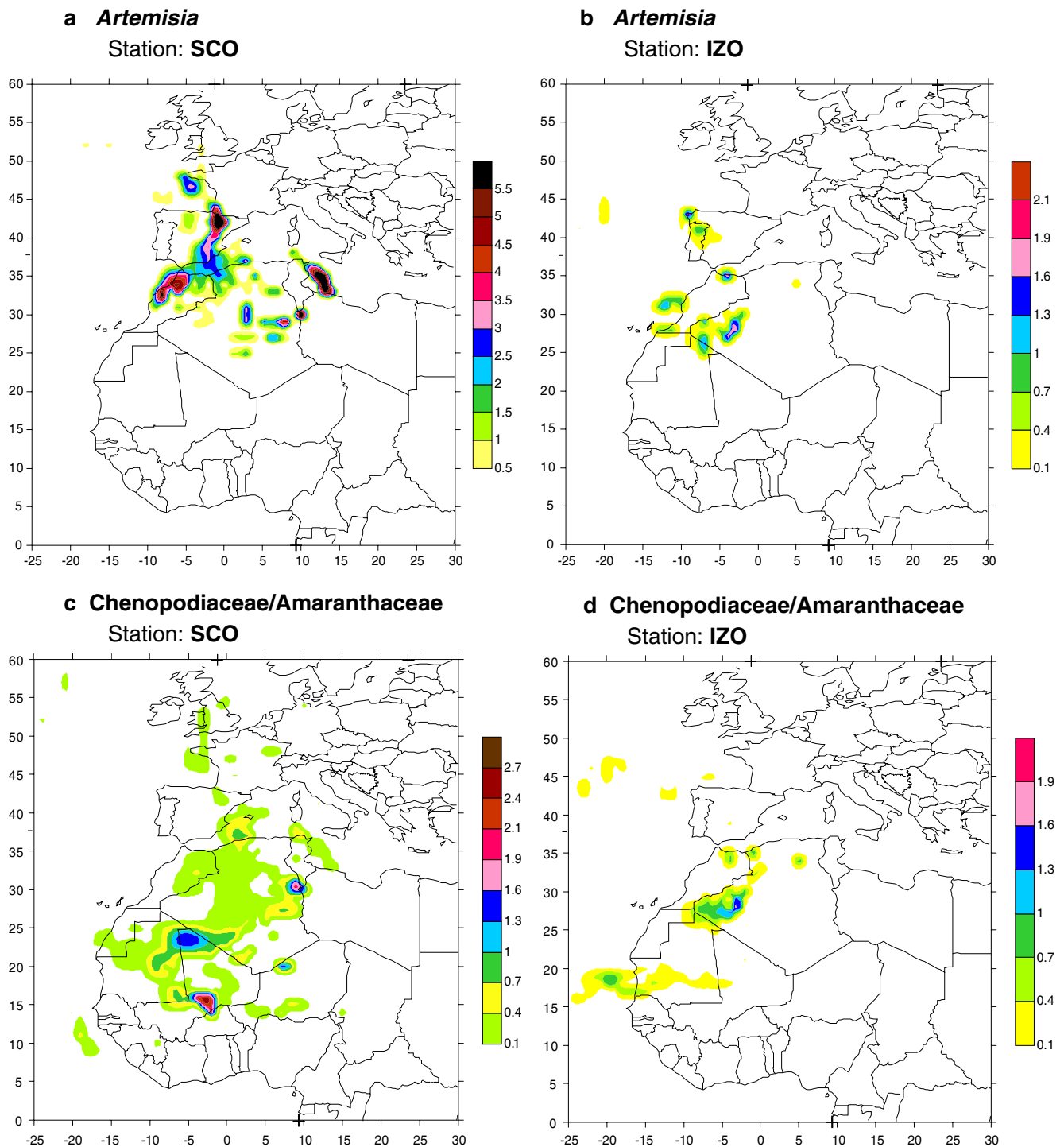


Fig. 8a–i Pollen concentration maps (p/m^3) derived from the application of Seibert et al. (1994) source–receptor model. **a** *Artemisia* at SCO, **b** *Artemisia* at IZO, **c** Chenopodiaceae/Amaranthaceae at

SCO, **d** Chenopodiaceae/Amaranthaceae at IZO, **e** Poaceae wild type at SCO, **f** Poaceae wild type at IZO, **g** Arecaceae at SCO, **h** Cyperaceae at SCO, **i** *Olea* at SCO

(broadly comprising the southern Iberian Peninsula and African Mediterranean regions) or the Sahara-Sahel are probable source areas for many of these pollens. Therefore, the meteorological information indicates that transport during these pollen peak days was from long-range transport. Based on this premise, we have evaluated the pollen contribution of peak days (extra-regional transport) and related it to the total

counts. Table 2 lists the percent contribution of the extra-regional sources for the two sites. It can be seen that *Olea*, *Vitis* and *Quercus* deciduous type were mostly of extra-regional origin (percentages between 86 and 97%). In other taxa (Cyperaceae and *Quercus* perennial type), outside sources predominated, though to a lesser extent (percentages of long-range transport 57–62%). On the other hand,

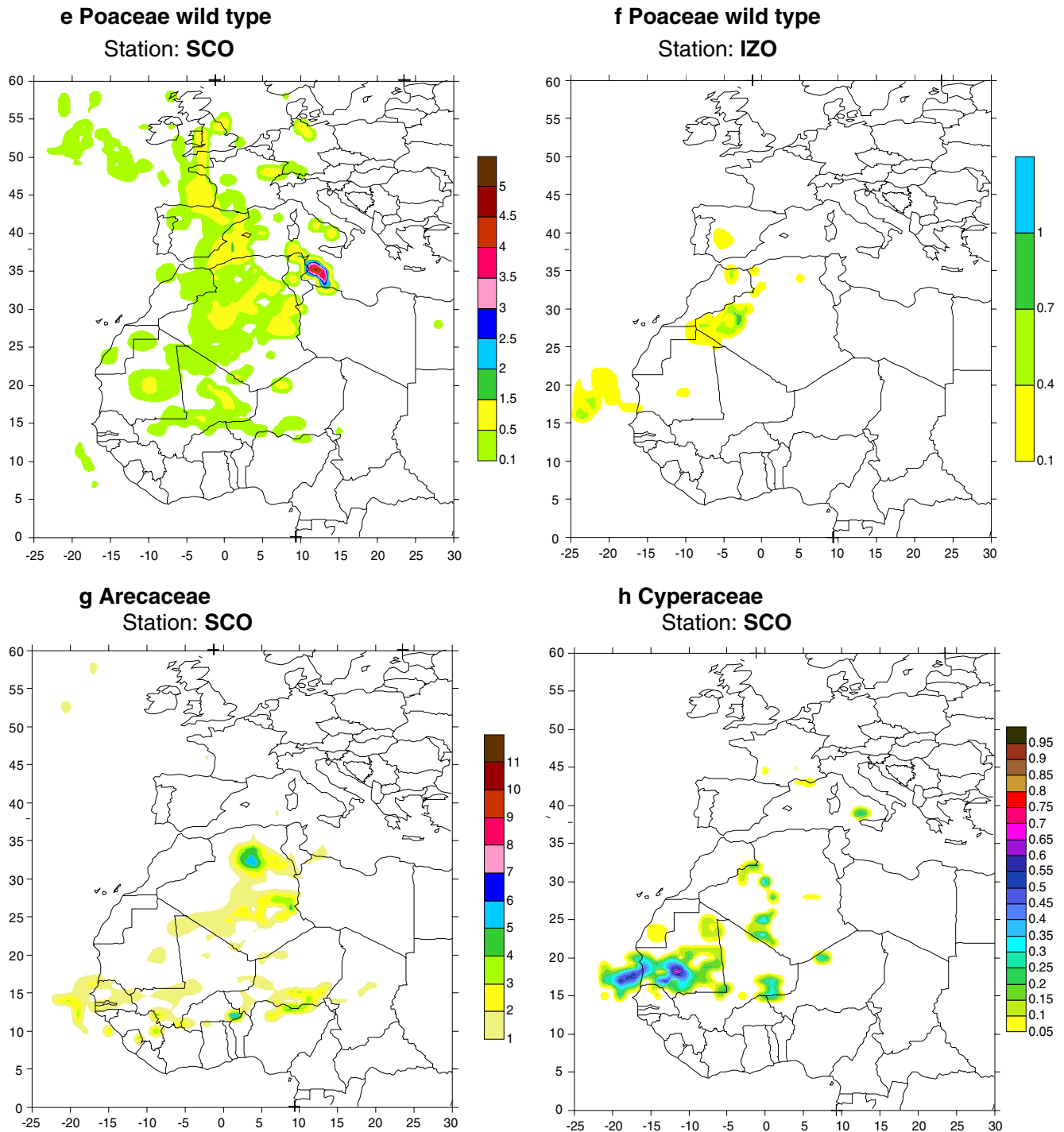


Fig. 8 (continued)

i *Olea*

Station: SCO

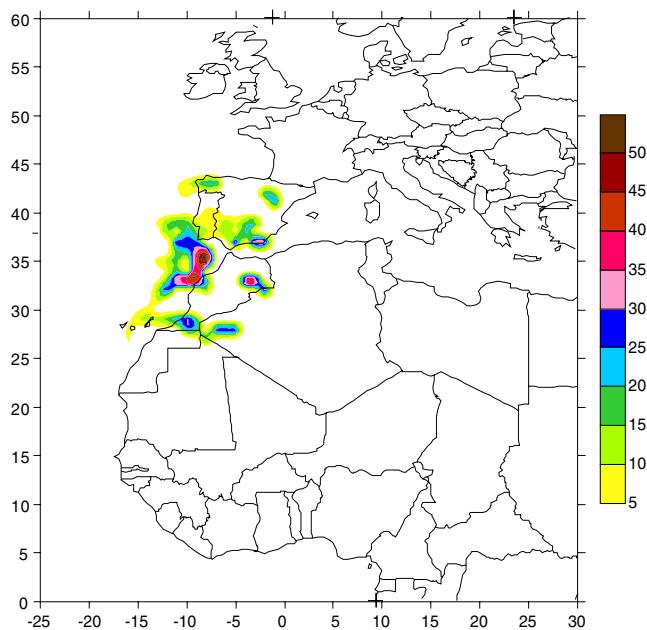


Fig. 8 (continued)

for very common and ubiquitous plants, such as the Poaceae and Chenopodiaceae/Amaranthaceae, only one-third of the annual counts was from extra-regional sources.

Source–receptor model

To further investigate the origins of the extra-regional pollen, a source–receptor model was applied to the taxa that indicated provenances from North Africa, Europe and Sahara-Sahel in the ANOVA analysis and the taxa that showed outstanding peaks (see above). Source–receptor models were applied to *Artemisia*, Chenopodiaceae/Amaranthaceae and Poaceae wild type at SCO and IZO, and to Arecaceae, Cyperaceae and *Olea* only at SCO (Fig. 8).

According to the maps of pollen concentration obtained with the source–receptor model (Fig. 8), the probable source areas were: North Africa and the Mediterranean region for Poaceae wild type; the Mediterranean region for *Artemisia* and *Olea*; Sahara and Sahel for Chenopodiaceae/Amaranthaceae and Arecaceae; and the Sahel for Cyperaceae.

Discussion

All pollen types identified as having a possible extra-regional origin in the island of Tenerife correspond to vegetation also present in the island, which illustrates the complexity of the subject studied. Most pollen transport

occurs within the island, but local pollen concentrations are usually low, and exhibit a narrow range of variation (Fig. 3). In the study cases presented here, pollen peaks increased drastically over background concentrations (Figs. 4–7). Furthermore, in all the presented cases, the pollen increase coincided with specific meteorological situations driving air masses from regions in which the plants providing the observed pollen are present. A synthesis of the evidence supporting long-range transport for pollen is summarized in Table 3. Considering the three approaches used to determine the transport (provenance analysis, specific case studies and source receptor modeling), four of the ten studied pollen types were associated with a possible Mediterranean origin: *Olea*, *Quercus* both deciduous and perennial types, and *Vitis*. It was estimated that 86–97% of the taxa pollen count of these types was from extra-regional sources. *Artemisia* and *Casuarina* were specifically related with the African Mediterranean Region. Arecaceae and Cyperaceae were probably transported from regions in the Sahel and the Sahara desert. Probable provenances for Chenopodiaceae/Amaranthaceae were North Africa, and for Poaceae wild type, provenance was North Africa together with the Mediterranean region. Other authors (see citations in Table 3) have also reported pollen transport from the proposed areas. The aerobiological study of Calleja et al. (1993) and the paleopalynological studies of Romero et al. (2003) and Hooghiemstra et al. (2006) reinforce the assumption of pollen transport from North Africa and from the southern Mediterranean to Tenerife for *Artemisia*, *Casuarina*, Chenopodiaceae/Amaranthaceae, Cyperaceae, *Olea*, *Quercus* perennial type and Poaceae wild type. Others studies carried out in Europe (Van Campo and Quet 1982; Franzen et al. 1994; Cariñanos et al. 2004) and at the Mediterranean Sea (Waisel et al. 2008) have also reported long-range transport of Arecaceae, *Artemisia*, Cyperaceae, *Casuarina*, Chenopodiaceae/Amaranthaceae and *Olea* originating in the Mediterranean area. The presence of these plants in the proposed source areas (African Flowering Plants Database, version 3.1, <http://www.ville-ge.ch/musinfo/bd/cjb/africa/>) supports the assumption proposed in this paper.

The strong influence of the trade winds from the northeast over Tenerife (Rodríguez 1999), together with the high plant diversity of the vegetation in the Mediterranean region can explain the high number of pollen types related with a Mediterranean provenance. In contrast, pollen types originated in the Sahel and the Sahara desert would correspond to vegetation in extreme environmental conditions that only occasionally finds climatic conditions adequate for pollination. With the exception of palm trees (Arecaceae), taxa from the African provenance were clearly characterized by the predominance of herbaceous taxa, similar to the findings of Hooghiemstra et al. (2006). Finally, the wide provenance area found for Chenopodiaceae/

Table 3 Summary of evidence supporting extra-regional pollen transport to Tenerife. Probable source areas are proposed, and references supporting this hypothesis are included. Period Index is the sum of the mean daily pollen concentrations during the study period (01/01/2006-31/12/2007 at SCO and 11/06/2006-11/11/2006 and 23/04/2007-04/11/2007 at IZO). References: ¹ Van Campo and Quet 1982; ² Calleja et al. 1993; ³ Franzen et al. 1994; ⁴ Romero et al. 2003; ⁵ Carriñanos et al. 2004; ⁶ Hooghiemstra et al. 2006; ⁷ Waisel et al. 2008

	Period Index (pollen)	Provenance by sectors from ANOVA	Date	Area of provenance for Specific case studies	Source area from source-receptor models	Probable extra- regional origin	Supporting references
<i>Olea</i>	SCO 295	-	May 2006, May 2007, June 2007	Mediterranean	Mediterranean (Iberian Peninsula and Morocco)	Mediterranean (SCO)	Calleja et al. 1993; Franzen et al. 1994; Hooghiemstra et al. 2006
<i>Quercus</i> deciduous type	IZO 23	-	May 2007, June 2007	Mediterranean	-	-	-
	SCO 14	-	May 2006, June 2007	Mediterranean	-	Mediterranean	-
<i>Quercus</i> perennial type	IZO 8	EU+MED-NAF	-	-	-	-	-
	SCO 102	-	May 2007, June 2007	Mediterranean	-	Mediterranean	Calleja et al. 1993; Hooghiemstra et al. 2006
<i>Vitis</i>	IZO 13	-	May 2007, June 2007	Mediterranean	-	-	-
	SCO 4	-	May 2006, June 2007	Mediterranean	-	Mediterranean	-
<i>Artemisia</i>	SCO 985	-	-	-	Mediterranean-Saharan Transitional Steppes	(SCO) African Mediterranean Region	Calleja et al. 1993; Franzen et al. 1994; Romero et al. 2003; Hooghiemstra et al. 2006
	IZO 68	MED-NAF	-	-	Mediterranean	-	-
<i>Casuarina</i>	SCO 26	MED-NAF	-	-	-	African Mediterranean Region	Van Campo and Quet 1982; Calleja et al. 1993; Carriñanos et al. 2004
	IZO 704	-	June 2007	African Mediterranean region	-	-	-
Poaceae wild type	SCO 449	-	May 2006, November 2006, June 2007	Mediterranean Sahara-Sahel	Sahel, Sahara desert and Mediterranean	Mediterranean and North Africa	Calleja et al. 1993; Romero et al. 2003; Hooghiemstra et al. 2006
	IZO 97	-	June 2007	Mediterranean	Sahara desert	-	-
Chenopodiaceae /Amaranthaceae	SCO 269	North Africa	November 2006, June 2007	Mediterranean Sahara	Sahara desert and Sahel (Mauritania, Mali, Algeria)	North Africa	Calleja et al. 1993; Franzen et al. 1994; Romero et al. 2003; Hooghiemstra et al. 2006; Waisel et al. 2008
	IZO 0	-	-	-	-	-	-
Arecaceae	SCO 720	SAHEL-SGR	-	-	Sahel and Sahara desert (Algeria)	Sahel and Sahara desert (Algeria) (SCO)	Waisel et al. 2008
	IZO 6	-	-	-	-	-	-
Cyperaceae	SCO 15	SAHEL-SGR	November 2006	Sahara	Sahel and Sahara desert	Sahel and Sahara desert	Franzen et al. 1994; Romero et al. 2003
	IZO 15	-	-	-	-	-	-

Amaranthaceae and Poaceae wild type pollen is explained by these families being cosmopolitan (Mabberley 1987)

The period index (Table 3) is the sum of the mean daily pollen concentrations during the study period. This value was larger at SCO than at IZO, except for *Casuarina*. Higher values at SCO come from: (1) the study period being longer at this site, and (2) the local vegetation at SCO producing higher amounts of pollen (for example, of Arecaceae and *Artemisia*). However, the observed higher period index for *Casuarina* at IZO was due to a combined mechanism in which the air mass containing this pollen was uplifted and moved to the west in a cyclonic motion by the action of the north African low as described above. This pollen then crossed the top of the MBL and entered the FT, where it could be transported by the eastern branch of the north Atlantic anticyclone (Fig. 7).

Concerning long-range transport, the values observed in the period index, along with evidence from the case studies, indicate that most such transport would occur through the trade winds. In some cases (such as Chenopodiaceae-Amaranthaceae at SCO and IZO, Cyperaceae at SCO and Poaceae wild type at IZO), the three approaches used indicate the same provenance, and other work supports this result (see references in Table 3). Although these taxa could also have a regional origin due to their cosmopolitanism (Mabberley 1987), the evidence revealed here reinforces the hypothesis that a long-range transport also exists.

For other taxa (such as Arecaceae at SCO, *Artemisia* at IZO and *Olea* at both sites) two of our approaches support the designation of a provenance that is also supported by the literature. Again, although these taxa can have a regional origin, evidence for provenance from far distant regions was found.

For other taxa, or for a given station, only one analysis suggested an extra-regional provenance and for some of these taxa (*Quercus* deciduous type and *Vitis*), no supporting reference was found in the literature. Finally, we found no evidence of transport from foreign areas for Arecaceae, Cyperaceae, and *Vitis* at IZO.

Conclusions

In conclusion, our results indicate several extra-regional pollen transport episodes to Tenerife. The main provenances were: (1) from the Mediterranean region, especially from the southern Iberian Peninsula and Morocco through the trade winds in the MBL. These episodes were characterized by the presence of tree pollen (*Casuarina*, *Olea*, *Quercus* perennial and deciduous types) and mixed with herbaceous pollen (*Artemisia*, Chenopodiaceae-Amaranthaceae and Poaceae wild type). (2) Transport from the Saharan sector at the MBL level, carrying principally herbaceous pollen

(Chenopodiaceae-Amaranthaceae, Cyperaceae and Poaceae wild type) and, in one case, *Casuarina* pollen, uplifted to the free troposphere. And (3) from the Sahel, which appears as episodes of low frequency associated to high pressure systems over north Africa and characterized by low concentrations of the transported pollen taxa (Arecaceae, Chenopodiaceae-Amaranthaceae, Cyperaceae and Poaceae wild type).

The capacity for sensitization to pollen is theoretically universal. Several of the studied taxa with an extra-regional origin (such as *Artemisia*, Chenopodiaceae/Amaranthaceae, *Olea*, Poaceae wild type and *Quercus* perennial type) are among those causing most common allergies (Bousquet et al. 2008). Other studied taxa (Arecaceae, *Casuarina* and Cyperaceae) have also been recognised as allergenic (Lewis et al. 1983). The prevalence (percentage of pollen causing the allergy) observed in Tenerife in patients with confirmed pollinosis has been: *Artemisia* 64.5%, Gramineae or Poaceae 45.2%, Urticaceae 24.5%, *Chenopodium* 9.4% and *Salsola* 6.2% (Belmonte et al. 2008b). This research shows that sporadic events of long-range pollen transport need to be taken into consideration as being responsible for respiratory allergy episodes, as has been found also in other studies (Estrella et al. 2006; Skjøth et al. 2007; Siljamo et al. 2007, 2008).

Acknowledgments This research received financial support from the Spanish government through the projects CGL2005-07543, CGL2009-11205, CGL2009-13188-01 and the “Subprograma MICINN-PTA” funded by the European Social Fund (ESF). We also thank the contribution of CONSOLIDER-Ingenio 2010 projects “Multidisciplinary Research Consortium on Gradual and Abrupt Climate Changes, and their Impacts on the Environment” (GRACCIE) and CSD2008-00040 “Los montes españoles y el cambio global: amenazas y oportunidades (MONTES)”. Also, the “COST Action ES0603: EUROL Assessment of production, release, distribution and health impact or allergenic pollen in Europe” and “Proyecto EOLO-PAT (Predicción Aerobiológica para Tenerife), which is a joint project between Laboratori d'Anàlisi Palinològiques, Centro de Investigación Atmosférica de Izaña (CIAI) and Air Liquide España S.A. The authors also gratefully acknowledge the collaboration of Sergio Afonso (responsible for collection samples in IZO y SCO) and Rut Puigdemunt (responsible for pollen analysis in SCO). Finally, we thank the NASA for satellite images acquired by SeaWiFS (Sea-viewing Wide Field of view Sensor) and MODIS (Moderate Resolution Imaging Spectroradiometer).

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