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A case study of anisotropic airborne pollen transport in Northern Patagonia using a Lagrangian particle dispersion model

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ABSTRACT

Accumulated pollen sequences are used to infer temporal changes in vegetation composition. Pollen transport and dispersal by winds introduce large biases in the interpretation of pollen records. In order to calibrate the models used to infer past species distributions, human activities or climate, contemporary time series of pollen records are assessed and modelled. The Gaussian plume model assumes that pollen transport takes place in a neutral atmosphere and pollen contribution is even from all directions (isotropy). In this study, we analyse these assumptions with airborne pollen measurements of *Weinmannia trichosperma*, a forest tree which grows mainly on the western slopes of the Andes, along with other characteristic species of the steppe which develops in eastern Patagonia. Instead of the Gaussian plume mixing model that is usually employed in the theory of pollen analysis, we apply a full 3D Lagrangian dispersion model, which allows calculation of potential source distributions (footprint) from modelled backward trajectories of airborne pollen observations. Results show that neutral atmospheric conditions are properly assumed for the region. The footprint calculated from the modelled trajectories of a five-year record is consistent with the location of pollen sources but the footprint shape showed that pollen contribution is uneven due to the influence of transient weather systems.

1. Introduction

Quaternary pollen analysis is concerned with inferring temporal changes in vegetation from pollen assemblages to reconstruct past species distributions, human activities and climate change (Davis, 1963; Webb, 1987; Faegri and Iversen, 1989; Kershaw et al., 2003). In order to infer past vegetation composition, palynologists wish to know pollen–vegetation relationships, but interpretation of pollen data is not straightforward. Two major sources of variation affect pollen percentages, the production bias and the dispersal bias (*sensu*Prentice, 1985). Production bias refers to different pollen quantities produced by different plant species, which is also affected by other factors such as soils, reproductive biology and climate. Dispersal bias is mainly related to the atmospheric physical processes involved in pollen transport from any source towards its final destination.

Traditionally, from the early beginnings to the latest attempts to formalise a quantitative theory of pollen analysis (*ie*. Tauber, 1965, 1977; Birks and Birks, 1980; Birks and Gordon, 1985; Prentice, 1985; Sugita, 1993, 1994, 2007a, 2007b), dispersal has been described using Sutton's equations. (1947, 1953). Sutton's equations are based on the Gaussian plume model that summarises the probabilistic behaviour of mass particles emitted from a point, line or area source. Some basic assumptions are made for those approaches: (1) transport occurs at 3 m/s in a neutrally stratified atmosphere (resulting in turbulence that is nearly of equal intensity in all directions), (2) pollen is emitted at ground-level, (3) pollen is mainly dispersed by wind and (4) airborne pollen contribution is even in all directions (isotropy). Tauber (1965) and Prentice (1985, 1988) confirmed the validity of the first two assumptions over a wide range of environmental conditions while assumption (3) could be achieved with careful site selection, such as closed small basins. Isotropy, however, could not always be easily sustained. Prentice (1985) argued that if the wind blows from some directions more frequently than from others, then source strengths should be directionally weighted. Recent improvements consider directional weighting using wind roses (Bunting et al., 2008) but, they do not account for multiscale atmospheric variability. As Gaussian models approximate the dispersal flow

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with probabilistic laws and parameters from a steady-state atmosphere, there is limited capability to incorporate transitory airflows that are likely to affect pollen dispersal (Kuparinen et al., 2007). They also have many features that do not necessarily apply to dispersion phenomena at all spatial scales (Gifford, 1968; Hanna et al., 1982; McCartney and Fitt, 1985) which imply severe restrictions to their applicability beyond a maximum distance, as already reported by Theuerkauf et al. (2013).

Empirical, quasi-mechanistic and fully mechanistic models have also been developed to address some of these limitations (Kuparinen, 2006). Empirical models are strongly dependent on the experimental conditions. As a consequence, generalising their results is difficult. Mechanistic models such as Lagrangian Particle Dispersion Models[1] are able to incorporate environmental variation in the predicted dispersal pattern and are thus preferable (Kuparinen, 2006). The theory of stochastic Lagrangian models was first published by Rodean (1996) and reviewed by Wilson and Sawford (1996). Although commonly applied to pollution studies (Liu and Seinfeld, 1967; Stohl, 1996, 1998; Jaffe et al., 1999), in the last two decades, LPDMs have also been applied to pollen and spore transport with great success (*e.g.*Rantio-Lehtimäki, 1994; Campbell et al., 1999; Van de Water and Levetin, 2001; Adams-Groom et al., 2002; Van de Water et al., 2003; Sofiev et al., 2006). LPDMs overcome limitations calculating trajectories of a large number of particles (not necessarily representing real particles, but infinitesimally small air parcels) to describe the transport and diffusion of tracers in the atmosphere (Stohl et al., 2005). Accurate turbulence parameterizations allow accounting for non-local transport, anisotropy and non-stationary conditions. LPDMs use meteorological fields (analyses or forecasts) on a 3D latitude/longitude/altitude grid format from numerical weather prediction models (Stohl et al., 2005). Running the model backwards is technically feasible with little or no modification to the forward mode. This allows for potential source distribution (footprints) to be calculated in any flow regime, *i.e.* a non-Gaussian convective atmosphere. According to Leclerc and Thurtell (1990), the footprint represents the effective upwind source area sensed by an atmospheric observation. While the potential source of pollen could be the total area of a species distribution, the footprint is a partition of this distribution where suitable weather conditions for transportation to a target location are met. Thus, footprints calculated with trajectories represent more realistic source distributions than those calculated with Gaussian plume models.

In this paper, we check the validity of atmospheric neutrality and isotropic contribution for Northern Patagonia (assumptions 1 and 4), studying the wind regime during the flowering period and applying FLEXPART, a model for atmospheric transport representing the Lagrangian trajectories of particles in the atmosphere, for the analysis of airborne pollen samples collected at Bariloche City (41°10′S, 71°15′W). Footprints were calculated and validated with ancillary pollen types from other biomes in order to assess the influence of pollen sources across the Andean range.

2. Data and methodology

2.1. Study area and period

The eastern flank of the Andes shows one of the sharpest ecotone in the world (Fig. 1) which is expected to undergo pronounced shifts and changes in plant composition in response to climate change and land use in the next decades. The multiscale response of the forest to steppe transition to climate is still poorly understood, therefore is being studied in many paleoecological investigations. This vegetation change responds to mean annual precipitation, which decreases from 3000 mm in rainforests to <500 mm only 80 km to the east in the steppe, due to the rain shadow effect produced by the mountain range (Whitlock et al., 2006).

Bariloche City (41°10′S, 71°15′W; 850 m elevation) is located in a hilly topography within the boundaries of the Nahuel Huapi National Park. The Sub-Antarctic, Alto Andean and Patagonian phytogeographic provinces are well represented in the region (Cabrera and Wilkins, 1973; Paruelo et al., 1991). Pollen from *Nothofagus dombeyi* and *Austrocedrus chilensis* the dominant tree species in the phytogeographic provinces accounts for ca 70% of airborne pollen measured in the city (Bianchi and Olabuenaga, 2006). In the steppe, xeric shrubs and herbs taxa, such as *Mulinum*, *Schinus*, *Acaena*, *Ephedra* and Asteraceae, are dominant.

The climate of the region is Cs type, temperate with dry summers (Köppen, 1948). Mean annual temperature is 8.1 °C, ranging from 2.5 °C in July to 14 °C in January. Sixty-four percent of the precipitation, falls between May and August, mostly in the form of snow. The mean annual relative humidity is 68%. Westerly winds prevail throughout the year, with an annual mean speed of 6.3 m/s (National Meteorological Service, period 1961–1990).

The study period comprises spring, summer seasons from 2002 to 2006 (OND-JFM in the Southern Hemisphere) when pollen production and release takes place (Bianchi and Olabuenaga, 2006). Dispersal and deposition on other seasons are negligible (Bianchi and Olabuenaga, 2006).

2.2. Analysis of wind frequency and stability classes

In order to test the assumptions of the Gaussian model, mean wind intensity and direction for the study period were clustered into 8 directions: N, NE, E, SE, S, SW, W and NW. Data were measured at Bariloche Aero station (National Meteorological Service, WMO station N: 87765, 854 m a.s.l.). Turbulence conditions were analysed using the Turner classification criterion, which considers seven classes: three unstable (1, 2, and 3), one neutral (4) and three stable (5, 6, and 7), (Turner, 1964). During unstable conditions, the turbulence is mostly triggered by temperature while during stable conditions it is inhibited. In neutral condition, turbulence is caused by wind. The Turner method requires data of wind speed and direction, cloud cover, ceiling height, date, hour and time zone.

2.3. Trajectory model

In this study we use FLEXPART (Stohl et al., 2005), which is a free software model (https://flexpart.eu/) for atmospheric transport representing the Lagrangian trajectories of a large number of particles in the atmosphere. These particles, which can be tracked forward or backwards in time, are driven by wind fields such as those produced by 3D meteorological forecast models. For typical atmospheric conditions, pollen dispersal over long distances follow the air flows, even turbulent eddies (Jackson and Lyford, 1999), and pollen fall speed has a small effect in LPDMs (Theuerkauf et al., 2013). Therefore, pollen transport in the atmosphere can be treated *via* existing advection–diffusion schemes (Sofiev et al., 2006).

To simulate transport processes FLEXPART calculates the trajectories of large number of particles as

$$X(t+\Delta t) = X(t) + v(X,t)\Delta t$$

With t being time, Δt the time step, X the position vector, and $v = \overline{v} + v_t + v_m$ the wind vector composed of the grid scale mean wind $\overline{v}$, the turbulent wind fluctuations v_t and large scale wind fluctuations v_m caused by weather systems (Zanetti, 1992; Stohl, 1998). A complete theory of modelling transport backward in time with LPDMs was developed by Flesch et al. (1995) and Seibert and Frank (2004).

Wind fields used in this study come from the ERA-Interim global atmospheric reanalysis provided by the European Centre for Medium-

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[1] From here on LPDMs

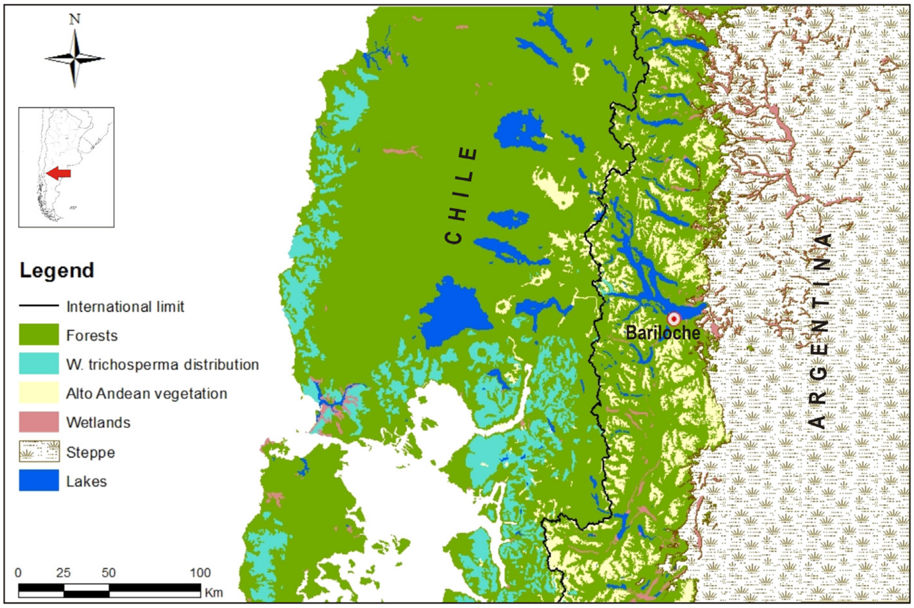

Fig. 1. Study area with its vegetation types. Modified from (Lara et al., 1999).

Range Weather Forecasts (ECMWF, http://www.ecmwf.int/). The spatial resolution of the data set is approximately 80 km on 60 vertical levels from the surface up to 0.1 hPa. The vertical coordinate was transformed from pressure to meters of altitude to be used by the model. FLEXPART was set to calculate an ensemble of 10 backward trajectories starting at each hour of each day of the study period, which gives a total of 240 daily runs and 172,800 for the entire period. Time and position coordinates were stored for 120 hourly time steps for each backward trajectory. Daily footprints were calculated considering grid-cells of 0.125° latitude × 0.125° longitude × 1000 m high above ground. Trajectories at higher levels were not considered as they correspond to free atmosphere that is not related with the underlying vegetation. The frequencies (number of trajectories within each grid-cell) were weighted considering the number of runs per day and the total time spent by the trajectories within each grid-cell. Therefore, weighted frequencies correspond to the "average residence time" of particles in each grid-cell. Results (Figs. 3 b, e, h and 5) are presented using a colour scale, which represents the average residence time.

2.4. Trajectory validation

Calculated trajectories are only based upon meteorological information. Therefore, they describe the position of air parcels in time and space but tell us nothing about their pollen content. Bariloche aerobiological station provided the airborne pollen data set used for trajectory validation. This monitoring station performed daily recordings of airborne pollen concentration from 2002 to 2006 with a Hirst type trap (Hirst, 1952) located at the top of a 15 m high building. Exotic urban trees and the Sub-Antarctic forest located several hundred meters to the west of the trap location were the main nearby pollen sources. The sampling technique consists in deposition of dust, pollen and spores suspended in a constant air flow on a sticky tape by inertial impaction. Microscope slides were prepared, and pollen grains were counted with standard techniques consisting of six longitudinal traverses, which represent 3% of the total slide area (Bianchi and Olabuenaga, 2006). Data are reported as number of pollen grains per cubic meter of air.

In order to evaluate trajectories, we tested whether daily westerly or easterly footprints matched with pollen coming from the western forest or the eastern steppe areas. Pérez et al. (2009) already confirmed the influence of westerly circulation on pollen transport in the region by the presence of "tineo" (*Weinmannia trichosperma*), a characteristic forest tree that grows predominantly on the western slopes of the Andes. *Weinmannia* pollen was solely selected as forest tracer, because it is the only pollen type that undoubtedly can be assigned to discrete source locations far enough from the sampling point (Fig. 1). Pollen types, which are considered as steppe tracers, are listed in Table 1.

The combined pollination season of the tracer species is long enough to cover the entire spring to summer period. Poaceae was not considered for the analysis because it is a large family with many species that grow in various environments.

Trajectories were also classified according to their meridional (north south) and zonal (west east) origins to study the monthly relative contribution to the sampling point. Particularly, we analysed the match of zonal trajectories with a daily forest pollen index (FPI_d) calculated as

$$FPI_d = \frac{\sum_{i=1}^{n_d} X_{id}}{PS_d} 100$$

Where PS_d is the pollen sum (forest and steppe species) for day d, n_d the number of forest species present at day d and X_{id} the pollen count of the forest species i at day d. For the complete list of forest pollen taxa see Bianchi and Olabuenaga (2006). This index describes the relative frequency of pollen input from the forest. Consequently, values higher than 50% indicate greater contribution from the forest, while those below this threshold show greater contribution from the steppe.

Table 1
List of taxa and pollination syndrome considered characteristic steppe pollen types.

Pollination syndrome	Pollen type
Anemophilous	*Plantago*
Anemophilous	*Rumex*
Entomophilous	*Acaena*
Entomophilous	Asteraceae
Entomophilous	*Nassauvia*
Anemophilous	*Ephedra*
Entomophilous	*Euphorbia*
Entomophilous	*Schinus*
Entomophilous	Apiaceae
Anemophilous	*Salix*
Entomophilous	*Gomphrena*

3. Results

3.1. Wind and stability class analysis

Westerly wind prevails at Bariloche City with monthly frequencies ranging from 53.7 to 62.8% followed by NW and SE directions (Fig. 2a). The highest calm frequencies (20%) are seen from January to March. Wind speed exceeded 3 m/s for 57 to 73% of the hours studied, depending the considered month (Fig. 2b). In accordance with the observations of van Loon (1964) for mid and high latitudes of the Southern Hemisphere, highest wind speeds near the ground were registered in November and December. Persistence of high wind speeds lead to proper conditions for the generation of mechanical turbulence, which led to the predominance of neutral conditions (class 4 in the Turner criterion) whose persistence varied from 48.4 to 60.8% (Fig. 2c).

3.2. Daily scale analysis

Fig. 3 shows three examples of the daily trajectory patterns registered in the study site. Western trajectories are the most common case over the entire study period (82.5%). In these cases, no steppe pollen was recorded. It is worth remembering that with western trajectories forest pollen is ubiquitous. However, within the flowering period of the chosen forest tracer (December–March), only 19% of the trajectories of western origin carried *Weinmannia* pollen to the sampling site. This small percentage is due to the distance to the source (Fig. 1), and the ecological conditions in which this species grows (see discussion). Fig. 3a corresponds to the situation recorded on 16 January 2005 when 4 grains/m^3 of *W. trichosperma* were detected at Bariloche aerobiological station. Trajectories arrive entirely from SW direction (Fig. 3c). The footprint therefore exhibits the same orientation (Fig. 3b).

Eastern trajectories reached a frequency of 11.5% during the study period, and 35% of them recorded steppe pollen tracers. Less than 1% of these trajectories also carried *Weinmannia* pollen as a result of recirculation. Fig. 3d shows the situation of 31 January 2006 when 7 grains/m^3 of steppe pollen types (*Rumex*, *Plantago* and Asteraceae) were recorded with trajectories coming from the east.

Only 6% of the analysed cases corresponded to trajectories coming from variable directions with forest and steppe pollen tracers. The example corresponds to the situation of 21 January 2006 when 4 grains/m^3 of steppe pollen (*Plantago, Rumex* and *Acaena*) and 1 grain/m^3 of *Weinmannia trichosperma* were recorded at Bariloche station (Fig. 3g).

3.3. Meridional and zonal contribution of trajectories

Calculations were made for the entire study period (30 months). As an example, Fig. 4 summarises the meridional and zonal origins of trajectories calculated for January 2006. There is similar chance to receive trajectories that arrive from north or south direction, while western trajectories are more frequent than eastern ones. The same pattern could be seen for the entire study period (not shown).

The forest pollen index calculated at the sampling point is related to the west to east trajectory frequencies (Fig. 4b). Both curves show a quasi-periodic oscillation between 4 and 7 days which corresponds to the characteristic frequency of the passage of weather systems.

3.4. Residence time of trajectories

Fig. 5 summarises the residence time of the air parcels for the whole study period. The air parcels that remain longer in each grid cell (longer residence time) are more likely to acquire a higher pollen load from the underlying vegetation. Consequently, these grid cells are also more

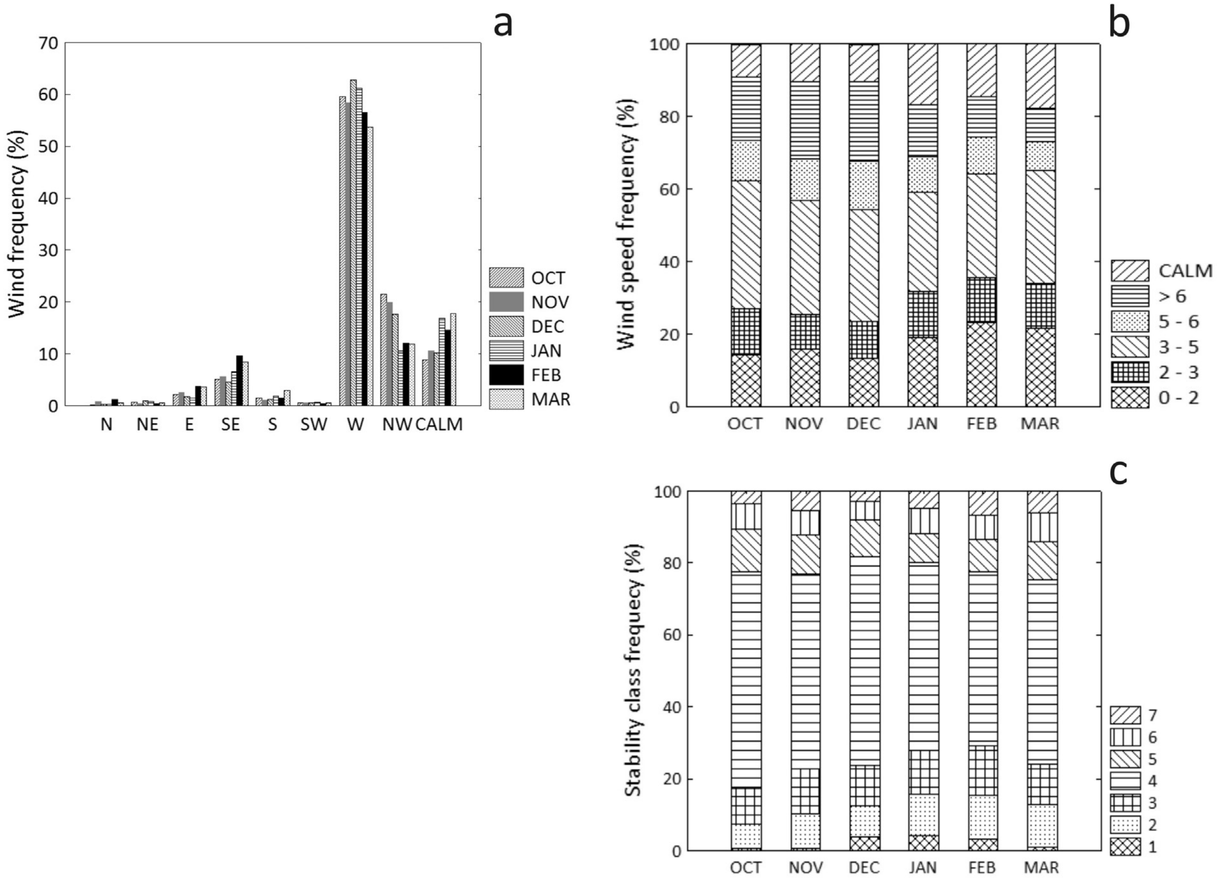

Fig. 2. Wind analysis and stability classes for Bariloche Aero station from October 2002 to March 2006. Frequencies of: (a) wind direction, (b) wind speed (m/s) and (c) Turner's stability classes: 1 - extremely unstable, 2 - unstable, 3 - weakly unstable, 4 - neutral, 5 -weakly stable, 6 - stable, 7 - extremely stable.

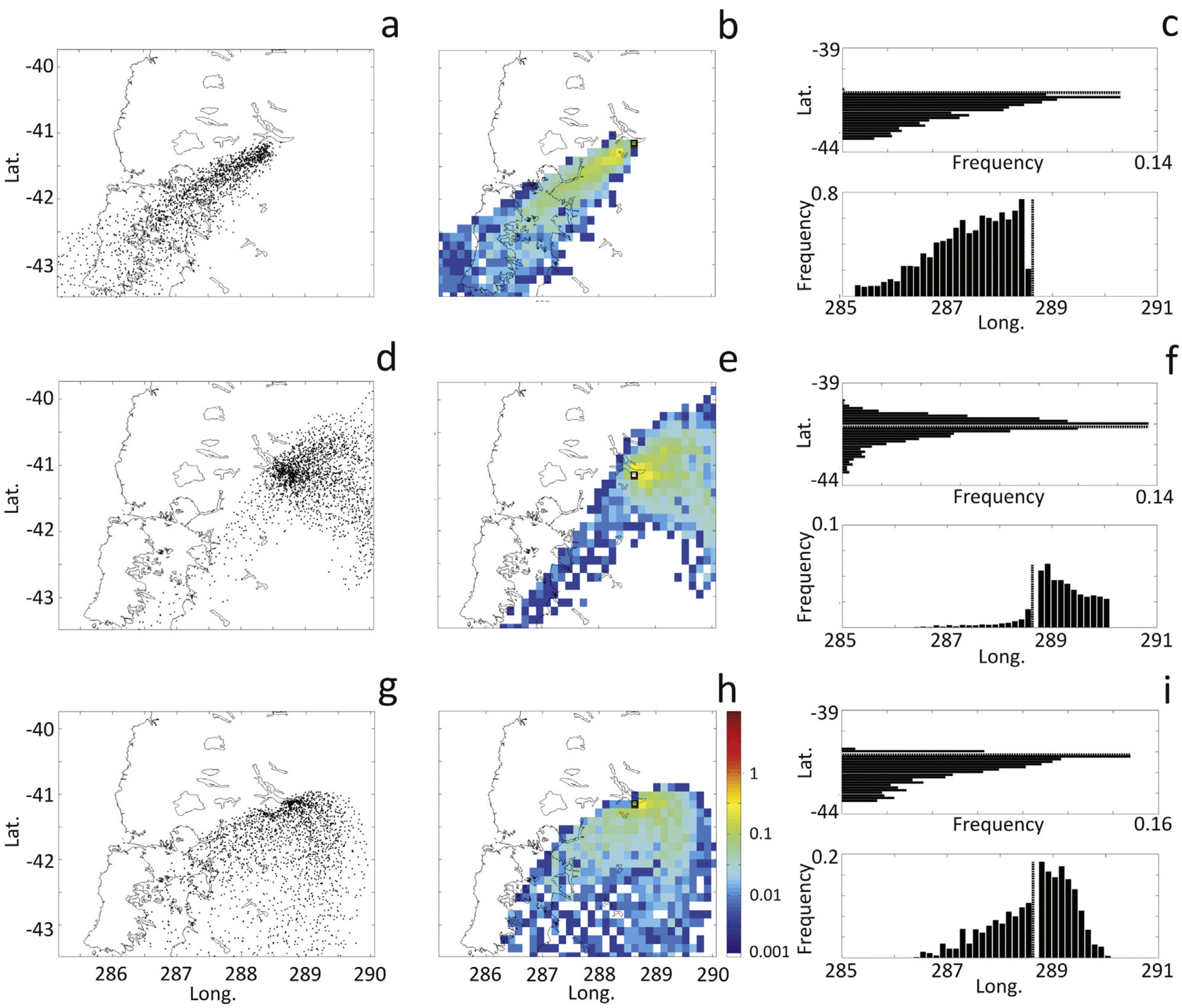

Fig. 3. Case examples of backward trajectories converging at Bariloche Station for 16 January 2005, 31 January 2006 and 21 January 2006 (a, d, g). Points represent the position at one-hour time steps. Density of trajectories (b, e, h) and calculated footprint (c, f, i) respectively.

likely to contribute to the pollen load registered in the target site. Two different areas can be distinguished: the first one shaded in dark red, extends approximately 50–60 km westward from the sampling point. In this area, air parcels on average spend 1 h on each grid cell. The second one is shaded in orange, and shows three lobes: the main one, extending towards the west as expected from the most frequent wind direction, and other two extending approximately 130 km to SW and 50 km to NE over the South Antarctic forest and the Patagonian steppe, respectively. The average residence time within this area range from 10 min to 1 h.

4. Discussion

4.1. Isotropy and neutral conditions: are these assumptions valid in Northern Patagonia?

Sutton's equations, adjusted to neutral atmospheric conditions, and isotropy, have been recognised as potential sources of error in reconstruction models (Brioude et al., 2012; Cassiani et al., 2015).

Atmospheric stability is an important characteristic because it affects the degree of turbulence and diffusive spread (Gifford, 1968). Neutral

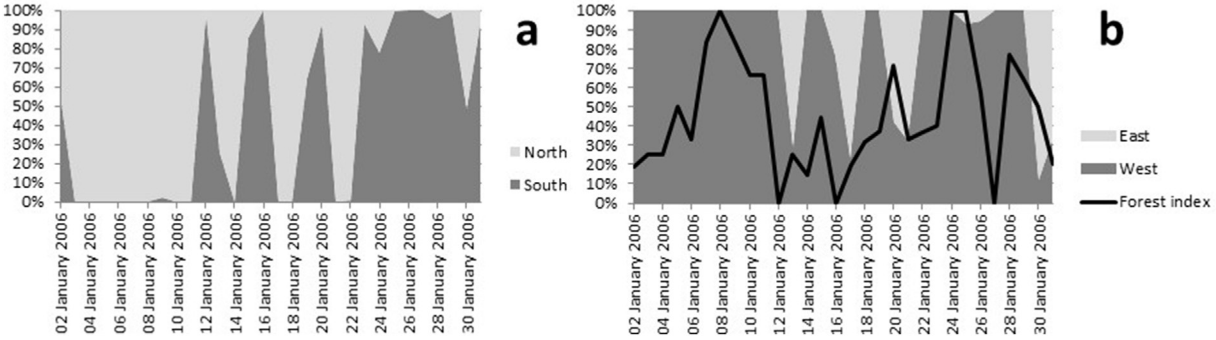

Fig. 4. Estimation of the air origin at Bariloche for January 2006. (a) Meridional origin (b) Zonal origin and daily forest pollen index calculated for January 2006.

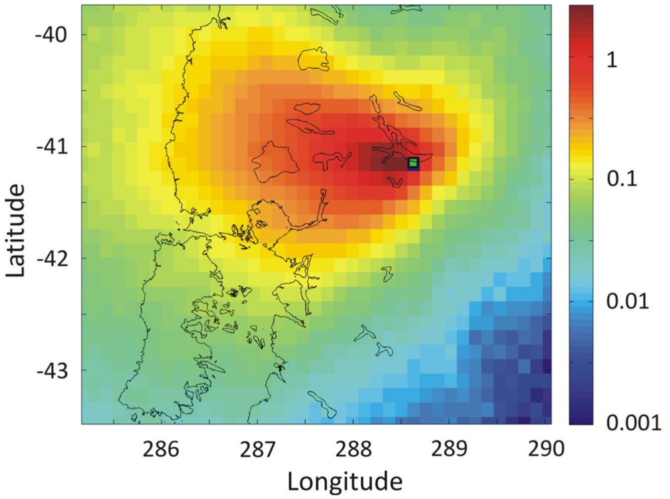

Fig. 5. Airborne transport around Bariloche. The scale shows the residence time (hours) of an ensemble of Lagrangian backward trajectories for OND-JFM 2002–2006.

conditions occur when the relationship between height and temperature above ground follow the adiabatic lapse rate. Low incoming radiation produces small buoyant forces and mechanical turbulence is induced by winds thus, neutrality prevails during days with cloudy skies and steady strong winds. In stable atmospheric conditions, temperature decreases with height more slowly than the adiabatic lapse rate, which causes rising air to be increasingly cooler and denser that its surroundings, and hence will sink supressing turbulence. This condition usually prevails at night. Conversely, unstable conditions occur when temperature decreases with height faster than the adiabatic lapse rate, which leads to buoyancy, faster rising air and larger eddies. These conditions are common during warm, clear sky days. Atmospheric stability usually alternates diurnally between stable conditions at night, unstable during daytime, while neutral is common at dawn and dusk (Gifford, 1968). According to literature, pollen is released mainly during daylight hours when the atmosphere is predominantly unstable (Jackson and Lyford, 1999 and references therein). As a consequence, pollen is entrained into upper air by vertical eddies, where it can be carried long distances. Airborne pollen transport calculations are usually made for neutral conditions due to the lack of *in situ* empirical measurements. This inevitably leads to underestimation of pollen dispersal (Jackson and Lyford, 1999 and references therein). Results show that in northern Patagonia, neutral stability prevails (see Fig. 2c). As a consequence, neutrality should be an appropriate assumption for applying Sutton's equation or Gaussian plume pollen transport models in northern Patagonia. Nevertheless, for reconstruction purposes these models cannot account for stability diurnal cycle or any stability change in other time scales. As an example, it has been shown that long distance transport in northern Patagonia occur with strong vertical mixing commonly associated with post-frontal clear skies (Gassmann and Pérez, 2006).

Aiming the estimation of the “relevant source area of pollen” *sensu*Sugita (1994), palynologists usually assume a roughly circular area with strong implications for paleoenvironmental reconstructions (Xu et al., 2016). This is equivalent to consider that the pollen contribution is even from all directions, which inevitably comes from even wind roses that never occur in nature. In northern Patagonia wind direction is predominant from the west regardless the considered month, thus the hypothesis of isotropic pollen contribution is not reliable (Fig. 2a). Recent developments account for wind direction improving the directionality of the pollen contribution (Bunting et al., 2008). However, the wind faithfully represents pollen transport only at local scale, where carrying air parcels follow roughly straight paths. At greater distance, the greater the possibility that the wind rose change due to topography, while from tens to hundreds of kilometres, synoptic systems (high or low-pressure systems, wedges, troughs and weather fronts) change wind direction and air parcel trajectories. As a result, pollen source area is neither circular nor isotropic, features that cannot be properly represented by Sutton's equation or Gauss plume models.

Theuerkauf et al. (2013) and Mariani et al. (2017) showed that differences arise when calculations are made with Gaussian or Lagrangian models, where the former tend to underestimate the pollen contribution from distant sources. The Gaussian approach requires crosswind dispersion parameters, which in the absence of research-grade turbulence measurements, are estimated as a function of downwind distance and stability. A few carefully performed diffusion experiments measured these parameters up to 1 km distance and extrapolated them to about 10 km, beyond which are no longer valid (Hanna et al., 1982). As a result, plume models are not recommended to calculate concentrations and particle deposition at distances greater than 10 km (Hanna et al., 1977, 1982; Pasquill and Smith, 1983; Panofsky and Dutton, 1984; Arya, 1999, 2001). Therefore, estimates of pollen contribution based on the Gaussian approach beyond 10 km should be considered misleading.

4.2. FLEXPART results for Northern Patagonia

A five-year airborne pollen record enabled us to study the daily trajectories reaching Bariloche. Three trajectory patterns were recognised:

1. Western trajectories are the most common, passing through the Subantarctic Forest, the main arboreal pollen source for the region. Trajectories arrived from SW to NW directions enhancing the probability that the air parcels carried pollen from the main arboreal types registered in the region. The presence of *Weinmannia* (an easily recognisable long distance tracer) and absence of steppe pollen tracers confirmed this hypothesis as shown in previous research (Pérez et al., 2009).
2. Eastern trajectories are following in importance, coming from the NE to SE of the target position. Trajectories cross the Patagonian steppe carrying characteristic herb and shrub pollen types.
3. Days with mixed trajectories are less frequent, bringing pollen types from both the forest and steppe vegetation to the sampling site.

Further investigation could bring insight into the characteristic weather patterns associated with the transport patterns described in this paper.

As a consequence of these combined patterns, in our study site, the pollen deposition should be influenced by the vegetation between 50 and 60 km from the west where trajectories mean residence time is approximately 1 h (dark red patch in Fig. 5), and to a lesser extent by vegetation located up to about 200 km from the western, southwest and northeast sectors (average residence time from 10 min to 1 h, orange patch in Fig. 5).

Only 19% of western trajectories registered during the pollination period recorded *Weinmannia* pollen at Bariloche. *Weinmannia* is a characteristic entomophilous taxon in the evergreen Valdivian and coastal forests that grows in the understory or in sheltered areas. These features hinder pollen escape above the canopy and thus restrict its access to higher levels of the atmosphere to be transported up to 200 km to the sampling point which explains this relative low percentage. Moreover, relatively low frequency (35%) of the simulated eastward trajectories carry pollen originated from the Patagonian steppe. Nevertheless, considering a predominantly entomophilous vegetation with low cover and low release heights (up to 50 cm), and that pollen is not released continuously, such as in humid or rainy days, we considered that it is a satisfactory result. It is worth to mention that estimation of airborne pollen concentrations was based only on 3% of the slide which probably produced an underestimation of the number of days when pollen tracers were recorded.

4.3. Implications for paleoenvironmental reconstructions

Using annual mean wind intensity as required by Gauss plume models to calculate pollen transport, implicitly supports the assumption that these processes are climate-driven. However, pollen emissions occur during a particular season of the year and very often during few weeks. Therefore, airborne pollen transport is determined by the cumulative effect of the passage of weather systems during the growing season rather than the average state of the atmosphere. Weather systems not only determine wind intensity but also the changing wind directions, which affect pollen contribution to a basin. Gassmann and Pérez (2006) and Pérez et al. (2009), showed examples of these effects in airborne pollen transport. Consequently, sedimentary pollen assemblages should be seen among other things, as the result of persistent seasonal weather conditions that favour pollen dispersal deposition over the years rather than the mean atmospheric state for several years. The change from a probabilistic paradigm to a deterministic one could correct this misunderstanding.

Great efforts have been made to improve the theoretical assumptions and methodologies of vegetation reconstruction, considering a large number of biases and environmental effects that distort the record (Gaillard et al., 2008). Anisotropy has been incorporated in reconstruction models, weighting the contribution of vegetation by means of a wind rose (Bunting et al., 2008; Theuerkauf et al., 2013), or including gridded factors to simulate the effects of topography and run-off (Bunting and Middleton, 2005). This is a correct approximation for static boundary conditions, however, it does not adjust to varying wind conditions. In this sense, the footprint methodology described in this paper can be used as input to computational suites like HUMPOL (Bunting and Middleton, 2005), to provide accurate representations of the wind field, the passage of weather fronts, ridges or troughs.

The potentialities of footprint analysis are numerous: They could be used to better understand the present system, evaluating significant changes due to changes in circulation patterns between ENSO and normal conditions, just to mention an example. On the other hand, general circulation models (GCM) are able to simulate the wind fields necessary to calculate footprints in the past. There are different simulation experiments (a list of models also with long- and near-term predictions can be found at the IPCC webpage, http://www.ipcc-data.org/sim/gcm_monthly/AR5/Reference-Archive.html and Taylor et al., 2012) which could be used to calculate footprints for key periods in the history of the Earth as: the pre-industrial period (Pi), the Middle Holocene (MH), or the Last Glacial Maximum (LGM). For example, early work of Dupont and Wyputta (2003) contrasted present and LGM seasonal atmospheric pathways of airborne pollen contribution (calculated with backward trajectories using modelled wind fields from the ECHAM3 model) to oceanic cores from the West African coast. Reliability of these type of reconstructions relies on the calibration of GCMs, a line of research that begins to develop through pioneering works like Prado et al., 2013, Berman et al., 2016, 2017. As these applications become more widespread in the community of palynologists, better interpretations of the inferred environmental changes of the past will be obtained.

5. Conclusions

In this work, we analyse neutral stability and isotropy, the two main assumptions of Gaussian plume models commonly used in quantitative pollen reconstructions. Our results showed that in Northern Patagonia, high wind speeds favour the predominance of neutral conditions, so that the first assumption is properly met. However, the analysis of backward trajectories shows that the pollen contribution has a strong W component at local regional scales, while at the regional and extra-regional scales it shows greater contribution from SW, W and NE directions. Therefore, the hypothesis of isotropy is not appropriate for the region. The use of a 3D Lagrangian model improves the simplistic 2D Gaussian Plume approach, considering real atmospheric conditions and transient atmospheric states from turbulent to large-scale motions. Since this new approach is more accurate, it may contribute to turn vegetation reconstructions more realistic than the previous ones, at least particularly when study sites are located in a complex topography, which disturbs surface winds or where climatology shows persistent wind directions as in the case of mean latitudes.

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