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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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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-

[1] From here on LPDMs