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ORIGINAL PAPER

First airborne pollen calendar for Mexico City and its relationship with bioclimatic factors

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Abstract The worldwide human population suffering from allergies continues to increase. Pollen grains are a major source of airborne allergens and significant cause of these diseases. Therefore, continuous monitoring of pollen grains released and transported in the air locally or regionally is required to determine the prevalence of various pollen types and identify intra-day and intra-annual seasonal variations over time. In this study, we developed the first pollen calendar for Mexico City, which includes a large variety of taxa, many of which show a long Main Pollen Season which may last throughout the year. The analysis and comparison of daily, monthly and annual values showed that the occurrence and abundance of the main types of aero-allergenic pollen in the atmosphere were species of *Fraxinus*, Cupressaceae and *Alnus*, which occur during the periods from December through March, whereas airborne pollens of several species of Poaceae and Urticaceae occurred throughout the year. The variation in pollen concentration showed that the greatest intra-diurnal variations occurred during the second half of the day. Regarding the relationship of pollen with bioclimatic factors, the increase in temperature favoured the presence of pollen in the air, whereas the increase in pluvial precipitation and relative humidity was associated with a decrease in airborne pollen. Large tracts of the Valley of Mexico have atmospheric conditions that are conducive to the accumulation of airborne particles, including pollen. Anomalous winds from the southeast dominated the surface wind variability during the first months of 2010. These patterns induced extreme values in wind convergence at the lower levels of the atmosphere, which resulted in high concentrations of pollen at our sampling site. We suggest that these conditions are related to the warm phase of the El Niño Southern Oscillation phenomenon (2009–2010).

Keywords Pollen calendar · ENSO · Mexico · Bioclimatic factors

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1 Introduction

The worldwide human population suffering from allergies continues to increase. Allergic diseases such as asthma and seasonal rhinitis affect approximately

20 % of the population in industrialised cities and are a product of immediate hypersensitivity responses to innocuous components in the environment (Eder et al. 2006; Pawankar et al. 2011). Pollen grains, which are released into the atmosphere through the reproductive processes of angiosperms and gymnosperms, are a major source of airborne allergens and significant cause of these diseases (de Weerd et al. 2002).

Therefore, continuous monitoring of pollen grains released and transported in the air locally or regionally is required to determine the prevalence of various pollen types and identify intra-day and intra-annual seasonal variations over time. Such measures can support the public sector and health sector in the prevention and control of respiratory diseases caused by exposure to airborne allergens, as also for studies into patterns of sensitisation and allergy to pollen and foods (Smith et al. 2014). Also, the generation of databases, airborne pollens over time (years), allow identifying the environmental conditions that influence their production and to develop predictive models (Helbig et al. 2004; Oteros et al. 2015), and also it allows us to infer the possible effects of climate change on the start and end of flowering plants, as well as its duration (Beggs 2004; Cariñanos et al. 2013).

The first record of atmospheric pollen in Mexico was conducted in 1940 in Mexico City, and it was followed by studies in the states of Veracruz, Tlaxcala, Michoacán, Oaxaca, Guadalajara and Puebla (Salazar-Coria 1995). In all locations, the importance of certain pollen types was noted for their role as pathogens in the development of allergic diseases. Between 1940 and 1990, knowledge of the role of different pollen types in the atmosphere was limited because the methods used to measure and analyse their effects did not permit correct interpretations and comparisons of results with respect to temporal variations, richness and concentrations (per unit volume of air) (Terán et al. 2009).

In 1940, Salazar-Mallén determined that during the rainy season in the Federal District (DF), the dominant pollen in the atmosphere belonged to the Poaceae and Compositae families, whereas in the dry season, the pollen count was characterised by a greater pollen density and was dominated by *Cupressus sp*., *Quercus sp*., *Populus sp*., *Pinus sp*. and *Alnus sp*., with the latter being the most abundant (Salazar-Mallén 1949).

In 1961, Ramírez-Oviedo and Rodríguez-Hernández conducted an illustrated study of the most common air pollen and reported 12 genera of trees, 11 genera of weeds and 8 genera of grasses (Ramírez-Oviedo and Rodríguez-Hernández 1961).

Cueva-Velázquez (1970) assembled a series of aeropalynological works conducted by himself and other collaborators between 1949 and 1970 in different states, including Guadalajara (1949), Oaxaca (1949), Puebla (1961), Veracruz (1962), Mexico State (1965) and Michoacán (1970), in the publication titled 'Flora and pollen allergens in the Mexican Republic', which focused on describing the type and frequency of pollen suspended in the air.

Airborne pollen grains have not been monitored continuously; however, the pollen types and concentrations in the air and the relationship between pollen an meteorological factors have been investigated by various authors, including Palacios (1977), Montes and Cisneros (1982), Rosales-Lomeli (1985) and Ramírez-Arriaga et al. (1995). These authors reported that in the Valley of Mexico, *Pinus* sp. was the most frequent pollen in the air and it increased in the dry season, whereas *Querc*us sp. *Abies sp*. and *Alnus sp*. were also common. The amount of pollen suspended in the atmosphere was found to be influenced by the start times of plant pollination as well as the climate and its daily variations. The highest pollen density corresponded with increased temperature, the absence of rainfall and a decrease in relative humidity (RH). Other pollen allergens, such as Poaceae, Chenopodiaceae-Amaranthaceae, Urticaceae, Cupressaceae, Casuarinaceae, *Schinus sp*., *Ligustrum sp*., Myrtaceae, *Salix sp*., *Populus sp*., *Ambrosia sp*. and Compositae, were also recorded.

Since the 1990s, aeropalynological studies have included volumetric sampling methods that have provided accurate information on the concentration of aerobiological particles per unit volume of air. Although samples have been collected using Hirst-type spore traps, accurate comparisons cannot be made because of differences in sampling periods and pollen grain counting methods (González-Macías et al. 1993; Bronillet-Tarragó 1992; Bronillet 1996; Rosas et al. 1998; González-Lozano et al. 1999; Torres-Valdos 2006; Cid-Martínez 2007). However, the results of these studies were consistent with the abundance of airborne pollen, with arboreal pollen grains composing the most diverse and abundant group during the dry season (November–April), which is the period when most the trees flower.

This study was conducted to provide continuous and permanent information on pollen diversity and concentration in the atmosphere of Mexico City as well as to determine the seasonal and intra-diurnal variations of pollen and its relationship with meteorological factors. Airborne pollen were monitored for five continuous years, and the collected data were used to develop the first pollen calendar for Mexico City and determine the relationship of airborne pollen with prevailing bioclimatic factors.

2 Methods

2.1 Sampling site and climate

Mexico City is located in the south central region of the country, and it lies within the basin of the Valley of Mexico at the coordinates 19°36′–19°02′N and 98°56′–99°22′W at a height of 2240 m.a.s.l. The city is surrounded by mountains except to the north (Fig. 1). Forty-five per cent of the city is urbanised (north and centre), whereas 55 % of the city distributed to the south and east is rural, with the land used for ecological reserves, forestry and agriculture (INEGI 2010).

An aerobiological monitoring station was installed in the facilities of the Atmospheric Sciences Centre at the Universidad Nacional Autónoma de México, which is located in Coyoacán a Delegation of Mexico City with a surface of 54.12 Km^2 (Fig. 1). The percentage of urban land is approximately 87.52 %, with a green area of 2.48 % (UNIATMOS 2013, oral communication).

The urban vegetation of Coyoacán is mainly represented by *Fraxinus* spp., *Pinus* spp., *Cupressus* spp., *Quercus* spp., *Alnus* spp., *Ulmus* spp., *Populus* spp., *Casuarina* spp., *Taxodium mucronatum*, *Ligustrum* spp., *Schinus molle*, *Salix* spp., *Eucalyptus* spp., *Liquidambar styraciflua*, *Acer* spp., *Washingtonia* spp., *Phoenix canariensis* (Martínez González, 2008). The station is adjacent to the Ecological Reserve Pedregal de San Angel, which has natural flora characteristics of the primary scrubs *Senecio praecox, Buddleia* spp., *Wigandia urens, Bursera spp.* and a large number of grass species.

As for soil conservation and natural areas, to the west, southwest, south and southeast, the forests are conifers, including forests of *Abies religiosa, Pinus* spp., *Quercus* spp. and mixed pine-oak associated with other species, such as *Buddleia* spp. and *Alnus jorullensis*, as well as natural and improved grasslands. In addition, desert scrub is found to the east and north (Rzedowski and Rzedowski 2001) (Fig. 1).

2.2 Pollen monitoring

Pollen sampling was performed using a Hirst-type volumetric spore trap (Burkard Manufacturing Co. Ltd., UK) placed in an open area at a height of 15 m from the ground. The atmospheric pollen records were obtained from 1 August 2008 to 31 August 2013. The sampler was located on the roof of Atmospheric Science Centre, Universidad Nacional Autónoma de México.

The sampler operated continuously and aspirated a constant flow of 10 L/min. After exposure, a Melinex tape that was impregnated with silicone fluid was cut into 24 fragments (48 mm) and mounted on slides using glycerine jelly stained with fuchsine. Counts of the different pollen types were performed with the aid of a light microscope, and four longitudinal sweeps per slide were performed at a magnification of 400× according to the methodology proposed by the Spanish Aerobiology Network (REA) manual (Galán et al. 2007).

The pollen grains were examined under a microscope at a magnification 400×, and the pollen was identified with the aid of a pollen atlas (Erdtman 1952; Pla-Dalmau 1960, 1961; Kapp 1969; Bassett et al. 1978; Moore et al. 1991; Smith 2000; Lacey and West 2006; Trigo 2007; Trigo et al. 2008) and a pollen collection of the local floral from Mexico City that is part of the palinoteque of the Mexican Aerobiological Network (REMA).

Pollen was counted along four longitudinal transects to estimate the daily mean pollen concentration. The pollen concentration was expressed as the number of pollen grains/m^3 of air, with the mean daily values used for the seasonal variation. The annual pollen index (API) was used to indicate the total amount of pollen for each year.

The main pollen season (MPS) for the most abundant pollen types was calculated as described by Andersen (1991). The MPS accounted for 95 % of the annual total, began on the first day with a cumulative daily count of 2.5 % of the annual figure and finished when 97.5 % of the annual total had been accounted for. The

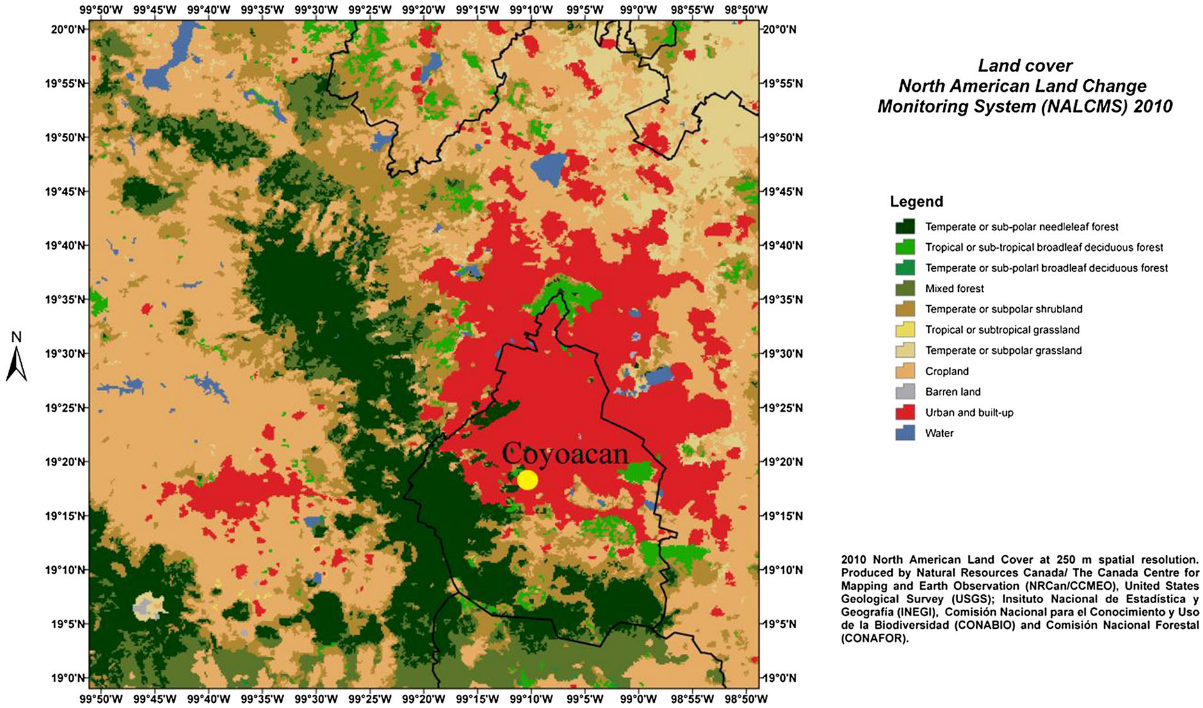

Fig. 1 Location of the pollen grain monitoring station south of Mexico City, and the distribution of vegetation cover and land use for the city and metropolitan areas

pollination period from the beginning of the MPS to the day with the highest pollen count is referred to as the prepeak period, whereas the days following this period are referred to as the postpeak period.

The diurnal pattern was determined by calculating the average concentration for each hour in percentage (of the 5 years of study) considering only dry days without rainfall, when the number of pollen grains for each day was equal to or more than the daily average [(total pollen/1825 days (=5 years)].

The pollen calendar was constructed by following Spieksma's model (Spieksma and Wahl 1991), which transforms 10-day mean pollen concentrations (pg/m^3 of air) into a series of classes according to Stix and Ferretti (1974) and represents the series in a pictogram that includes columns of increasing height. Each month is divided into three parts, and the average of each year is calculated. The pollen calendar is prepared with the different taxa of airborne pollen following the order in which the maximum concentrations appeared. Only taxa that showed a minimum 10-day mean equal to or greater than 1 pollen grain/m^3 of air were included (Fig. 2).

2.3 Statistical analysis

The values used to determine the concentration levels of major categories pollen taxa were obtained by calculating percentiles: low levels indicate concentrations below the 50th percentile; moderate levels indicate concentrations between the 50th and 75th percentile; high levels indicate concentrations between the 75th and 99th percentile; and very high

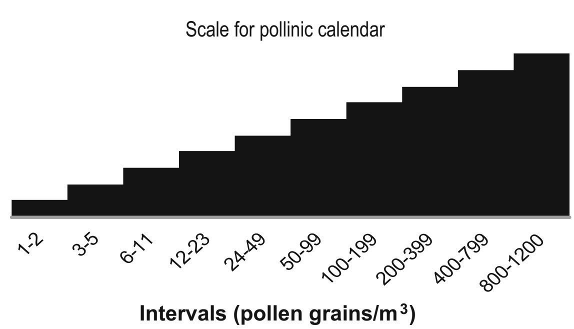

Fig. 2 Scale for pollen calendar based on Spieksma and Wahl (1991)

levels indicate concentrations above the 99th percentile.

Statistical analysis with daily averages of the 5 years of monitoring of airborne pollen was performed, and Spearman's correlation coefficients were calculated to determine the relationships between the daily average pollen concentrations and meteorological parameters, such as rainfall, temperature (maximum, minimum and average), average wind speed and maximum wind speed, RH and air pressure. Statistical analyses were performed with Statistica software version 9.0.

2.4 Meteorological data

Meteorological variables were obtained from a weather station (Davis Vantage PRO 2) installed at the Atmospheric Sciences Centre (CCA in Spanish) at the Universidad Nacional Autónoma de México (UNAM) in a location next to the pollen sampler. This meteorological station is part of the 'Programa de Estaciones Meteorológicas del Bachillerato Universitario' (PEMBU) network, which has been maintained operationally since 2008.

In addition to the meteorological data recorded in situ, monthly wind fields and their convergence were derived from the first 24 h of 5-day forecasts conducted at the CCA-UNAM using a regional numerical weather prediction model (NWPM) for Mexico. This prediction system, which is based on the Weather Research and Forecasting (WRF) model (NCAR 2009), has been running operationally since 2010. On a daily basis, WRF is integrated for up to 120 h using initial and boundary conditions from the Global Forecast System. The nested (one-way) computation domains cover all of Mexico, and the highest resolution domain has a grid of 205 $\times$ 124 points and horizontal resolution of approximately 7 km (the Valley of Mexico is located within this enhanced resolution area). The available forecast period is from 2010 to 2013. See Lopez-Espinoza et al. (2012) for further details and applications of this NWPM.

3 Results

The main airborne pollen types collected in Coyoacán over five years are shown in Table 1.

The highest percentage of pollen were from trees, such as *Fraxinus* spp. (52.39 %), Cupressaceae (17.70 % *Cupressus, Cedrela, Thuja* and *Juniperus*) and *Alnus* spp. 6.84 %, as well as herbaceous Poaceae (2.43 %).

The monthly and annual values of total pollen during the sampled years are presented in Table 2. The concentration of pollen grains in the atmosphere collected from August 2008 to August 2013 fluctuated throughout the year, with the highest average values between the months of December and February. The highest concentrations of pollen were primarily obtained in January 2008 (34.56 %), 2009 (30.24 %) and 2010 (42.13 %), whereas the highest concentrations in 2009 and 2011 in February were 27.83 and 28.10 %, respectively.

The highest annual pollen index (API) was registered in the period from August 2009 to July 2010 with a count of 113,253, with the highest concentrations observed in January and February 2010.

The characteristics of the main pollen season for the most important taxa are presented in Table 3, and the seasonal variation of total pollen for trees, grasses, *Fraxinus, Alnus,* Cupressaceae, Poaceae and Urticaceae in the atmosphere of Coyoacán is shown in Fig. 3. The range of values determined for tree pollen in the air was from 1 to 15 pg/m^3 (low level), 16–90 pg/m^3 (moderate level), 91–12,000 pg/m^3 (high level) and >1200 pg/m^3 (very high level). Similarly, the range of values determined for herbaceous plant pollen was from 1 to 4 pg/m^3 (low level), 5–10 pg/m^3 (moderate level), 11–35 pg/m^3 (high level) and >35 pg/m^3 (very high level).

The annual variation of total airborne pollen indicates that concentrations of pollen grains in the air increased from December to February primarily for tree species (Table 3; Fig. 3).

The most commonly collected airborne herbaceous pollen types were those of the Poaceae (2.48 %) and Urticaceae (1.29 %) families, which are present in the air throughout almost the entire year (3.77 % of the total pollen). The quantities fluctuated substantially from year to year in relation to the annual quantities, MPS start and end dates, season length and daily maximum values (Table 3; Fig. 3).

The intra-diurnal variation of pollen from species belonging to the genera *Fraxinus* and *Alnus* and families Cupressaceae, Poaceae and Urticaceae that were collected from the Coyoacán are shown in Fig. 4. Generally, the concentration of pollen grains begins to increase over the course of the morning, with the

Table 1 Airborne pollen types collected in Coyoacán over 5 years

Taxa	%
Fraxinus	52.39
Cupressaceae	17.70
Alnus	6.84
Type Pinus	4.95
Quercus	4.95
Casuarina	2.67
Poaceae	2.43
Liquidambar	2.02
Urticaceae	1.29
Myrtaceae	1.18
Schinus	0.82
Amaranthaceae	0.49
Moraceae	0.42
Citrus	0.24
Tilia	0.23
Asteraceae: Type Senecio	0.20
Salix	0.17
Ambrosia	0.17
Buddleia	0.16
Rumex	0.13
Rosaceae	0.11
Acer	0.10
Populus	0.08
Asteraceae: Type Helianthus	0.08
Asteraceae: Type Anthemidae	0.07
Ricinus	0.07
Ligustrum	0.06
Artemisia	0.06
Arecaceae	0.04
Casuarina	0.04
Mimosa	0.04
Ulmus	0.03
Wigandia	0.02
Celtis	0.02
Thypaceae	0.02
Juglans	0.02
Olea	0.02
Carya	0.02
Plantago	0.01
Grevillea	0.01
Asteraceae: Type Lactucca	0.01

maximum concentrations occurring as follows: *Fraxinus* at 13 h; Cupressaceae at 15 h; *Alnus* at 20 h; and Poaceae and Urticaceae at 18 h. Nocturnal and early morning wind patterns are favourable for convergence of airborne pollen in the sampling station. From 9 a.m. to 11 a.m., the wind-induced convergence sharply increases and it is maintained for some hours, gradually decreasing towards the evening (figure no shown). Thus, the diurnal cycle of the wind-induced convergence patterns favours accumulation of pollen, reaching a peak around noon.

Here, we present the first atmospheric pollen calendar for Mexico City (Fig. 5). Only taxa reaching a ten-day mean of 1 pg/m^3 were included; therefore, the calendar consists of 20 pollen types. The different taxa are ordered as a function of the length of pollination and time at which their maximum peaks appear. The scale is exponential, and each step doubles (Fig. 2).

In general, the pollination periods of the arboreal taxa (*Fraxinus*, Cupressaceae, *Alnus*) are shorter than those of the herbaceous taxa (Urticaceae and Poaceae).

The Coyoacán atmosphere can be characterised as follows: arboreal pollen grains, such as *Alnus* and *Fraxinus* pollen, begin to increase starting in October, reach their peak concentrations in January, and subsequently decrease towards the months of March and April. *Fraxinus* spp. flower again from May to July, although to a lesser extent, and several genera of the Cupressaceae and Myrtaceae families release pollen grains throughout the year, although their greatest concentrations are recorded during January and February, respectively. Pollen concentrations from various species of *Pinus* are highest from February to April, whereas for *Liquidambar* spp., the highest concentrations are between February and March. *Quercus* pollen occurs from February to June, with its maximum in March, and the highest concentrations of *Schinus* pollen are usually between April and May. Other tree pollen types that are present in the air at low concentrations and only at certain times of the year include species of *Casuarina, Salix, Ligustrum* and *Morus*. With respect to the pollen of herbaceous plants, concentrations in the air are generally low and only pollen grains of various species of the Urticaceae and Poaceae families are

Table 2 Monthly and annual values (total and percentages) of total pollen during the years studied and their averages

	2008–2009		2009–2010		2010–2011		2011–2012		2012–2013		Average (2008–2013)	
	Total	%	Total	%	Total	%	Total	%	Total	%	Total	%
August	951	1.40	498	0.44	929	1.09	1179	1.75	432	1.72	798	1.11
September	1260	1.85	1499	1.32	781	0.91	1147	1.71	557	2.22	1049	1.46
October	1757	2.58	1460	1.29	779	0.91	1407	2.09	729	2.91	1226	1.71
November	2393	3.52	1662	1.47	2989	3.49	2870	4.27	927	3.70	2168	3.02
December	14,013	20.59	20628	18.21	19,100	22.32	9986	14.85	4646	18.54	13,675	19.04
January	23,522	34.56	34,245	30.24	36,049	42.13	13,296	19.78	6285	25.08	22,679	31.57
February	9340	13.72	31,522	27.83	12,523	14.63	18,892	28.10	5659	22.58	15,587	21.70
March	4649	6.83	10,172	8.98	4198	4.91	10,379	15.44	2250	8.98	6330	8.81
April	2879	4.23	6070	5.36	2604	3.04	3500	5.21	1444	5.76	3299	4.59
May	3180	4.67	2008	1.77	1217	1.42	2373	3.53	914	3.65	1938	2.70
June	3281	4.82	917	0.81	1066	1.25	717	1.07	783	3.12	1353	1.88
July	829	1.22	2572	2.27	3334	3.90	1479	2.20	436	1.74	1730	2.41
API	68,054	100	113,253	100	85,569	100	67,225	100	25,062	100	71,833	100

present throughout the year. *Ambrosia, Buddleia*, Amaranthaceae, Asteraceae–Anthemidae type and Asteraceae-*Senecio* type were recorded in the air at different times of the year (Fig. 5).

Thus, most of the pollen types that occur in the atmosphere of Coyoacán in Mexico City show long MPS (long-tailed curves) over several months, with certain MPS occurring throughout or for most of the year (Poaceaes, Urticaceae, *Fraxinus*, Cupressaceae, Myrtaceae).

Spearman's rank correlation coefficients were calculated between the reported meteorological parameters and pollen concentrations collected from the air for both the MPS period as well as prepeak and postpeak periods for each of the pollen types evaluated. The analysis was performed for each of the years that were monitored (data not shown) as well as for the 5 years of continuous monitoring (Table 4).

Significant negative correlations ($p < 0.05$) were observed between the concentrations of *Fraxinus* and meteorological variables recorded during the MPS and postpeak period, including the average, maximum and minimum temperature and wind speed, although the RH was positively correlated. In addition, the airborne pollen types belonging to the Cupressaceae family showed significant negative correlations with the average, minimum and maximum temperature in the MPS, prepeak and postpeak periods.

Alnus pollen was also negatively correlated with wind magnitude, average, maximum and minimum temperature during the MPS and postpeak periods, although it was positively correlated with RH. Therefore, the presence of the main tree pollen types in the atmosphere was generally influenced by decreases in temperature and wind magnitude and increase in RH.

The presence of Poaceae pollen and Urticaceae family pollen in the atmosphere and their relationship with the prevailing meteorological parameters generally showed few significant correlations, although positive correlations were observed with the average temperature and wind magnitudes and negative correlations were observed with RH and precipitation. Thus, an increase in temperature and wind magnitude and decrease in precipitation and RH in the environment increased the presence of this pollen in the atmosphere.

3.1 Pollen dispersal by wind

To determine how pollen is transported by wind and collect PEMBU meteorological data, other databases available in the Valley of Mexico region were reviewed to obtain a more realistic approach for describing the spatial distribution of near-surface wind fields. For the initial months of 2010, however, no usable records were available because of a large number of gaps found in the time series. Therefore, data from weather forecasts were used to determine the average wind conditions for the months of January to April from 2010 to 2013.

Table 3 Characteristics of the main pollen season (MPS) for the most important taxa: starting and ending dates, season length, maximum daily value and date, and number of days with daily pollen concentrations over an allergenically significant value

	2008–2009	2009–2010	2010–2011	2011–2012	2012–2013
Fraxinus spp.					
Pollen season	29 November–17 March	9 December–28 February	28 November–25 July	31 October–7 April	23 November–2 April
Season length	109	82	240	160	131
Daily maximum value (Date)	904 (05 January)	2642 (07 February)	2595 (31 December)	1206 (29 February)	461 (25 December)
Annual pollen index	30 631	58 965	56 521	29 836	12 287
Five-year average (%)	37,636 (52. 4 %)				
No. of days 16–90 pg/m^3	49	20	44	65	46
No. of days 91–1200 pg/m^3	84	79	68	99	62
No. of days > 1200 pg/m^3	0	9	12	1	0
Cupressaceae					
Pollen season	14 September–26 May	19 September–18 April	4 November–7 July	6 October–20 April	13 September–28 June
Season length	255	212	246	198	289
Daily maximum value (Date)	504 (24 January)	2146 (20 January)	381 (6 February)	692 (18 February)	86 (15 January)
Annual pollen index	12 740	21 718	11 344	14 013	3 759
Five-year average (%)	12,714.8 (17.7 %)				
No. of days 16–90 pg/m^3	127	103	104	92	74
No. of days 91–1200 pg/m^3	32	51	36	43	0
No. of days > 1200 pg/m^3	0	1	0	0	0
Alnus					
Pollen season	29 November–13 April	3 December–1 April	5 December–25 March	27 November–17 March	17 December–29 April
Season length	136	120	111	112	134
Daily maximum value (date)	176 (11 January)	221 (7 February)	283 (19 January)	205 (2 February)	83 (26 January)
Annual pollen index	5 914	5 671	5 536	5 000	2 455
Five-year average (%)	4915.2 (6.84 %)				
No. of days 16–90 pg/m^3	75	74	55	70	65
No. of days 91–1200 pg/m^3	17	15	19	11	0
No. of days > 1200 pg/m^3	0	0	0	0	0
Urticaceae					
Pollen season	17 August–17 July	10 August–25 July	9 August–27 July	8 August–14 July	6 August–27 July
Season length	335	350	353	342	356
Daily maximum value (date)	44 (14 June)	38 (30 June)	31 (11 June)	29 (4 February)	12 (13 November)

Table 3 continued

	2008–2009	2009–2010	2010–2011	2011–2012	2012–2013
Annual pollen index	1393	535	788	1042	879
Five-year average (%)	927.4 (1.29 %)				
No. of days 5–10 pg/m^3	41	18	32	54	48
No. of days 11–35 pg/m^3	22	4	12	9	2
No. of days > 35 pg/m^3	3	1	0	0	0
Poaceae					
Pollen season	20 August–11 July	17 August–9 June	7 August–23 July	10 August–19 July	3 August–20 July
Season length	326	297	351	345	352
Daily maximum value (date)	87 (5 January)	105 (20 January)	18 (13 September)	14 (26 September)	14 (12 October)
Annual pollen index	3187	2776	864	1164	926
Five-year average (%)	1783.4 (2.48 %)				
No. of days 5–10 pg/m^3	125	114	51	82	47
No. of days 11–35 pg/m^3	68	43	6	8	7
No. of days > 35 pg/m^3	10	9	0	0	0

Surface wind fields simulated by the WRF model (Fig. 6) show strong patterns of interannual variability. Large values of wind speeds were observed from January to April 2010 along the Sierras de las Cruces and Ajusco-Chichinautzin, with maximum values during February. This result is consistent with pollen peaks recorded in the first 2 months of 2010. Note that winds from the southeast (mountain to valley) are dominant during the first months of the year, and their greater persistence and magnitude also correspond to the results for the year 2010. These wind fields produce large areas of convergence which is an atmospheric condition that exists when the winds cause a horizontal net inflow of air into a specified region. On the other hand, divergence is the opposite, where winds cause a horizontal net outflow of air from a specified region. Thus, these large areas of convergence, closely related to the mountain-valley circulation, are favourable for the transport and accumulation of pollen. The most intense areas of convergence (extreme negative values shown in Fig. 7) occurred in February 2010, the month in which the magnitude of the southwest winds was greatest. These intense anomalous wind events are consistent with extreme weather associated with the warm phase of the El Niño Southern Oscillation phenomenon, which occurred from July 2009 to April 2010.

4 Discussion

Ecosystem health is determined by the quantity and quality of atmospheric biological load that is generated within a region or may be transported from other regions; Therefore, it is important to know the type of biological particles in the air and its potential to cause harm to both human health and the environment.

This paper presents the first pollen calendar conducted for the Valley of Mexico, and it was produced from the results of 5 years of monitoring airborne pollen grains in the locality of Coyoacán. Of the 41 pollen types recorded, 70 % corresponded to tree pollen and 30 % corresponded to herbaceous pollen. The different pollen grains collected from the air are shown in Table 1, with the most abundant representing species from *Fraxinus,* Cupressaceae*,* *Alnus* and Poaceae. The pollen types recorded are consistent with those reported for Mexico City in

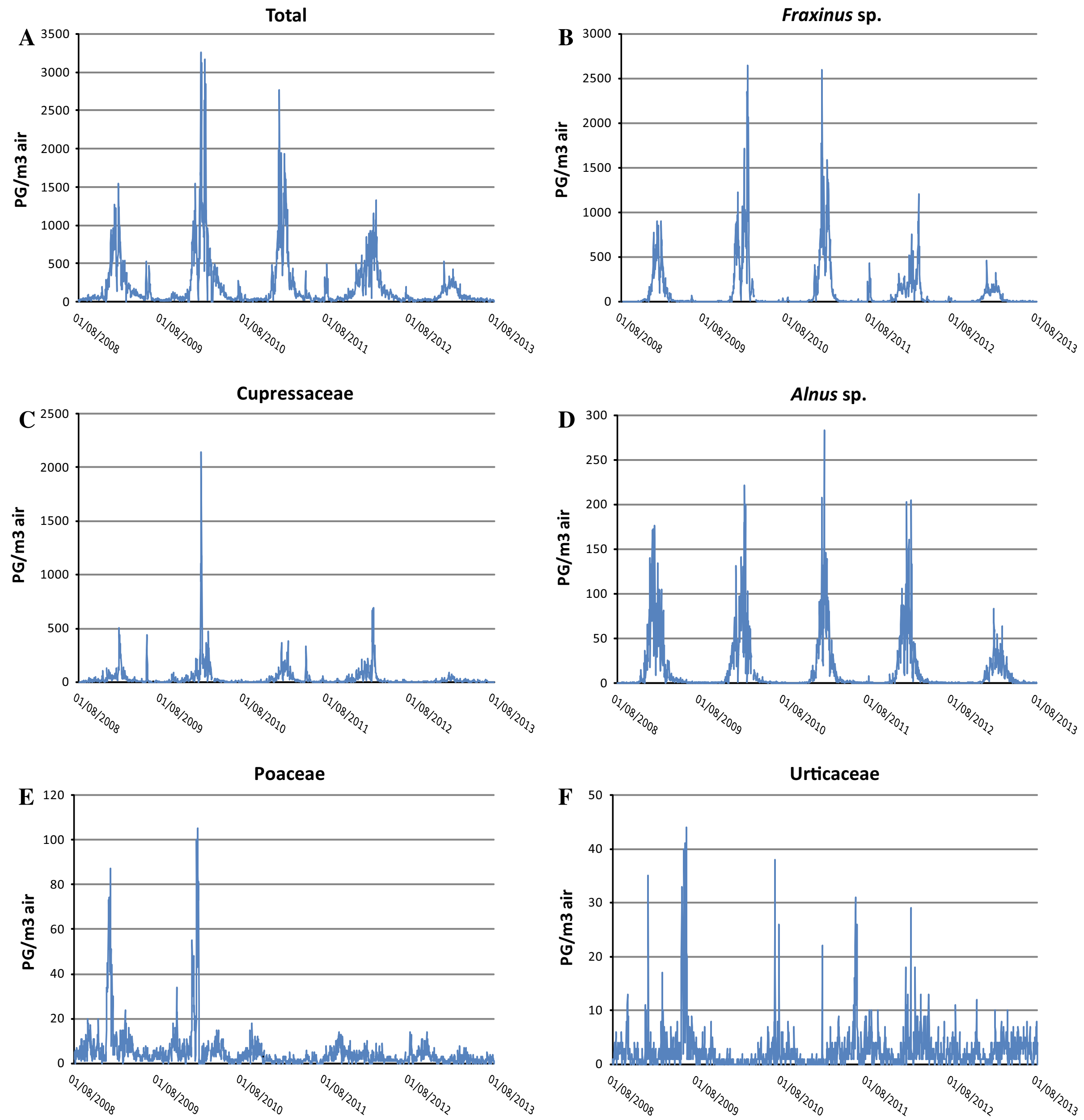

Fig. 3 Seasonal variation of total pollen in the atmosphere of Coyoacán (**a**), *Fraxinus* spp. (**b**), Cupressaceae (**c**), *Alnus* spp. (**d**), Poaceae (**e**) and Urticaceae (**f**)

studies from the early 1940s to the end of the 1980s, in which the pollen of *Pinus* was the main and most abundant pollen type in the city air, followed by pollen of *Quercus* sp. *Abies sp*. and *Alnus sp*. as well as pollen from herbaceous species. However, our results are also consistent with those reported by aerobiological studies conducted from the 1990s, which used volumetric methods of sampling (m^3 of air). Although air monitoring was not conducted continuously, these studies reported high concentrations of pollen mainly from species of *Fraxinus*, Cupressaceae, *Alnus*, *Pinus*, *Quercus, Casuarina* and *Poaceae* (González-Macías et al. (1993), Bronillet-Tarragó (1992), Rosas et al. (1998), González-Lozano et al. (1999), Torres-Valdos

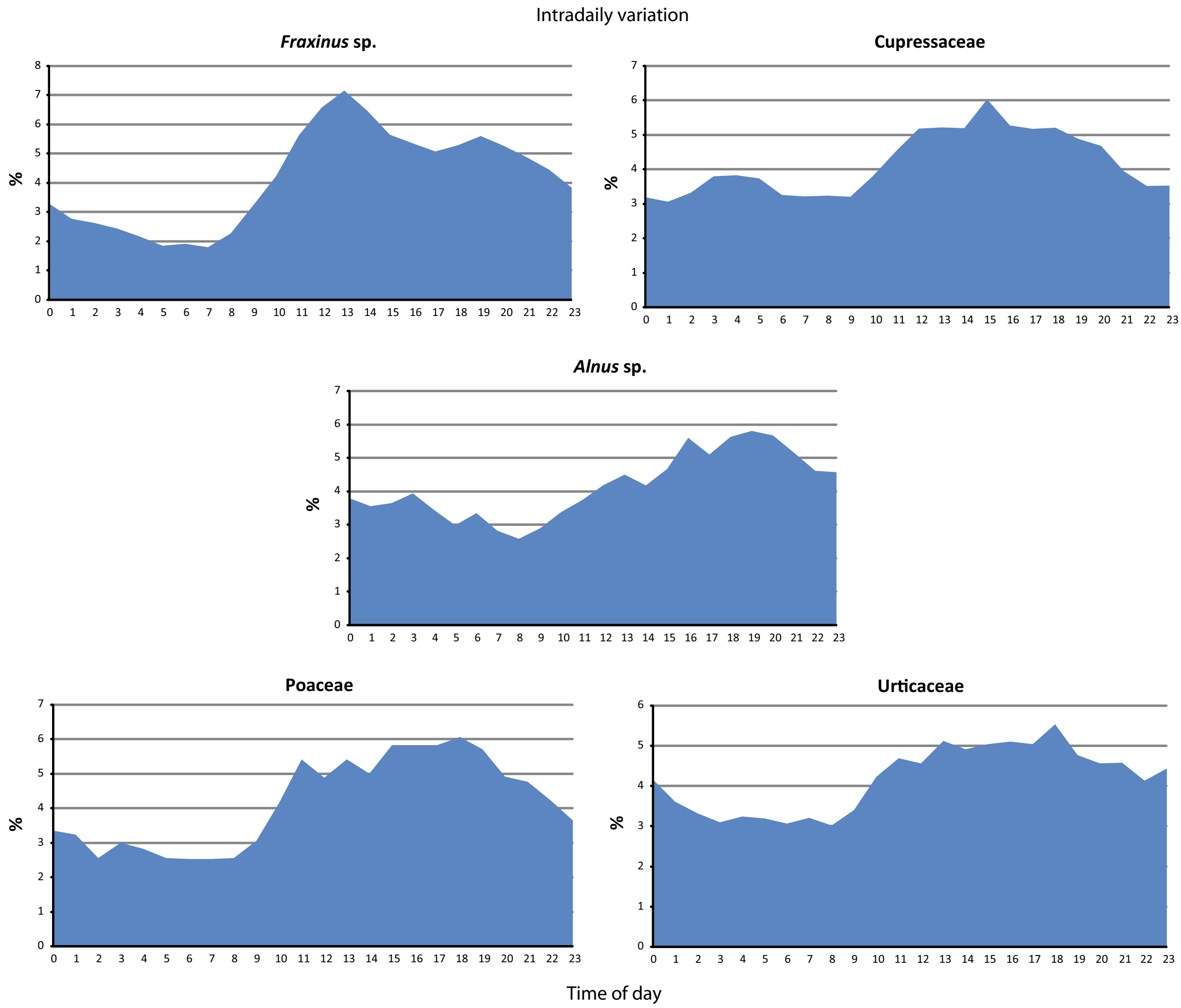

Fig. 4 Intra-diurnal variation of the main pollen types collected from the air of Coyoacán

(2006), Cid-Martínez (2007). The high abundance of *Fraxinus*, Cupressaceae and *Alnus* pollen, which have significant allergenic properties, recorded since the 1990s could have occurred because these types of trees have been extensively used to reforest large areas of forests, parks, avenues and gardens of Mexico City.

The marked seasonal variation of the pollen types collected from the air is caused by changes in the composition of the aeropalynological spectrum, which is influenced by different prevailing weather conditions throughout the year. In addition, such variation is determined by the flowering periods of the plants identified as sources of the most abundant pollen types.

The concentrations of total air pollen showed significant differences in the API between monitored years (Table 2), and the value for the second monitoring period (2009–2010) was the highest (113,253 pg), whereas the value for the period from 2012 to 2013 was lowest (25,062 pg). The annual and interannual variation in pollen quantity indicates variations in the abundance of sources, and these variations have been used to assess changes in vegetation (Kobzar 1999) and environmental conditions (Damialis et al. 2007). The pollen index can provide a biased measure of the reproductive yield of pollen, which is influenced by factors such as atmospheric transport, pollen deposition and climatic factors that affect emission processes (Rantaa et al. 2008). In trees and other perennial plants, reproductive efforts commonly vary between years (Emberlin et al. 1993; Dahl and Strandhede 1996; Galán et al. 2001;

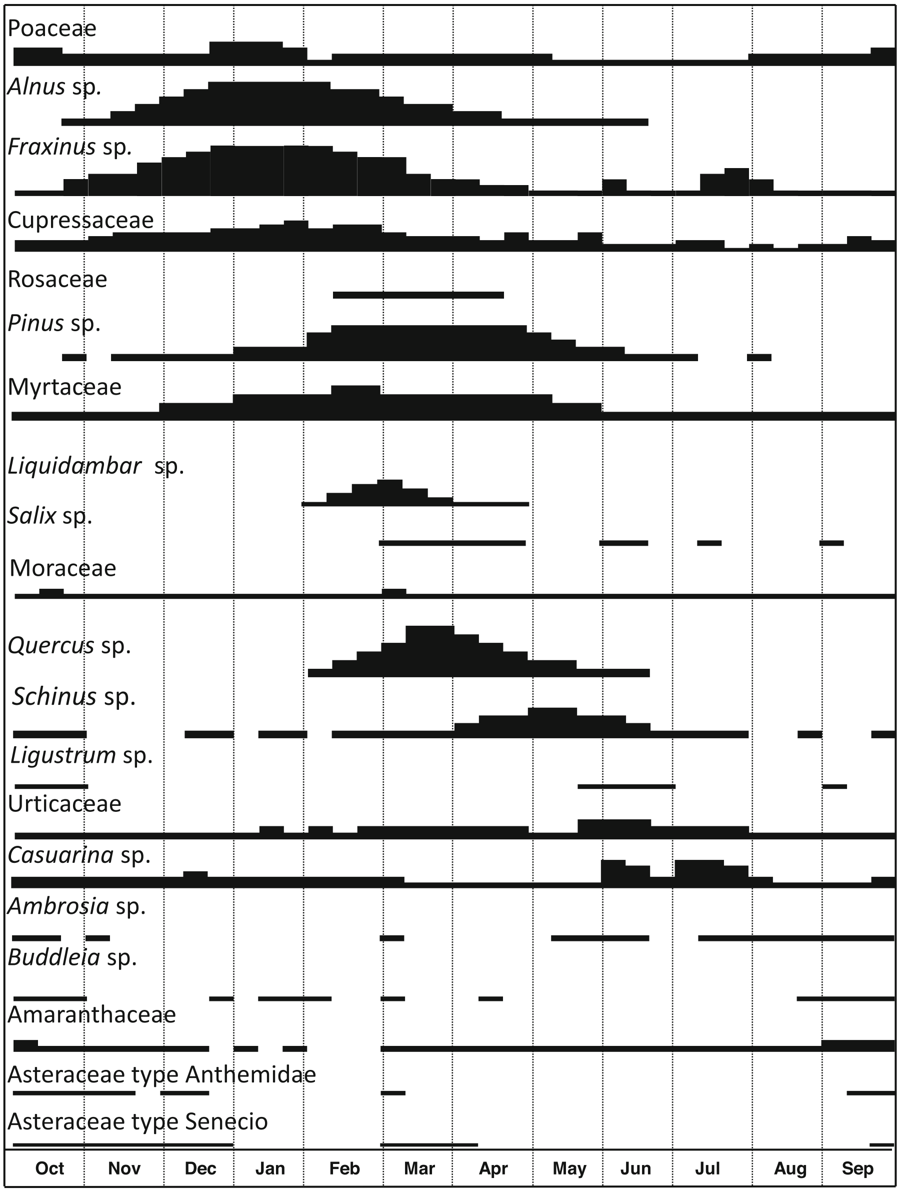

Fig. 5 Pollen calendar for Mexico City using data from October 2008 to September 2013 following Spieksma's model (1991)

Jato et al. 2007; Rantaa et al. 2008). In a year, many flowers and fruits may be produced within a local population or over an entire region, whereas in other years, reproduction may be moderate or scarce (Sofiev and Bergmann 2013). Many species have an innate flowering rhythm, where reproductive years are repeated every 2 or 3 years depending on the characteristics and specific processes within the tree. A two-year cycle has been described for trees such as *Betula* (Jäger et al. 1991; Jato et al. 2002), *Olea europea* (Lavee 2007), *Alnus glutinosa* (Rodríguez-Rajo et al. 2006) and *Quercus ilex* (Latorre 1999). Although for *Fraxinus*, a cycle tendency of every 3 years has been observed, and it corresponds to the number of seasons between the initiation of flowering and pollen emission (Sofiev and Bergmann 2013).

Fraxinus was the most common pollen type in the atmosphere during the dry (winter) season, and in the Valley of Mexico, this genus occurs in natural populations as a single species (*F. uhdei*) and in association

Table 4 Spearman's correlations between meteorological variables and airborne pollen concentrations for *Fraxinus,* Cupressaceae, *Alnus*, and Poaceae (five-year average)

		Spearman's correlations (means of 5 years)							
		Mean temperature	Maximum temperature	Minimum temperature	Mean wind speed	Maximum wind speed	Atmospheric pressure	RH	Rain
Fraxinus	MPS	−0.64*	−0.63*	−0.65*	−0.52*	−0.55*	−0.39*	0.52*	0.00
Fraxinus	prepeak	−0.17	−0.24	−0.10	−0.17	−0.06	0.05*	−0.19	0.20
Fraxinus	postpeak	−0.87*	−0.78*	−0.87*	−0.52*	−0.63*	0.02	0.61*	0.05
Cupressaceae	MPS	−0.54*	−0.36*	−0.67*	−0.33*	−0.43*	−0.10	−0.15*	−0.32*
Cupressaceae	prepeak	−0.75*	−0.49*	−0.78*	−0.71*	−0.59*	−0.21*	−0.61	−0.37*
Cupressaceae	postpeak	−0.65*	−0.59*	−0.70*	−0.21*	−0.46*	−0.06	0.16	−0.30*
Alnus	MPS	−0.71*	−0.72*	−0.69*	−0.63*	−0.62*	−0.40*	0.61*	−0.07
Alnus	prepeak	−0.26	−0.43*	0.01	−0.19	−0.05	0.02	0.02	0.33*
Alnus	postpeak	−0.88*	−0.84*	−0.85*	−0.63*	−0.68*	−0.02	0.62*	−0.09
Poaceae	MPS	−0.38*	−0.37*	−0.35*	−0.15*	−0.26*	−0.36*	−0.02	−0.30*
Poaceae	prepeak	−0.13	−0.12	−0.12	0.10	0.06	0.04	−0.15	−0.09
Poaceae	postpeak	−0.22*	0.00	−0.51*	0.24*	0.00	−0.09	−0.57*	−0.56*
Urticaceae	MPS	0.55*	0.53*	0.45*	0.28*	0.45*	0.32*	−0.08	0.28*
Urticaceae	prepeak	0.54*	0.54*	0.41*	0.37*	0.48*	0.38*	−0.22*	0.23*
Urticaceae	postpeak	0.24	0.16	0.14	0.33*	0.01	0.15	−0.30	−0.23
Total		−0.55	−0.37	−0.74	−0.10	−0.31	−0.04	−0.42*	−0.60*

* $p > 0.05$

with oak, pine and pine-oak forests as well as populations of *Alnus*, *Juniperus*, *Abies*, *Salix*, *Schinus* and *Buddleia* (Francis 1990; Rzedowski and Rzedowski 2001; CONABIO 2011). The second most abundant pollen type was that of the Cupressaceae family; in the Valley of Mexico natural populations of *Cupressus lusitanica*, *Juniperus flaccida* and *Juniperus montícola* occur in association with oak, oak-pine, pine, mountain mesophyll and tropical deciduous forest as well as populations of *Fraxinus uhdei*, *Liquidambar styraciflua*, *Cornus*, *Alnus* and *Abies* (Rzedowski and Rzedowski 2001; CONABIO 2011). Introduced species, such as *Cupressus macrocarpa*, *Cupressus sempervirens* and *Thuja orientalis,* are also used in urban area reforestation programs by the Environment Secretariat of the Federal District. Pollen from species of *Alnus* were the third most abundant pollen type in the city atmosphere, and the main species are *A. acuminata* and *A. jorullensis,* which are associated with oak, oak-pine and tropical deciduous forests as well as populations of *Abies*, *Fraxinus*, *Salix*, *Prosopis*, *Tilia*, *Cornus* and *Liquidambar styraciflua* (Rzedowski and Rzedowski 2001; CONABIO 2011).

The presence of high pollen concentrations during the months of January and February are dependent on flowering processes that are controlled by the circadian clock (endogenous oscillator) of the plants, which are influenced by environmental factors, such as light (photoperiod), temperature and RH. Depending on the duration of light–dark cycles, photoperiodic regulation of flowering ensures that the plant thrives in the most appropriate season to facilitate sexual reproduction (Green et al. 2002; Nefissi et al. 2011). In addition, temperature acts in conjunction with the photoperiodic signalling pathway, and its increase modifies the transcription of repressors of the genetic cascade for flower induction and promotes the expression of genes involved in the generation of floral stimuli (Scortecci et al. 2003; Balasubramanian et al. 2006; Penfield 2008). For plants that require a period of low temperatures to stimulate flowering (vernalisation), the expression of genes for flower induction is blocked by a repressor gene that is expressed during periods of long days during spring–summer and inhibited when there is a decrease in temperature during short days in autumn–winter (Yan et al. 2004).

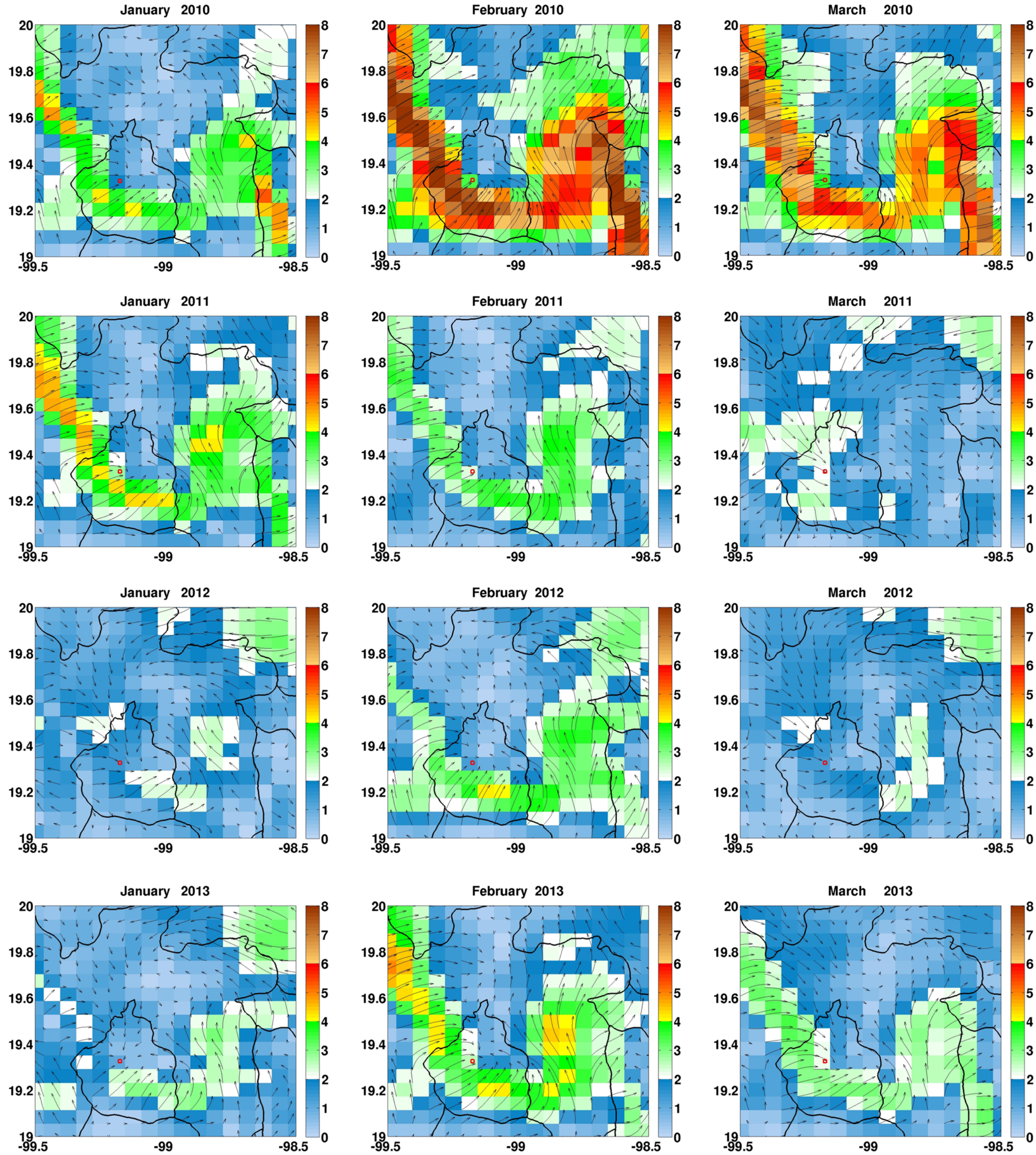

Fig. 6 Monthly mean surface wind field and its magnitude (colour classes in m/s) from January to April in 2010–2013. Hourly wind data were extracted from the first 24 h of the WRF model forecast output and used to build these fields

In the Valley of Mexico, the elevation, geographical location and tropical climate do not provide for well-defined thermal seasons; however, there are rainy and dry seasons, with the latter providing environmental conditions that precondition plants and promotes their subsequent bloom (INEGI 2010; Jáuregui 2000).

The increase in pollen grains of *Fraxinus, Alnus* and Cupressaceae recorded in the air of the Valley of Mexico showed that their flowering occurred

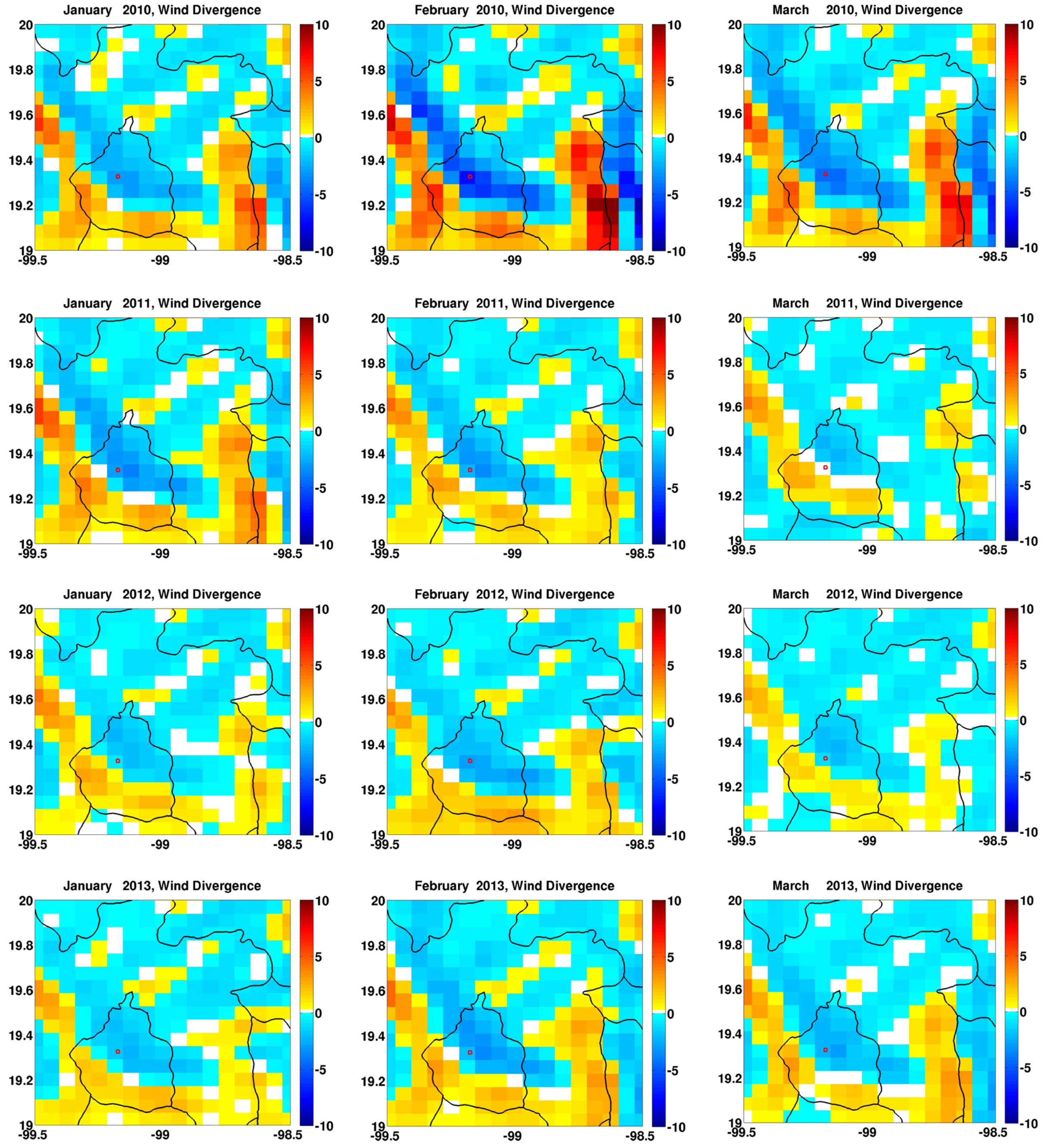

Fig. 7 Wind divergence derived from the wind fields shown in Fig. 6. Negative values correspond to convergence regions that favour the accumulation of airborne particles

primarily from December to February. The ranges of minimum temperatures between October and November fluctuated on average between 10.9 and 6.9 °C, respectively, with a maximum of 21.9 °C. The temperature then increased from 22.6 to 25.5 °C from December to March, the period that corresponded to high concentrations of pollen in the air. Correlations between temperature and pollen concentrations of *Fraxinus, Alnus* and Cupressaceae during the MPS, prepeak and postpeak periods were generally significant ($p < 0.05$) and negative. Therefore, the presence of these pollen types in the air was influenced by temperature prior to the flowering period (October–November), which created the conditions necessary to exit the resting metabolic state and initiate the specialisation and development of floral meristems (flowering) and production of pollen (Frenguelli et al. 1991; Cesaraccio et al. 2004; Yan et al. 2004; González-Parrado et al. 2006). Subsequently, increases in the photoperiod in late December and rising temperature produced an increase in the presence and abundance of pollen in the air that coincides with reports from aerobiological studies conducted in Monterrey (Rocha-Estrada et al. 2008) and Mexico City, which indicated that the flowering period of *Fraxinus*, Cupressaceae and *Alnus* occurred during the cold months of the dry season from December to March (Bronillet-Tarragó 1992; Salazar-Coria 1995; Torres-Valdos 2006).

Intra-diurnal variation of airborne pollen is related to anther dehiscence, which is a mechanism in plants that includes targeted differentiation processes and cellular degeneration; in combination with an increase in temperature and decrease in RH during the day, this mechanism determines the opening of the anthers and exposure of the pollen grains to air currents after midday (Yang et al. 2009; Pacini 2008). In the Valley of Mexico, the temperature increase towards midday along with the strong solar radiation and drop in RH generate a significant difference in the amount of water present in the air in the morning and after midday, which is between 60 and 65 % during the dry season and 40 % during the rainy season (Rzedowski and Rzedowski 2005). Therefore, the low RH conditions in the air after midday contributed to the 73, 60 and 55 % of *Fraxinus*, Cupressaceae and *Alnus* pollen, respectively, which was observed in the highest concentrations at 13 h and maintained high concentrations during the afternoon.

The daily wind patterns favour convergence of air in the low levels of the Valley of Mexico City, allowing the accumulation of pollen, reaching its maximum concentration around noon. This pattern of variation coincided with the results obtained by Bronillet-Tarragó (1992) for the region north of Mexico City and with Salazar-Coria (1995) for the region to the south.

Conifers forests dominate the mountain ranges that delimit the Valley of Mexico to the south, southwest and southeast, and they are associated with mixed forests in the regions to the south and southwest of Mexico City in the Sierras de las Cruces and Ajusco-Chichinautzin, which are dominated by *Fraxinus, Alnus, Cupressus*, *Juniperus* and *Taxodium* trees. Species of *Quercus* are distributed in the Valley of Mexico and occur naturally in oak, oak-pine and pine forests (Valencia 2004; Rzedowski and Rzedowski 2005; CONABIO 2011) as well as in mixed *Abies*, *Pinus*, *Juniperus* and mountain mesophyll forests located towards the southern and southwestern regions of the city and oak forests to the north. In general, the predominant vegetation within and at the periphery of the Valley of Mexico is represented by coniferous forests to the southwest and southeast; broadleaf forest within the urban area and to the west; coniferous-broadleaved forests to the southwest and south; primary grasslands to the northeast; introduced grasslands to the southwest, south and southeast; xeric scrubland to the north, northeast and south; irrigated agriculture to the southeast; and seasonal agriculture to the southeast, south, southwest and north of the city and at the periphery.

Other pollen types produced by *Casuarina*, *Liquidambar,* Myrtaceae (*Eucalyptus sp*. and *Callistemon sp*.), *Schinus* and *Morus* correspond to introduced species that are widely used to reforest green areas (parks, gardens and ridges), with certain species used as ornamentals within the Valley of Mexico.

In Mexico, there are 206 genera in the Poaceae family, of which 49 are introduced species; this vegetation represents species that constitute the food base of the population (corn, rice, wheat, sorghum, oats, rye, barley, sugar cane), with wild and cultivated species used as fodder, such as *Avena sp.*, *Hordeum sp.*, *Dactylis sp.* and *Festuca sp.*, and other genera used as lawn forming grasses in urban green areas of Mexico City, such as *Lolium sp.*, *Pennisteum sp.* and *Cynodon sp.*

The annual or perennial life cycle of the various species of the Poaceae family is mainly controlled by environmental factors, such as rainfall, temperature, and photoperiod, which influence the growth and development of plants and produce different phenological behaviours (Laaidi 2001). In Mexico, aerobiological studies (Rosales-Lomeli 1985; Bronillet-Tarragó 1992; Rosas et al. 1998; Salazar-Coria 1995; Torres-Valdos 2006) have reported the presence of Poaceae throughout the year, with an increase during the rainy season (June–October). These results coincide with those reported in this study with respect to the uninterrupted presence of grass pollen during the year, which can be attributed to the variability of flowering times for the 76 genera of grasses of the Valley of Mexico (Rzedowski and Rzedowski, 2005); however, our results are inconsistent with the studies of Rosales-Lomeli (1985) and Rocha-Estrada et al. (2008), who found that the rainy season coincided with the period of increased pollen for the Coyoacán Delegation. In the present study, the highest concentrations occurred primarily in December (dry season), and by correlating the pollen quantity with meteorological factors, an increase in temperature and wind magnitude and decrease in precipitation and RH were found to coincide with the increased occurrence of these pollen in the atmosphere, which is consistent with most of the data on Poaceae as reported by Bronillet-Tarragó (1992), Salazar-Coria (1995) and Torres-Valdos (2006).

The results reported here may have been caused by the physiological adaptation (vernalisation) of certain species (winter pastures), and the period of increased pollen incidence (December–January) may also be influenced by the blooming of non-native winter pastures (such as *Poa sp*., *Lolium sp*., and *Festuca sp*.), which are used in the Valley of Mexico for the production of fodder. Generally, the development and growth of these species are favoured by environmental changes (climate and soil) in the area, with the plants utilising abiotic resources more efficiently than native species (Brooks 2000; Corvin and D'Antonio 2004).

The Urticaceae family in the Valley of Mexico is represented by three genera: *Parietaria sp.* with one species (*P. pensylvanica* Muhl.); *Urtica sp.* with five species (*U. chamaedryoides* Pursh., *U. dioica* L., *U. mexicana* Liebm., *U. subincisa* Benth. and *U. urens* L.); and *Soleirolia sp.* with one species (*S. soleirolii*) (Rzedowski and Rzedowski 2005). In this study, pollen from this family was recorded throughout the year.

With regard to the dispersion of the pollen in the air, it is important to note that almost the entire urban region of the Valley of Mexico is located in a zone of wind convergence, which moves almost in unison depending on the prevailing winds. Therefore, airborne material will have a certain residency time before it is deposited; however, pollen transport out of the urban area is difficult, which implies that extreme surface winds or a greater vertical transport must occur to facilitate its expulsion at higher levels. To determine the contribution of these mechanisms is beyond the objectives of the present study.

The winds from the SE and SW mainly transport pollen grains from trees, which favours the increase in this pollen type in the city air along with pollen from local sources, such as parks and gardens. More than 8000 *Fraxinus* trees have been recorded in the University City and Chapultepec Forests alone. In addition, winds from the northeast and northwest of the city favour an increase in the pollen of herbaceous plants in the air.

5 Conclusion

In this study, we developed first pollen calendar for the City of Mexico, which includes a large variety of taxa, many of which show a long MPS (with long tails) and may last throughout the year. The analysis and comparison of daily, monthly and annual values showed that the occurrence and abundance of the main types of aero-allergenic pollen in the atmosphere were species of *Fraxinus*, Cupressaceae and *Alnus*, which occur during the periods from December to March, whereas airborne pollens of several species of Poaceae and Urticaceae occurred throughout the year. The variation in pollen concentration showed that the greatest intra-diurnal variations occurred during the second half of the day.

The increase in temperature was associated with the presence of pollen in the air, whereas the increase in pluvial precipitation and RH was associated with a decrease in airborne pollen.

Large tracts of the Valley of Mexico have atmospheric conditions that could be conducive to the accumulation of airborne particles, including pollen. Anomalous winds from the southeast dominated the surface wind variability during the first months of 2010. These patterns induced extreme values in wind convergence at the lower levels of the atmosphere, which were conducive to the accumulation of pollen at our sampling site. We suggest that these conditions are related to the warm phase of the El Niño Southern Oscillation phenomenon (2009–2010); however, further investigations are required. For example, investigations of the winds in the cold phase and associated atmospheric conditions would provide important information on the quantity of available pollen.

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