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Strong seasonal effects and long-term weather-related factors drive the temporal variability of airborne pollen in the atmosphere of San Miguel de Tucumán, Argentina

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Abstract

Knowledge about variations in allergenic pollen in the atmosphere is essential for human health programmes. This study aims to evaluate the influence of climatic variability on the arboreal pollen (AP) load, considering the annual, seasonal and intra-diurnal variability during ten years. We obtain data using a volumetric Burkard spore trap in San Miguel de Tucumán city. The seasonal behaviour of AP showed a short and intense flowering period from August to October. However, annual pollen concentrations varied considerably with 2008 and 2012 the years with the lowest and highest pollen contributions, respectively. The qualitative composition of the AP was represented mainly by *Broussonetia papyrifera*, *Morus*, *Celtis*, *Alnus*, *Platanus*, *Fraxinus*, *Myrtaceae*, *Juglans* and *Salix*. During the ten years of continuous sampling, there was little variation in the pollen concentration per hour. The lowest and highest contribution occurred at 2 p.m., and 2 a.m., respectively. There was a strong seasonal effect on AP concentration. Air temperature positively affected AP concentrations, while air humidity negatively affected AP concentrations. Overall, the shape and intensity of the seasonal AP pattern in this region appears to be driven by long-term phenological dynamics.

Keywords: aeropalinology, long-term temporal dynamics, meteorological factors, volumetric sampler, urban ecology, allergic diseases

Aeropalynology studies pollen grains and plant spores, as well as the different weather-related factors linked to their release, dispersion, and permanence in the atmosphere. Climatic variability affects the production and release of pollen by plants (Recio et al. 2009; Ziello et al. 2012; Rojo et al. 2015). How this variability drives airborne pollen loads at different timescales is still poorly studied and generally using short-term time series (e.g. Rojo et al. 2017; Fang et al. 2018; Maya-Manzano et al. 2021).

A typical city landscape includes, for instance, industrial waste and car emissions that are two significant drivers of pollution with consequences for both the environment and human health. In addition,

a high pollen content of the atmosphere causes allergic diseases (Leuschner et al. 2000; Teran et al. 2009; D'Amato et al. 2015, 2020; Salmun & Salmun 2016). Therefore, there is a growing interest in studying and solving this problem on the part of society and institutions (García et al. 2018; Haines & Ebi 2019; Solomon & LaRocque 2019). Among tools for understanding palynological phenomena, the modelling of airborne pollen time series is a primary tool to understand the wide variability among pollen seasons, either in terms of timing, plant biological rhythms or meteorological conditions (Nitiu 2006a, 2006b; Damialis et al. 2020; Maya-Manzano et al. 2021). Therefore, knowledge

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of the main allergenic pollen present in the atmosphere, and their behaviour throughout the year, may serve as a guide for clinicians to manage allergic diseases accurately. However, no long-term data for airborne pollen in the Tucumán zone have previously been published.

Meteorological factors, particularly air temperature, air relative humidity, rainfall, and wind speed, directly influence the release of pollen from the anthers and its dispersal throughout the atmosphere. Sunny and warm weather periods generally corresponds with higher pollen production, although a long-lasting dry period may, conversely, have a negative effect due to plant stress (Cariñanos et al. 2013). Cold and humid weather negatively influences pollen release and dispersal, as rainfall directly removes pollen grains from the atmosphere. Strong winds increase pollen release and dispersal, although they dilute pollen concentration in the air (Rodríguez-Rajo et al. 2003). Also, circadian patterns associated with air temperature, air relative humidity, and wind speed influence anthesis and pollen release (Kasprzyk 2006; Borycka & Kasprzyk 2018). Thus, investigating weather-related factors will aid us to understand airborne pollen dynamics.

At the regional scale of South America, Mar del Plata was the first city to conduct aerobiological studies in South America (Bianchi 1994; Latorre 1999; Latorre & Caccavari 2009; Abud Sierra & Latorre 2020). Other representative studies were carried out in the cities of La Plata (Nitiu & Romero 2001; Nitiu & Mallo 2002; Nitiu 2004, 2006a, 2006b), Bahía Blanca (Murray & Galán 2004; Murray 2007; Murray et al. 2010), Bariloche (Bianchi et al. 2004; Bianchi & Olabuenaga 2006), and San Antonio (Latorre et al. 2020). For the north-western region of Argentina, this study is the first with a volumetric method, as part of permanent monitoring started in 2006 (García de Albano 2013), while previous studies in the region use the gravimetric method (García 2010; Torres & Flores 2013). This study aims to determine the annual, seasonal, and daily variability of arboreal pollen (AP) concentrations in the atmosphere of the San Miguel de Tucumán city from August 2006 to July 2016 and to assess the influence of the weather-related factors on the variability of airborne pollen. This is achieved by the use of time-series analysis to disentangle how climatic variability drives airborne pollen load.

Material and methods

Study area

San Miguel de Tucumán (26° 50' S, 65° 15' W; 450 m above sea level [a.s.l.]) is the capital city of

Tucumán province, northwest Argentina (Figure 1). The climate is subtropical, with warm, rainy summers and mild, dry winters; and an annual mean temperature of 18 °C. The yearly minimum and maximum temperatures range between 11 °C and 24 °C, respectively; while the average yearly rainfall in San Miguel de Tucumán is 969 mm, reaching annual values between 1500 and 2000 mm (Minetti 1975, 2005).

The city borders the Sierra de San Javier in the west. Since 1973, 70% of the area of Sierra de San Javier has belonged to 'Parque Sierra de San Javier' natural reserve. The vegetation corresponds to the Biogeographical Province of the Yungas (Cabrera & Willink 1973), which includes the Montane Forest, characterised by the presence of characteristic large trees (e.g. *Anadenanthera colubrina* (Vell.) Brenan, *Enterolobium contortisiliquum* (Vell.) Morong, *Tipuana tipu* (Benth.) Kuntze, *Ocotea porphyria* (Griseb.) Van der Werff, *Eugenia uniflora* L., *Blepharocalyx salicifolius* (Kunth) O. Berg, *Juglans australis* Griseb., *Cedrela angustifolia* Moc. et Sessé ex DC., *Podocarpus parlatorei* Pilg., and *Alnus acuminata* Kunth.), vines and epiphytes (Ayarde 1995; Grau 2010).

There is a clear gradient of increasing vegetation cover from east to west of the city. The central area shows the highest urbanisation density, there are few trees, mostly in squares and parks and to a lesser extent along sidewalks and in gardens. Towards the west, the arboreal vegetation intersperses among high buildings and along the paths. As we continue progressing to the west, we enter the city of Yerba Buena (adjacent to San Miguel de Tucumán) where the density of urbanisation is lower, with low dwellings and with more significant vegetation cover in gardens and sidewalks (Grau 2010). The foothills of the Sierra de San Javier represent the end of the vegetation cover gradient in the urbanised areas (Grau & Kortsarz 2012). The sampled area is wholly urbanised, mostly with low constructions that alternate with higher buildings. The streets and avenues have abundant exotic and generally ornamental native tree vegetation. Near the sampling location, some squares and parks contribute with its native and exotic flora. A survey at the sampling area showed 127 plant species; 62.20% autochthonous, dominated by *Handroanthus impetiginosus* (Mart. Ex DC.) Mattos, *Enterolobium contortisiliquum*, *Peltophorum dubium* (Spreng.) Taub., *Ceiba* sp., *Tipuana tipu*, *Jacaranda mimosifolia* D. Don, *Anadenanthera colubrina*, *Bauhinia forficata* subsp. *pruinosa* (Vogel) Fortunato and Wunderlin, *Lonchocarpus lilloi* (Hassl.) Burkart, and *Juglans australis*. The remaining 27.79% corresponds to exotic species represented by (in decreasing order) *Citrus aurantium* L.,

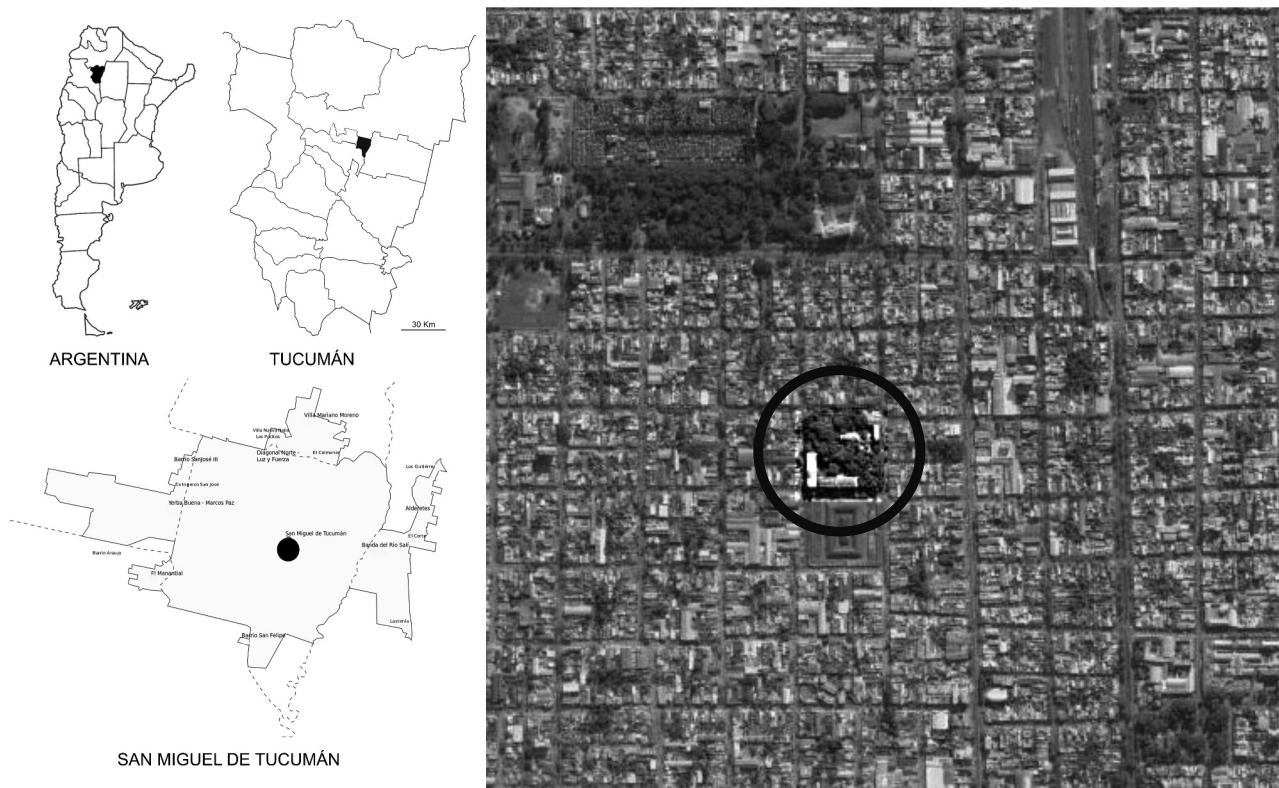


Figure 1. The geographic location of the monitoring site for airborne pollen; Fundación Miguel Lillo, San Miguel de Tucumán city, Tucumán province, Argentina.

Broussonetia papyrifera (L.) Vent., *Fraxinus* sp., *Ficus* sp., *Ligustrum lucidum* W. T. Aiton, *Lagerstroemia indica* L., *Morus* sp., *Pinus* sp., *Platanus* sp., *Bauhinia* sp., *Cupressus* sp. and *Eucalyptus* sp. However, the number of individuals is higher for exotic species, compared to native species. Also, entomophilic pollination species predominate (66.66%) compared to anemophilic ones (33.61%) (García de Albano 2013).

Pollen sampling

For pollen sampling, we use a Hirst-type (Hirst 1952) volumetric spore trap placed at a height of 20 m on a building of Fundación Miguel Lillo. The preparation of individual slides follows the standard methods of the Spanish Network of Aerobiology (REA) (Aira et al. 2005; Galán Soldevilla et al. 2007). We use a microscope at a magnification of $200\times$ to identify pollen grains. For each day we established six transects, perpendicular to the turning direction of the drum (2 a.m., 8 a.m., 10 a.m., 2 p.m., 8 p.m. and 10 p.m.) to count pollen grains. We selected these six sampling periods that are not equidistant because they respond to periods of

micro-climatic changes during the day, in the study area – for example, post-sunrise and post-sunset air temperature changes (Minetti 2005; García et al. 2018). We follow O'Rourke (1990) to estimate pollen concentration. For converting each daily sampling to pollen grains per air volume, we take into account (1) the total area of slide = $14\text{ mm} \times 48\text{ mm} = 672\text{ mm}^2$; (2) the slide area sampled = number of transects (six) $\times$ length of the tape (14 mm) $\times$ field of view (0.899 mm); (3) the volume of air sampled = $10\text{ l/min} = 14.45\text{ m}^3$; and (4) a conversion factor = $(1)/((2) \times (3)) = 0.62$. The area of the slide examined (11.2%) is in accordance with the minimum requirements for aerobiological monitoring described by Galán et al. (2014). The results are expressed as pollen grains per cubic metre (pollen grains/ m^3) (Galán et al. 2017).

We identified pollen types at the family, genus or species levels, using a reference collection with materials from the area (Palinoteca of the Fundación Miguel Lillo, PAL-TUC; <http://www.lillo.org.ar/atlaspolinicodeleao/>), and specialised literature (Erdtman 1952; Faegri & Iversen 1966; Heusser 1971; Markgraf & D'Antoni 1978; Moore et al. 1991; Pire et al. 1992, 1994, 1998, 2001; García et al. 2008, 2012). All records were also separated

by its life form, in arboreal (trees and shrubs AP), and non-arboreal pollen (herbaceous group NAP), although in this study we only consider AP.

Weather-related factors

For the same sampling hours, we obtained data from the meteorological station of the Estación Experimental Agrícola Obispo Colombres (EEAOC; 26° 47' 16" S, 65° 11' 32" W). Specifically, hourly records of air temperature, air relative humidity (RH), rainfall (Rf), wind speed and wind direction (WS and WD, respectively). As WD has a periodic behaviour, we use a circular instead of a linear scale (Mardia & Jupp 2009).

Data analysis

To describe the pollen time series, at first, we characterised the annual, monthly, and hourly profiles. The yearly cycle began on 1 August and finished on 31 July. In this way, the annual profile corresponds with the seasonal pattern of Tucumán (Minetti 1975; Ayarde 1995). To determine the temporal trend, we applied a linear regression with time (month as a unit) as the explanatory variable, and a monthly average of AP per hour of sampling as the response variable. To allow a continuous time series, and to improve model optimisation, we transformed the response variable to $\log(X + 1)$. To evaluate the influence of meteorological factors on AP variation, we applied generalised least square (GLS) models (Pinheiro & Bates 2000; Venables & Ripley 2002; Zuur et al. 2009; Gałeczki & Burzykowski 2013). These models allowed the characterisation of both the variance and error structure, which is essential for considering the auto-regressive process of time series (Pinheiro & Bates 2000). We also evaluated the variance inflation factor (VIF). Because the hour of the day, temperature and humidity correlate positively; we drop at least one of these factors from the alternative suggested models. Based on that, we built the following model:

Mean AP = season + hour + temperature + humidity + precipitation + wind velocity + wind direction (1)

We transformed the raw wind direction data to circular data before analyses. Circular statistical methods for studying pollen and land cover analysis were used by Maya-Manzano et al. (2017). In the initial model, the temporal correlation structure for AP was ARMA (1,0), with a variance structure corresponding to different error variances between sea-

sons within the year. In this way, the model considered deviations from the variance homogeneity expected for Gaussian models (Gałeczki & Burzykowski 2013). The alternative models considered (1) a variance structure was corresponding to different error variance between seasons (without considering the year and therefore weighting for seasonal dynamics); (2) without variance structure; (3) with and without the inclusion of humidity or temperature (given the variance inflation effects associated with the factor hour, as explained earlier). We considered the best (optimal) model to be that with the lowest AIC value, according to the Akaike Information Criteria (AIC). Finally, we fitted the selected model by restricted maximum likelihood (REML). This optimised model would indicate how much of the variation in mean AP is explained by the factors indicated in Equation (1). The model outcomes were plotted as partial residuals, allowing to visualise the effects of each variable when accounting for the effects of the other variables in the model. All the analyses and figures were made in R 3.5.3 (R Development Core Team 2019) using the following packages: car (Fox & Weisberg 2011), circular (Agostinelli & Lund 2013), mgcv (Wood 2004), nlme (Pinheiro et al. 2015), and visreg (Breheny & Burchett 2015).

Results

Pollen composition

We collected 100 pollen types in the atmosphere over the ten year sampling period. Specific pollen types were observed throughout the whole period, while others were found only in particular years (e.g. Tiliaceae, Malpighiaceae, *Ruprechtia*, *Notophagus*, Meliaceae, *Prunus*, Portulacaceae, *Peltophorum dubium*, *Handroanthus*). Despite the apparent high diversity, only 14 pollen types contributed to 90% of total atmospheric pollen (TP) found, including the following (in decreasing order of importance): *Broussonetia papyrifera*, *Morus*, Urticaceae, *Celtis*, Asteroideae, *Alnus*, Poaceae, *Fraxinus*, Solanaceae, Amaranthaceae, *Platanus*, Myrtaceae, *Juglans*, and *Salix*. In this list, the predominance of exotic species with anemophilic pollination is highlighted (*Broussonetia papyrifera*, *Morus*, Urticaceae, *Fraxinus* and *Platanus*). However, we rarely detected in the atmospheric record those pollen types coming from the entomophilous trees, widely cultivated along the city streets (García de Albano 2013), such as *Citrus*, *Handroanthus*, *Jacaranda mimosifolia*, *Tipuana tipu*, *Bauhinia variegata*.

The total value of pollen (TP) captured within the 2006–2016 period was 67 917.67 pollen grains/m³, of which 49 730.20 pollen grains/m³ corresponded to

AP (73%). This percentage indicates that AP dominates the annual spectrum. The most abundant AP identities in the atmosphere of San Miguel de Tucumán were *Broussonetia papyrifera* (52%), *Morus* (16%), *Platanus* (2.21%), *Fraxinus* (2.66%) within exotic pollen types; and *Celtis* (12.50%), *Alnus* (4.60%), *Juglans* (1.21%), Myrtaceae (1.71%), *Salix* (1.20%) and *Anadenanthera* (0.30%) within native pollen types.

Time series description

The time series profile was markedly seasonal, and this seasonal AP pattern was similar over the ten years (Figure 2). The lowest concentrations were recorded between May and July (late autumn to winter) (less than 1% of annual AP). However, the percentage of recorded pollen did not exceed 1.5% between January and April (i.e. late summer to autumn). In contrast, the maximum concentrations were recorded between August and October (late winter and spring) with at least 89% of the annual AP. September was the month with the highest pollen contribution in almost every year, except for 2009 and 2013 (October); and 2016 (August) (Supplementary online material, Table S1). Additionally, the magnitude of the variation in winter and spring was twice the magnitude of variation in summer and autumn, and such marked seasonality was related to the high contribution of *Broussonetia papyrifera* (52%), as previously noted.

While seasonality occurred in all the years, the pollen concentration values were markedly different (Figure 3). The amount of AP collected per year

varied, with 2008 showing the lowest values ($AP = 1344.23$ pollen grains/ m^3) and 2012 showing the highest values ($AP = 11\,126.73$ pollen grains/ m^3) (Supplementary online material, Table S1).

The profile of pollen concentration per hour of sampling over the ten-year period showed a low variation between hours (Figure 4). On average, the highest concentrations occurred at 2 a.m., and the lowest at 2 p.m. *Broussonetia papyrifera* was the pollen type that contributed the most to pollen concentration per hour, reaching its maximum at 10 a.m. (6041.65 pollen grains/ m^3), but with similar values at 8 a.m. (5169.47 pollen grains/ m^3) and 2 a.m. (5099.67 pollen grains/ m^3). *Morus* (1808.78 pollen grains/ m^3) and *Fraxinus* (248.68 pollen grains/ m^3) showed the highest contribution at 2 a.m. *Platanus*, whose highest contribution (424.39 pollen grains/ m^3) was at 2 p.m. presented a similar value (407.73 pollen grains/ m^3) at 2 a.m. Based on the earlier mentioned, we conclude that these pollen types (which were the most abundant in the atmospheric record) showed a higher contribution to pollen concentration at 2 a.m. If we take the diurnal variation yearly, specific differences become evident (Supplementary online material, Table S2): the highest total pollen concentration occurred at 2 a.m. in most years (2006, 2010, 2011, 2012, 2014 and 2016), while it occurred at 10 a.m. in 2007, 2013 and 2015; and at 8 a.m. in 2008 and 2009. However, the lowest pollen concentration occurred at 2 p.m. in 2006, 2008, 2009, and 2012. In the other years, the difference between the lowest pollen accumulation by hour period and the amount

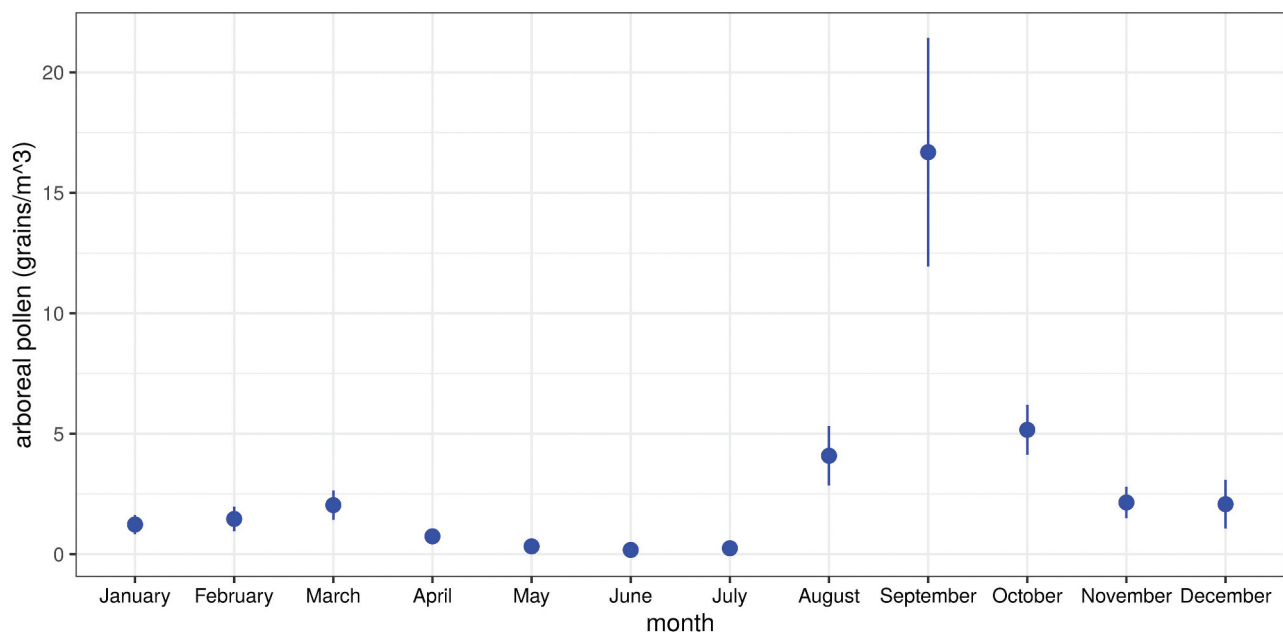


Figure 2. The monthly profile for the August 2006–July 2016 period for the Tucumán city monitoring site. The central point represents the mean, and the whisker represents one standard deviation.

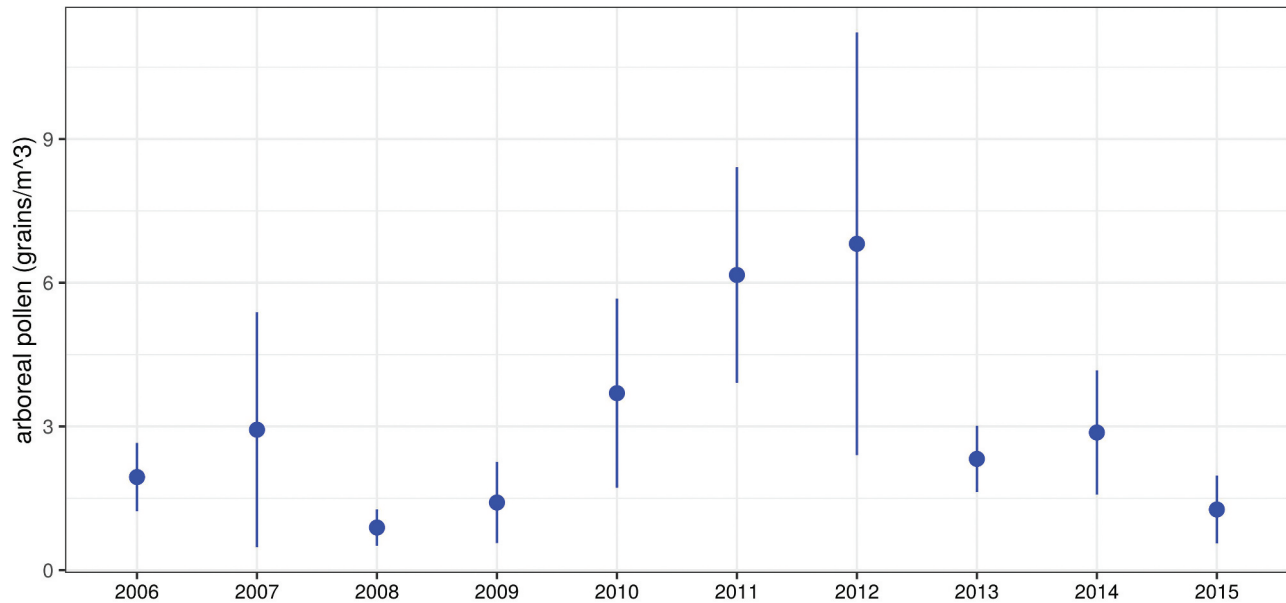


Figure 3. The annual profile for the August 2006–July 2016 period for the Tucumán city monitoring site. The central point represents the mean, and the whisker represents one standard deviation.

recorded at 2 p.m. was minimal (Supplementary online material, Table S2).

The monthly average of AP per hour showed a slight increasing temporal trend (adjusted- $R^2 = 0.013$, $F[1,718] = 10.68$, $p = 0.001$). However, when the monthly average excluded the hourly variation, the temporal trend was not significant (adjusted- $R^2 = 0.006$, $F[1,118] = 1.758$, $p = 0.18$).

Together, these results suggest that, in general, AP increased slowly on a per-hour basis.

Weather-related effects

The selected model showed a strong seasonal effect on AP dynamics (Table I). The AP was significantly higher during winter, spring, and summer, although

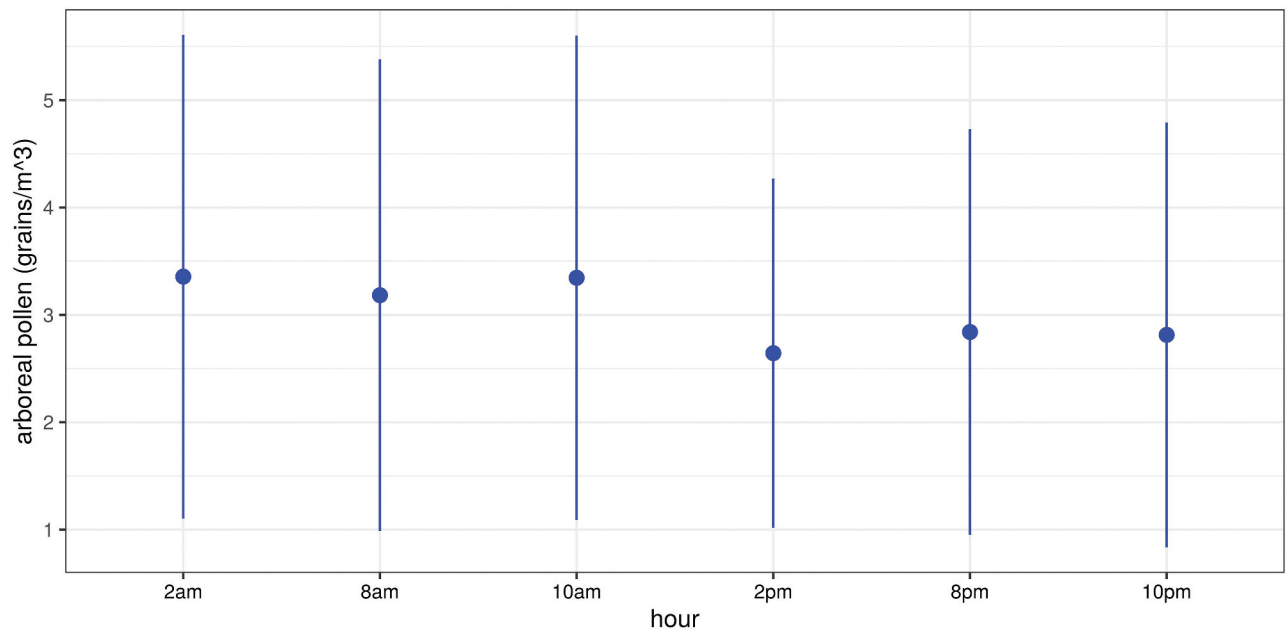


Figure 4. The hourly profile for the August 2006–July 2016 period for the Tucumán city monitoring site. The central point represents the mean, and the whisker represents one standard deviation.

Table I. Summary of the generalised least square (GLS) models addressing the effects of year, season, and hour of the day on arboreal pollen, taking into account the effects of air temperature, air humidity, precipitation, in San Miguel de Tucumán, Tucumán province, Argentina.

Parameter	Estimate	SE	<i>t</i>	<i>p</i> -Value
Intercept	0.543	0.285	1.907	0.0570
Year 2007	-0.117	0.176	-0.666	0.5059
Year 2008	-0.088	0.181	-0.484	0.6282
Year 2009	0.069	0.181	0.380	0.7039
Year 2010	0.534	0.181	2.953	0.0032
Year 2011	0.549	0.181	3.038	0.0025
Year 2012	0.294	0.182	1.622	0.1052
Year 2013	0.030	0.181	0.169	0.8661
Year 2014	0.031	0.182	0.168	0.8667
Year 2015	0.013	0.182	0.074	0.9411
Winter	0.647	0.142	4.542	<0.0001
Spring	0.487	0.095	5.114	<0.0001
Summer	0.263	0.056	4.677	<0.0001
Hour 8 a.m.	0.036	0.022	1.648	0.0998
Hour 10 a.m.	-0.059	0.033	-1.775	0.0763
Hour 2 p.m.	-0.290	0.065	-4.475	<0.0001
Hour 8 p.m.	-0.146	0.039	-3.700	0.0002
Hour 10 p.m.	-0.071	0.026	-2.798	0.0053
Temperature	0.021	0.007	3.118	0.0019
Humidity	-0.007	0.003	-2.713	0.0068
Precipitation	-0.006	0.005	-1.415	0.1574
Wind speed	-0.002	0.008	-0.253	0.8007
Wind direction	0.0002	0.000	-1.545	0.1229

Note: The model has a different variance structure per season. Autoregressive parameter (ϕ_1) = 0.859. SE: standard error. Significant parameters are in bold. The value and sign of the estimate indicate the magnitude of change in respect to the mean.

during winter the highest magnitude of change occurred. Also, the AP was significantly lower in the evening hours, and before midnight. A significant positive effect of air temperature and a signifi-

cant negative effect of air humidity explained the variability in AP load (Figure 5, Table I).

When meteorological variables were excluded from the model, there was a significant effect of the hour,

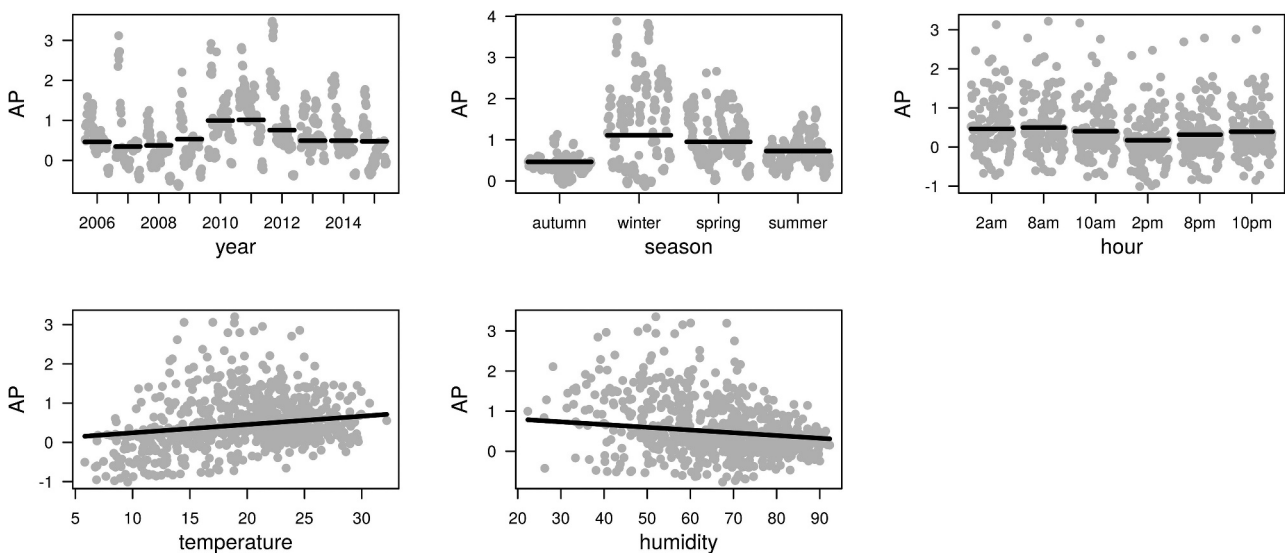


Figure 5. Direct influence of climatic variables and seasonality on the arboreal pollen (AP, in grains/m³) in Tucumán city, Argentina. The observed points (partial residuals) are shown in grey. Fitted lines correspond to predictions from the selected GLS models (see Data analysis section) and indicate partial regressions, representing the magnitude of change controlling for the other variables.

Table II. Summary of the generalised least square (GLS) models of the effects of year, season, and hour of the day on arboreal pollen in San Miguel de Tucumán, Tucumán province, Argentina.

Parameter	Estimate	SE	<i>t</i>	<i>p</i> -Value
(Intercept)	0.227	0.138	1.643	0.1008
Year 2007	−0.115	0.184	−0.624	0.5327
Year 2008	−0.002	0.189	−0.012	0.9901
Year 2009	0.130	0.189	0.687	0.4921
Year 2010	0.546	0.190	2.882	0.0041
Year 2011	0.649	0.190	3.427	0.0006
Year 2012	0.408	0.190	2.152	0.0318
Year 2013	0.100	0.190	0.528	0.5977
Year 2014	0.133	0.190	0.703	0.4821
Year 2015	0.001	0.192	0.004	0.9965
Winter	0.827	0.146	5.661	0.0000
Spring	0.629	0.094	6.714	0.0000
Summer	0.366	0.048	7.623	0.0000
Hour 8 a.m.	−0.008	0.020	−0.410	0.6821
Hour 10 a.m.	0.020	0.025	0.829	0.4076
Hour 2 p.m.	−0.027	0.026	−1.016	0.3100
Hour 8 p.m.	−0.017	0.025	−0.691	0.4897
Hour 10 p.m.	−0.017	0.020	−0.845	0.3984

Note: The model has a different variance structure per season. Autoregressive parameter (ϕ_1) = 0.868. SE: standard error. Significant parameters are in bold. The value and sign of the estimate indicate the magnitude of change in respect to the mean.

season, and year (Table II). This result suggests that (1) AP variability during the day was due to weather variability within the day; and (2) the increases recorded during 2010 to 2012, with a peak in 2012, might be due to long-term variations related to seasonal reproductive phenological variability.

Discussion

AP was predominantly recorded in the atmosphere of San Miguel de Tucumán city from July to October. The highest atmospheric AP concentrations occur from mid-winter and spring until early summer when arboreal species pollination is underway. In summer, airborne AP concentrations began to diminish, since anemophilous trees in bloom are scarce. The lowest airborne AP concentrations occurred at the end of autumn and early winter when there are practically no trees in bloom. This pattern indicates a strong seasonal effect on the airborne pollen load in the atmosphere, coinciding with previous studies on climate variability and pollution in the region (García et al. 2018).

Broussonetia (Moraceae), a highly allergenic exotic species (Hsu et al. 2008), stood out in the AP spectrum of San Miguel de Tucumán city. However, other alien (*Morus*, *Platanus* and *Fraxinus*) and native species (*Celtis*, *Alnus*, *Juglans*) had an important secondary role. The composition and abundance of urban vegetation were partially reflected in the atmospheric pollen spectrum, due

to the pollination type of specific taxa, the aerodynamic characteristics of the pollen grains, and the productivity of each taxon. These results confirm a previous study using the gravimetric method in Yerba Buena city, Tucumán (García 2010), which detected a seasonal effect. A high contribution (75%) of AP occurred from July to October. It is worth highlighting that the floristic and urban characteristics of Yerba Buena are different from those of San Miguel de Tucumán, for which the dominant pollen types found were consequently different. The dominant pollen type corresponded to the Cupressaceae family (*Cupressus* sp., *Juniperus* sp. and *Thuja* sp.), followed by *Pinus*, *Morus*, *Broussonetia*, *Fraxinus* and *Liquidambar* within the exotic species; and *Celtis*, *Alnus acuminata* and *Juglans* among the native species (García 2010).

Using the volumetric method, other studies from other climatic regions of Argentina revealed strong seasonal effects too. For example, from the cities of La Plata (Nitiu & Mallo 2002), Rosario (Gattuso et al. 2003), Mar del Plata (Latorre & Pérez 1997; Latorre 1999), and Buenos Aires (Nitiu et al. 2003; Abud Sierra & Latorre 2020). The pollen calendars of such cities were mainly defined by pollen from exotic anemophilous urban trees such as Cupressaceae, *Platanus* and *Fraxinus*, which are very common in all these cities. Also, we found a vast difference in the amount of pollen collected in San Miguel de Tucumán, compared to that of the cities

mentioned earlier. This result might be since, in San Miguel de Tucumán, many native and exotic species exhibit entomophilic pollination, with a low contribution to airborne concentrations (García de Albano 2013).

In Tucumán, the year with the highest pollen contribution was 2012. This value is three times lower compared to the concentrations obtained in other cities of Argentina, such as in Buenos Aires (Nitiu & Mallo 2012). This remarkable difference might also be because Buenos Aires has abundant exotic, anemophilous urban vegetation. Regarding the pollen spectrum of San Carlos de Bariloche (Bianchi et al. 2004; Olabuenaga et al. 2007), which is dominated by native vegetation, it shows a vast difference with both Tucumán and the other Argentine cities mentioned earlier. We can attribute these discrepancies to the most prominent pollen types in Bariloche, which are mainly *Austrocedrus chilensis*, *Fitzroya cupressoides* (Mol.) Johnston in a lower proportion, and *Pilgerodendron uviferum* (D. Don) Florin, among the native species; and *Cupressus* sp, and *Thuja* sp among the exotic species. In Bariloche, the amount of pollen collected per year was significantly lower than in other cities. In Tucumán, we recorded lower amounts of pollen grains than other places of South America with different phytogeographic and climatic characteristics; such as Caxias do Sul, Rio Grande do Sul, Brazil (Vergamini et al. 2006), and Santiago de Chile (Rojas Villegas & Roure Nolla 2001).

The considerable variation in terms of the amount of captured AP observed from one year to another (Figure 2) might be partly explained by the 'Vecería' phenomenon (Oliver 2009). In the Yungas phytogeographical zone, which partially ranges together Tucumán city, the 'Vecería' has been observed by Ayarde (1995, 2006), particularly reported for *Cedrela* and some species of Myrtaceae (*Myrcianthes callicoma*, *Blepharocalyx salicifolius*) (Ayarde 1995, 2006; Hugo Ayarde pers. comm. 2020). Therefore, tree pollen concentration would likely be high after a year of low flowering intensity. One plausible explanation is that pollen seasons often follow long-term reproductive cycles (Latorre 1999). This biennial pattern is more regularly observed since 2012.

The analysis of daily variations within the ten-year sampling period identified a maximum pollen peak at 2 a.m., and minimum concentrations at 2 p.m. Thus, AP did not follow a typical daily trend described in other articles, with high concentrations during daylight hours and low concentrations at night (Bianchi 1994; Pérez et al. 2003; Nitiu 2006a, 2006b; Latorre & Caccavari 2009). In Tucumán, due to its topography (mountains to the west

and plain to the east), the south winds predominate during the day, and the heating of the urban surface produces turbulence (thermal and mechanical) that determines the suspension and vertical diffusion of the pollen grains, while the wind produces its horizontal transport. At sunset, there is a calm and the winds rotate and appear as soft breezes from the north. This explains, along with the thermal inversion of atmospheric layers during the night (Minetti 2005; García et al. 2018), the increased deposition of particles (pollen grains) after 8 p.m.

We observed an increase in hourly pollen concentration curve in night hours from 8 p.m. and 10 p.m., reaching a peak at 2 a.m. According to Kämpylä (1984), this could be explained by the thermodynamic stability of the atmosphere. Solar heating of the air close to the ground produces a 100 to 200 m layer with positive buoyancy, in which small chimneys of hot air are formed, which come together to create a sizeable thermal column that ascends a few hundred metres both in width and height. These thermals are 1 °C or 2 °C above the environment with an ascent speed 1–3 m/s and they are cooled until they condense. When exceeding the height of the boundary layer and the stable atmosphere, the thermal current diverges horizontally and tends to fall (with lower velocity) on the outside of the ascending column (Martínez 2010). The thermal and mechanical turbulence is the driving factor of the suspension and vertical diffusion of the pollen grains, while wind produces its horizontal transport. The net result of this combination produces a pollen deposition curve with decreasing values from very high close to the source; to asymptotic, usually a few hundred metres away (Lanner 1966). In our study area, the peaks of thermal inversion occur at night, and winds from the southwest and southeast move air masses to the zone of Tucumán city (García et al. 2018). Given that wind has negative effects on the dispersal of particulates (García et al. 2018), a plausible explanation of the peak of airborne pollen at night is the decrease in wind velocity at sunset and night hours. Our findings are supported by the study of Maya-Manzano et al. (2017), who concluded that local wind direction patterns influence airborne pollen concentrations.

In the South America region, there are few studies on the diurnal variations of airborne pollen. Observations made by Pérez et al. (2001a, 2001b) in Mar del Plata city, showed maximum values of AP between 10 a.m. and 12 a.m. until 4 p.m. However, the authors mention an increase at 10 p.m., which could be due to the re-entry of local and extra-local pollen. Similarly, Latorre et al. (2013) described diurnal variations in airborne *Araucaria angustifolia*

pollen in San Antonio (Misiones, Argentina) and showed a maximum between 10 a.m. to 2 p.m. and minimum values between 10 p.m. and 6 a.m. Although a small increase in pollen was occasionally observed at night. However, Pérez et al. (2003) showed that the highest proportion of *Celtis* and *Platanus* pollen recorded in Mar del Plata in 1988 settled between 8 p.m. and 6 a.m. In other locations outside America, Pérez-Badia et al. (2010) described intradiurnal variations of allergenic tree pollen in the atmosphere of Toledo (central Spain) and found that Cupressaceae species and pollen types from the genera *Olea*, *Populus* and *Ulmus* showed peak concentrations between 12 p.m. and 6 p.m., and *Quercus* and *Platanus* pollen types peaked between midnight and 2 a.m., respectively. These examples suggest that local geographic characteristics and weather-related factors determine hourly variations in airborne tree pollen.

Conclusions

The present study provides the first volumetric monitoring and airborne pollen spectrum for San Miguel de Tucumán city and enhances our knowledge of AP behaviour in the air. The annual pollen spectrum is dominated by AP, whose significant contribution has a marked seasonality with short and intense flowering periods. Although seasonal patterns of AP were similar over the ten years of study, the amount of pollen from trees collected per year varied. Despite the great variety of taxa identified, a few contributed more than 80% (*Broussonetia*, *Morus*, *Platanus*, *Fraxinus*, *Celtis*, *Alnus*, *Juglans*), with *Broussonetia* being the most abundant. The amount of pollen collected annually is not as high as in other places, likely because entomophilous trees are dominant in urban areas. The hourly analysis in our ten-year sampling period identified a peak in airborne pollen concentrations at 2 a.m. and minimum concentration at 2 p.m. The co-variation between AP concentration and meteorological parameters in our study period showed a positive effect of air temperature, and a negative effect of air humidity, with a strong seasonal effect. Studies of pollen dynamics are essential to evaluate the environmental quality of a given area. Additionally, we can use the findings of this study to examine the impacts of airborne pollen on human health.

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No potential conflict of interest was reported by the authors.

Supplementary material

Supplemental data for this article can be accessed [here](#).

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