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Key Points:
- Two pollen concentration peaks were recorded, a spring peak dominated by arboreal pollen types and a fall peak dominated by upland herbs
- Pollen concentration values were markedly different between the two years, probably reflecting differences in weather
- Pollen signal responses to weather conditions have to be considered at a taxon level rather than at the assemblage level

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Airborne Pollen Concentration in Nanjing, Eastern China, and its Relationship With Meteorological Factors

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Abstract This paper presents the results of airborne pollen and spore trapping in Nanjing city, eastern China, using a Burkard pollen trap during two consecutive years (2013–2014). A total of 103 pollen and spore taxa were identified. Two concentration peaks are observed in the annual cycle, a spring peak dominated by arboreal pollen types (*Morus*, Cupressaceae, *Pinus*, *Pterocarya*, and *Quercus*) and a fall peak dominated by upland herbs (Compositae, Poaceae, *Humulus*, and Cruciferae). Wetland herbs and ferns dominate summer assemblages and winter assemblages are characterized by sporadic records of *Artemisia*, Chenopodiaceae, and *Pinus*. Strong year-to-year differences in measured pollen concentration are seen, probably in response to interyear differences in weather. Compared to long-term means, 2013 was comparatively hot and dry and 2014 had a higher than average number of rain days during the flowering periods. Rising temperatures in early spring are connected with the timing of flowering and therefore pollen release, while rainfall during the flowering period appeared to remove pollen from the air, leading to lower recorded pollen concentration values. Four taxa, Cupressaceae, *Quercus*, *Pinus*, and *Humulus*, were considered in more detail. Each has a different pattern of variation in pollen concentration between the studied years. Cross correlation between pollen concentration and daily temperature, relative humidity, and precipitation at lags from 0 to −30 days also showed different responses for each taxon, suggesting that pollen signal responses to weather conditions have to be considered at a taxon level rather than at the assemblage level.

1. Introduction

Aeropalynology trapping programs provide a large amount of data on patterns of airborne pollen both within and between years and have enabled the development of models for short-term forecasting of pollen counts and allergy risk. Daily pollen counts have been recorded for many years in some locations, especially in Europe (e.g., García-Mozo et al., 2006; Haberle et al., 2014; Jäger et al., 1991; Latorre et al., 2008). These data sets have enabled aerobiologists to develop statistical models for predicting plant flowering phenology (García-Mozo et al., 2000) and the time course of specific pollen types in the atmosphere (Chuine & Belmonte, 2004). In other parts of the world these basic data are missing. For example, Nanjing is a large city in eastern China (Figure 1), but the only available pollen trapping data cover subannual time periods and report the main airborne pollen types during peak seasons (e.g., Wei et al., 2008; Zhang et al., 2009). In these situations, even 1- to 2-year monitoring sequences can provide useful new insights into the annual pattern of airborne pollen and relationships between meteorological conditions and the abundance of the main pollen types.

Modern pollen dispersal and deposition models are also valuable as a means of improving the reconstruction of past land cover and environmental change from Quaternary pollen records preserved in sedimentary systems. Relationships between land cover pattern, diversity and abundance of airborne pollen grains, and meteorological variables combine to determine the pollen assemblages deposited into the sedimentary record. While aeropalynological data are recorded at a much finer time scale than is possible from sedimentary archives, where samples typically represent a decade or more of pollen deposition, studies of airborne pollen have still played an important role in improving scientific understanding of the relationships between pollen assemblages and source vegetation. Aeropalynology shows that meteorological factors affect both the production of pollen by plants (Cariñanos et al., 2004) and the transport of

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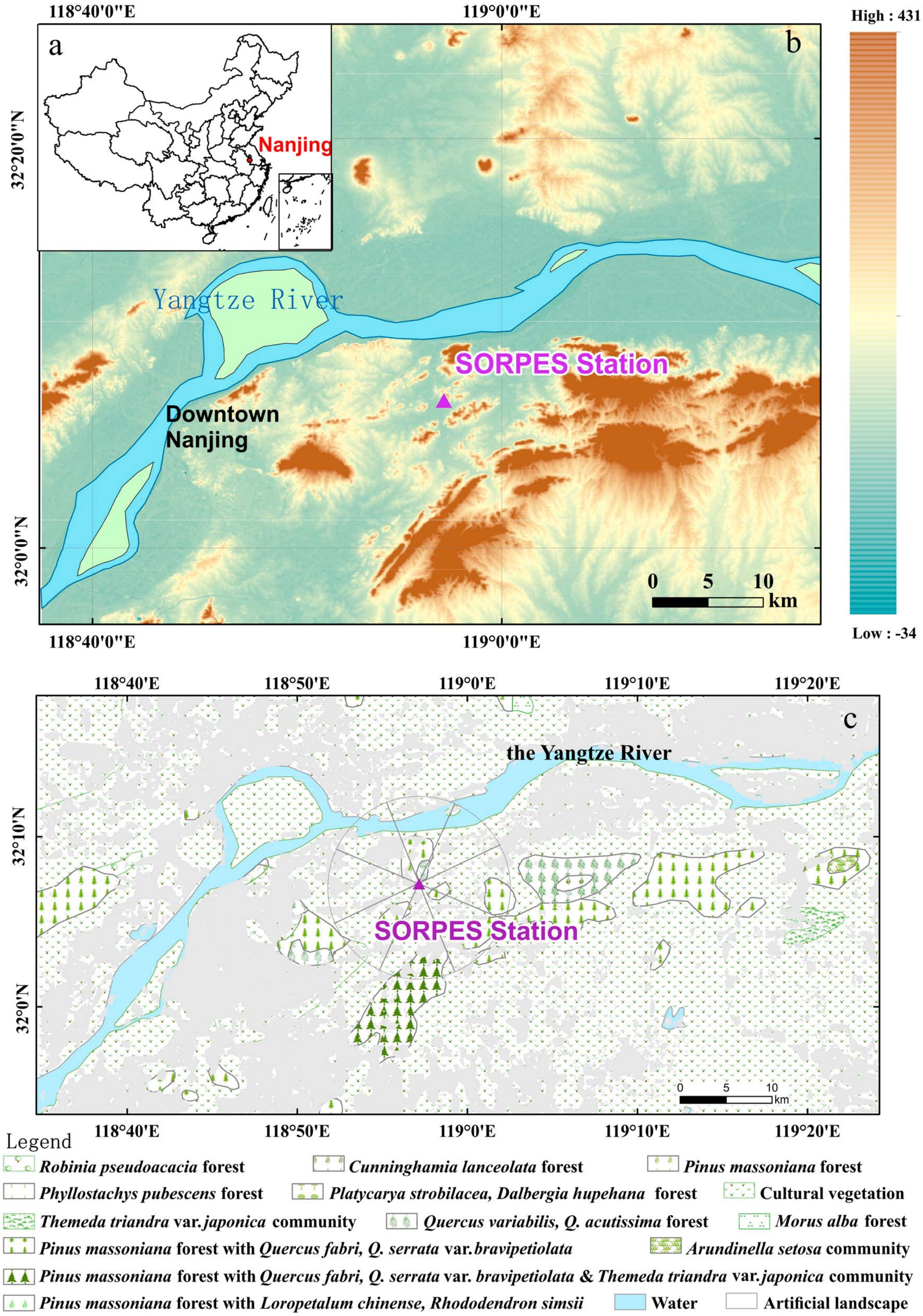

Figure 1. Location and context of pollen trap and meteorological station. (a)The location of Nanjing city in China, (b) the location of SORPES in Nanjing in relation to topograph, (c) the location of SORPES in Nanjing in relation to land cover (after Editorial Board of Vegetation Map of China, 2007; An and Zhao, 1990; Zhao et al., 2009). The "wheel" superimposed on SORPES delimits a 10-km radius circle centered on the station, divided into wind octants, used for more detailed investigation of pollen-land cover relationships (see Table 1 and Figure 7).

pollen through the air (Latorre, 1999), and in at least some cases that these relationships are generalizable between sites (Ranzi et al., 2003). Meteorological conditions were almost certainly different in the past, but understanding the general patterns of long distance pollen transport today can still inform reconstructions (Rousseau et al., 2006) by linking climate models with sedimentary pollen records. For example, Dupont and Wyputta (2003) used paleo-wind-field models to translate the changing pollen assemblages in marine sediment cores from the southeast Atlantic into reconstructions of paleovegetation in different parts of southern Africa during the last glacial period.

The aims of this paper are to present a data set of daily airborne pollen assemblages and meteorological factors collected over a 2-year period in Nanjing and to investigate the relationships between the observed abundance of four common pollen taxa (Cupressaceae, *Quercus*, *Pinus*, and *Humulus*) and meteorological factors.

2. Location

Nanjing is a large city in the lower Yangtze River drainage basin of eastern China (Figure 1a) located close to the coastal region of the Northwest Pacific Ocean. The climate is dominated by the East Asian monsoon. Prevailing winds in this region are from the southeast in summer and northeast in winter (Ding et al., 2013). The long-term average precipitation is 1091 mm per annum, and the mean annual temperature is 15.9 °C (China Meteorological Administration Data Service Center, 1981–2010).

In order to record the airborne pollen, a Burkard pollen trap was placed on the roof of the Station for Observing Regional Processes of the Earth System (SORPES), a meteorological station situated in a suburb of Nanjing (Figures 1b and 1c: 118°57′10″E, 32°07′14″N). This allowed direct comparison of trap data and daily meteorological data from the same location. The station is located on a flat roof with an elevation of 43 m above sea level. More details about SORPES are presented in Ding et al. (2013, 2016).

A land cover map for the landscape around the trapping station is shown in Figure 1c. Outside the central Nanjing urban area, forest patches remain, especially in the eastern suburbs. These forest patches include both deciduous and evergreen broadleaved communities (Yan et al., 1995). Field surveys show that the major arboreal species in the forests are *Pinus massoniana*, *Liquidambar formosana*, *Quercus fabri*, *Quercus variabilis*, *Quercus acutissima*, *Platycarya strobilacea*, *Dalbergia hupeana*, *Castanea henryi*, *Cyclobalanopsis glauca*, *Pistacia chinensis*, *Loropetalum chinense*, *Aphananthe aspera*, *Albizzia kalkora*, *Ilex chinensis*, *Celtis sinensis*, *Sapium sebiferum*, *Acer mono*, *Robinia pseudoacacia*, *Lindera glauca*, *Rhus chinensis*, *Koelreuteria paniculata*, *Photinia serratifolia*, *Symplocos paniculata*, and *Rhamnus globosa*, and the main herbaceous species are *Sanguisorba officinalis*, *Trachelospermum jasminoides*, *Parthenocissus tricuspidata*, *Deyeuxia sylvatica*, *Arthraxon hispidus*, *Aster panduratus*, and *Carex lanceolata* (An & Zhao, 1990; Zhao et al., 2009). In the urban area (mapped as “artificial landscape” in Figure 1c), planted species include *Sabina chinensis* (L.) Ant., *Platycladus orientalis* (Linn.) Franco, *Ginkgo biloba*, *Pterocarya* spp., *Acer palmatum* Thunb., *Sorbus alnifolia* (Sieb. et Zucc.) K. Koch, *Malus halliana* Koehne, *Typha orientalis* Presl, and *Spiraea salicifolia* L.

3. Materials and Methods

A Burkard trap was chosen for pollen monitoring. Multiple sampling methods for aerial pollen trapping are available, which can be classified into two basic types, gravimetric and volumetric traps (Latorre et al., 2008). Gagnon and Comtois (1989) demonstrated that the results from volumetric traps (Burkard or Rotrod) are more representative of the regional vegetation than those from gravimetric traps, and pollen assemblages from Burkard traps (SporeWatch electronic spore and pollen sampler, Burkard Scientific Ltd, Uxbridge, Middlesex, UK) are considered to be more responsive to maximum floral phenophase and temperature changes than records from Rotrod traps (Latorre et al., 2008).

Daily airborne pollen was recorded over 2 years, using a constant air intake speed of 10 l min^{-1} and drum rotation of 2 mm hr^{-1}. Collection of pollen samples began on 1 January 2013 and ended on 31 December 2014. Due to technical problems, pollen data from two periods, 25 January to 2 February and 9 March to

Table 1
Summary of Land Cover (km^2) of 8 Land Cover Classes in a 10-km Radius Around SORPES, Divided into Wind Direction Octants (see Figures 1c and 7)

Wind direction	N (km ^{2})	NE (km ^{2})	E (km ^{2})	SE (km ^{2})	S (km ^{2})	SW (km ^{2})	W (km ^{2})	NW (km ^{2})	Total (km ^{2})	%
Water	10.02	7.79	0.00	0.00	0.00	0.00	0.00	6.70	24.51	7.80
Crop 1	8.62	0.79	0.00	0.00	0.00	0.00	0.00	4.25	13.67	4.35
Crop 2	3.30	25.15	24.38	18.21	18.69	25.25	24.03	12.39	151.40	48.19
Crop 3	0.00	0.00	0.00	0.00	0.00	1.33	0.00	0.00	1.33	0.42
Forest 1	1.30	0.99	0.00	0.00	0.00	0.00	0.00	0.00	2.29	0.73
Forest 2	0.00	0.00	0.00	0.26	7.01	0.00	0.00	0.00	7.27	2.31
Forest 3	6.50	0.40	11.33	9.42	0.41	3.66	0.09	2.27	34.09	10.85
Artificial landscape	8.98	6.25	5.57	10.68	12.82	8.22	13.50	13.58	79.60	25.34

Note. Crop 1: rice, winter wheat. Crop 2: upland and irrigated land bearing two crops per year, evergreen and deciduous orchards, and economic forest. Crop 3: areas bearing three crops in 2 years or two crops annually without irrigation, deciduous orchards. Forest 1: *Quercus variabilis/acutissima* forest. Forest 2: *Pinus massoniana* forest with *Quercus fabri*, *Q. serrata* var. *bravipetiolata* and *Themeda triandra* var. *japonica*. Forest 3: *Pinus massoniana* forest with *Quercus fabri* and *Q. serrata* var. *bravipetiolata*.

11 April in 2013, were lost. Pollen grains were identified under ×400 magnification using standard texts (Qiao, 2005; Wang et al., 1995) as references.

The first step in analysis was the identification of the annual pollen season for each taxon. The pollen season is the period during which most of the pollen of a specified type is recorded, but the means of delimiting it vary between studies (Jato et al., 2006). In this study, the pollen season for individual taxa was defined following Andersen (1991) as the period of time during which 95% of the annual total of that pollen type is recorded, beginning when the sum of the daily mean pollen concentrations reaches 2.5% of the annual total and ending when the sum reaches 97.5% of the annual total. The Seasonal Pollen Index (SPI) was then calculated as the sum of daily pollen concentrations during the pollen season (Clot, 2003; Comtois, 1998; Mandrioli et al., 1998).

A small number of taxa were selected for more detailed investigation of patterns of daily pollen concentration and relationships between environmental factors and pollen concentration levels. Taxa were selected, which made a comparatively large contribution to the overall pollen assemblage, had broadly comparable concentration trends in both years, and peaked at different points in the overall pollen season. The presence and abundance of pollen grains in an air sample depends on many factors, including the environmental conditions and the availability of source plants in the surrounding vegetation (Galán et al., 1989; Mesa et al., 2003; Tormo-Molina et al., 2015). Although 2 years of data are not sufficient to identify long-term relationships confidently, we consider that our findings form useful hypotheses to be tested in future as the data set increases in length.

In order to identify possible influences of meteorological conditions that might affect plant growth and floral development (temperature, precipitation, and relative humidity) on daily pollen concentration of selected pollen types, simple cross correlations were carried out. Daily mean pollen concentration during the pollen season was correlated with daily measurements of each of the meteorological parameters from the weather station at lags from 0 days to −30 days using steps of 1 day.

Local vegetation makes an important contributor to the airborne pollen assemblage. However, differences in overall transport distances have been observed for different pollen types; *Pinus*, *Picea*, and *Betula* can travel thousands of kilometers into the Arctic (Campbell et al., 1999; Hjelmroos, 1991), while other pollen loads (e.g., *Plantago*, *Fraxinus-Phillyrea*, and *Alnus*) are sourced within the immediate surrounding landscape (Maya-Manzano et al., 2017). In this study, we chose to explore a circular area around the pollen trap location with a radius of 10 km. Maps of land cover for each taxon were taken from existing sources (Editorial Board of Vegetation Map of China, 2007; An and Zhao, 1990; Zhao et al., 2009) and simplified into eight wedges (Figure 1c) created using ArcGIS 10.5.1. The area of land cover of each taxon inside eight wedges centered on the pollen trap location and defined by the eight compass octants (Table 1).

Pollen grain fall speed for selected taxa was approximated as sedimentation velocity and calculated using Stoke’s law, which takes particle size and density into consideration (Gregory, 1973; Sugita et al., 1999; see the Appendix for details).

Table 2
Airborne Pollen Types Recorded at SORPES, Nanjing, in the Period 2013–2014

Arboreal and shrubs	Acanthaceae, *Acer*, *Alnus*, Aquifoliaceae, *Aralia*, Araliaceae, Berberidaceae, *Betula*, *Broussonetia*, Caprifoliaceae, *Carpinus*, *Carya*, *Castanea*, *Castanopsis*, *Cyclobalanopsis*, *Celtis*, *Corylus*, *Cotinus*, Cupressaceae, *Engelhardtia*, Ephedraceae, Euphorbiaceae, *Fagus*, Flacourtiaceae, *Ginkgo*, Hamamelidaceae, *Hypericum*, *Ilex*, *Juglans*, *Koelreuteria*, *Larix*, Lauraceae, Leguminosae, *Liquidambar*, *Lonicera*, Magnoliaceae, Malvaceae, Moraceae, *Morus*, *Myrica*, Oleaceae, *Palmae*, *Pinus*, *Platanus*, *Platycarya*, Polygonaceae, *Pterocarya*, *Pteroceltis*, *Quercus* (D), *Quercus* (E), Rhamnaceae, *Rhus*, Rosaceae, Rutaceae, *Tilia*, *Salix*, Sapindaceae, Scrophulariaceae, Solanaceae, Sterculiaceae, *Symplocos*, Theaceae, Thymelaeaceae, *Tsuga*, Ulmaceae, *Ulmus*
Herbs	*Aster*, *Ambrosia*, *Artemisia*, Boraginaceae, Caryophyllaceae, *Caryopteris*, Chenopodiaceae, Compositae, Cruciferae, Gentianaceae, Poaceae, *Humulus*, Labiatae, Ranunculaceae, Loganiaceae, Onagraceae, *Rostellularia*, Rubiaceae, *Spiraea*, *Taraxacum*, *Thalictrum*, Umbelliferae
Ferns	undetermined monolete and trilete types *Hicriopteris*, *Lycopodium*, Osmundaceae, Polypodiaceae, *Pteris*, *Selaginella sinensis*
Aquatics	Liliaceae, *Typha*, Potamogetonaceae, *Nymphoides*, Cyperaceae

4. Results

A total of 103 pollen and spore taxa were identified during the 2-year recording period. Of these, 66 originated from arboreal plants or shrubs, 28 from herbs and 8 from ferns (Table 2). *Morus* is the dominant arboreal pollen taxon in both years, with *Platycarya*, Cupressaceae, and *Pinus* each contributing around 2% to the total, and *Quercus* and *Platanus* around 0.5–1%. Herb pollen types make up around 10% of the total in 2013 and around 18% in 2014. The main herb pollen types are *Humulus* and Poaceae in both years, each accounting for 5–6% on average.

4.1. Pollen Concentration

Figure 2 shows the daily variations in airborne pollen concentration over the two years. The SPI in 2013 is 36,344 pollen/m^3, which is around 3 times higher than in 2014 (10,881 pollen/m^3), but the seasonal distribution of concentration and the dominant pollen types were comparable (Figures 2c and 2d), with around 80% of the recorded pollen types originating from trees and shrubs. There are two peaks in total concentration in both years, with a stronger peak in spring and a weaker peak in autumn (Figures 2a and 2b). The airborne pollen assemblages showed distinct differences in both abundance and composition during the four seasons (Figure 2d). Arboreal pollen types dominate the spring (March to May) peak in concentration, while herbaceous types dominate in the autumn (September to November) peak. In summer (June to August), the annual pollen concentration is characterized mainly by wetland herbs and ferns. Winter (December to February) concentration is lowest and made up of regionally sourced pollen types such as *Artemisia*, Chenopodiaceae, and *Pinus*.

The seasonal variations of pollen are influenced by the reproductive cycles of plants (Latorre, 1999), with airborne pollen occurring mainly during the flowering periods for most taxa. This is especially clear in the Nanjing data set for *Platycarya*, *Typha*, Cupressaceae, *Morus*, and *Humulus*.

4.2. Meteorological Data

Observed hourly meteorological data from 2013 to 2014 were provided by SORPES (Station for Observing Regional Processes of the Earth System), Nanjing University, and processed to provide values of daily and monthly total precipitation and mean temperature, wind speed, and relative humidity. Monthly variations over the two study years are summarized in Figure 3. The annual mean temperature in both years is warmer than the long-term average, and July and August were clearly hotter in 2013 than 2014 (Figure 3a), giving a greater annual range (28.1 °C in 2013 as opposed to 22.7 °C in 2014). The average relative humidity (Figure 3b) shows less inter- and intraannual variation, averaging around 70% in both years. The total annual rainfall is below the long-term average in both years, with marked differences in the monthly totals between years seen in February, April, July, and November (Figure 3c). The annual and monthly average wind speeds (Figure 3d) are all greater in 2014 than 2013. The winter season of 2013–2014 was unusually mild, with a mean temperature of 5.4 °C compared to a 56-year mean (1951–2007) of 3.7 °C (China Meteorological Administration Data Service Center, 1981–2010).

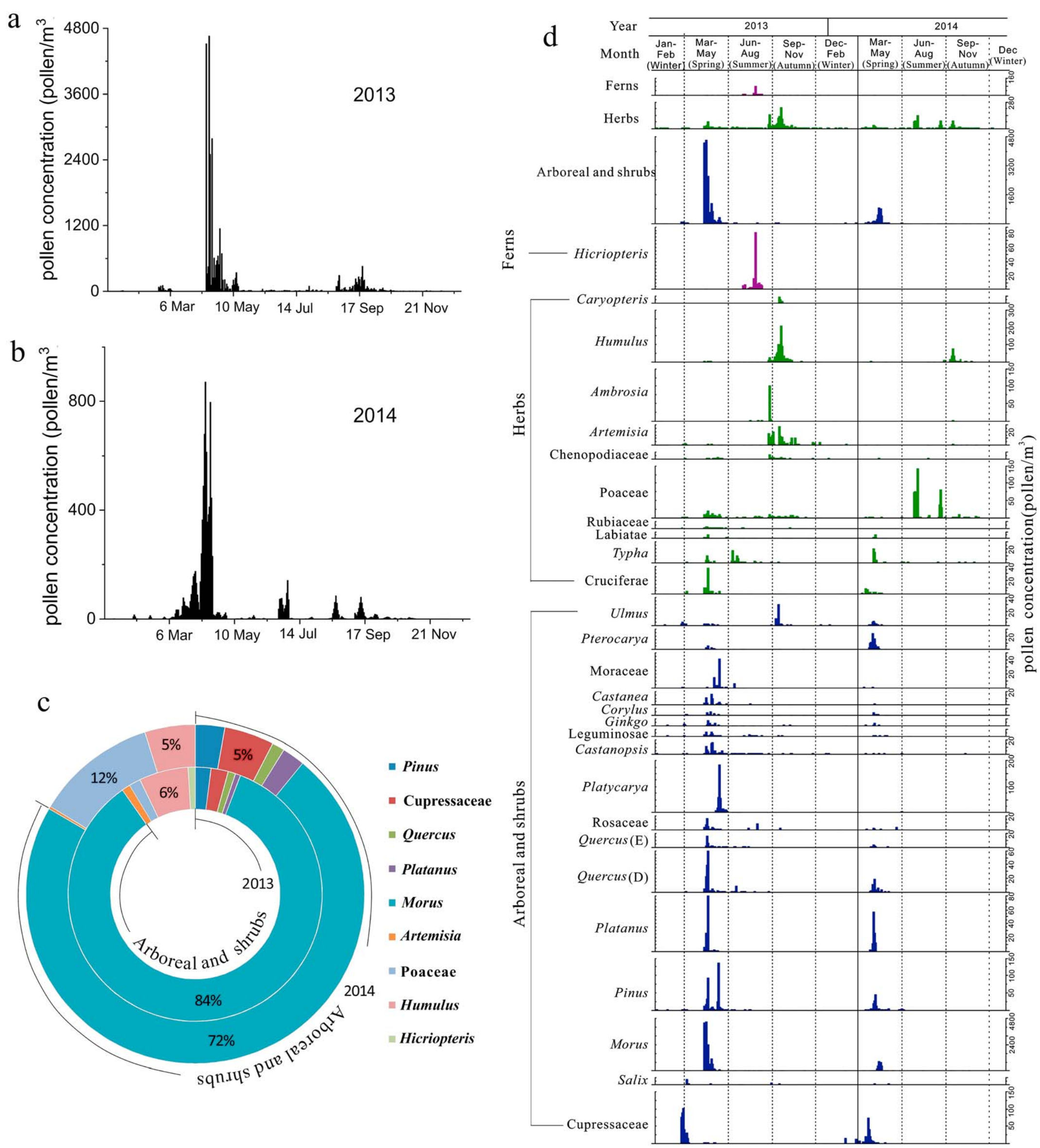

Figure 2. Airborne pollen concentration and pollen composition recorded in Nanjing in 2013 and 2014. (a)Variation in total daily pollen concentration in 2013; (b) variation in total daily pollen concentration in 2014 (note difference in *y* axis scale from a); (c) breakdown by taxa of all pollen recorded in 2013 and 2014, shown as proportions; (d) daily pollen concentration in 2013 and 2014 plotted for key individual taxa (note variable *y* axis scales). The dashed vertical lines denote division of the years into seasons.

5. Analysis and Discussion

5.1. Comparison of Trends in Total Pollen Concentration and Meteorological Parameters

Figure 4 shows the daily total pollen concentration plotted against key meteorological parameters for the whole study period. The lower overall pollen concentration observed in 2014 compared with 2013, especially for tree species, might be a lag effect from the comparatively hot and dry conditions in 2013, which may have caused particular physiological stress for tree species and thereby had a negative effect on floral production for the following year. The greater proportion of rainy days during the flowering periods in 2014 may also have reduced recorded pollen concentration by removing airborne pollen from the atmosphere more rapidly than expected on dry days. The peak periods of airborne pollen appear to occur during favorable weather conditions with higher temperature, lower relative humidity, and low precipitation.

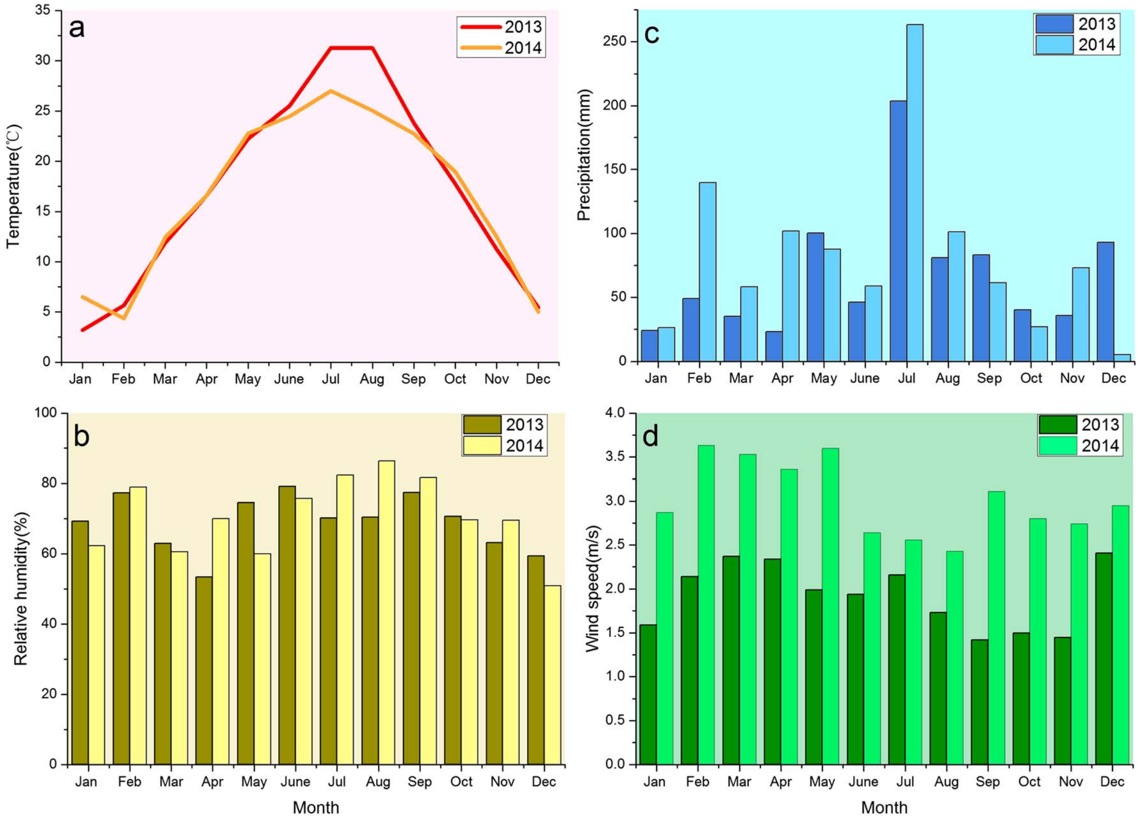

Figure 3. Summary climate data for SORPES in Nanjing during the two study years, 2013 and 2014. (a)Monthly mean temperature, (b) monthly mean relative humidity, (c) monthly total precipitation, and (d) monthly mean wind speed.

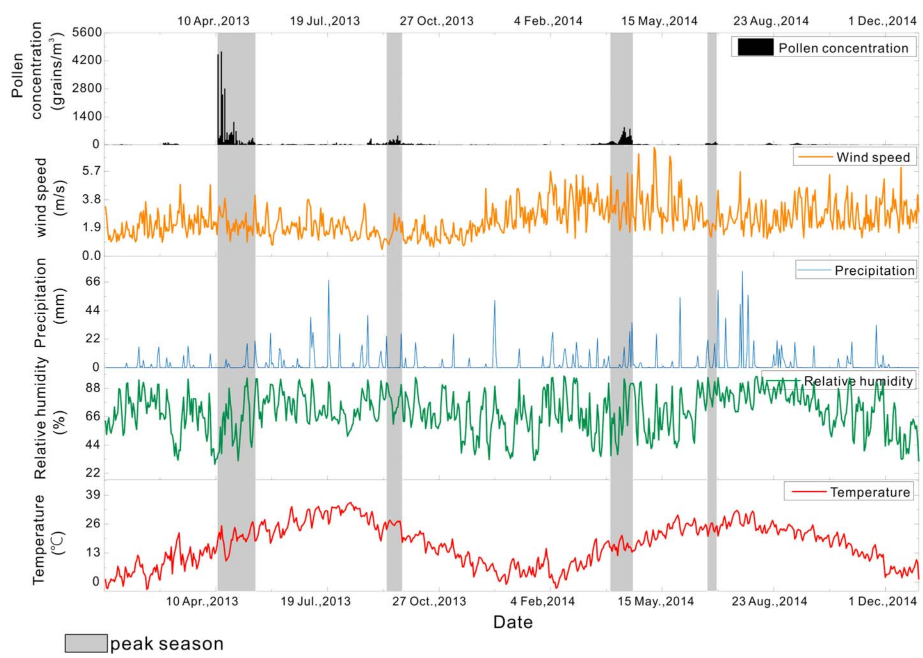

Figure 4. Daily mean pollen concentration recorded at SORPES, Nanjing, compared with daily means of four meteorological parameters recorded at the same station in 2013 and 2014.

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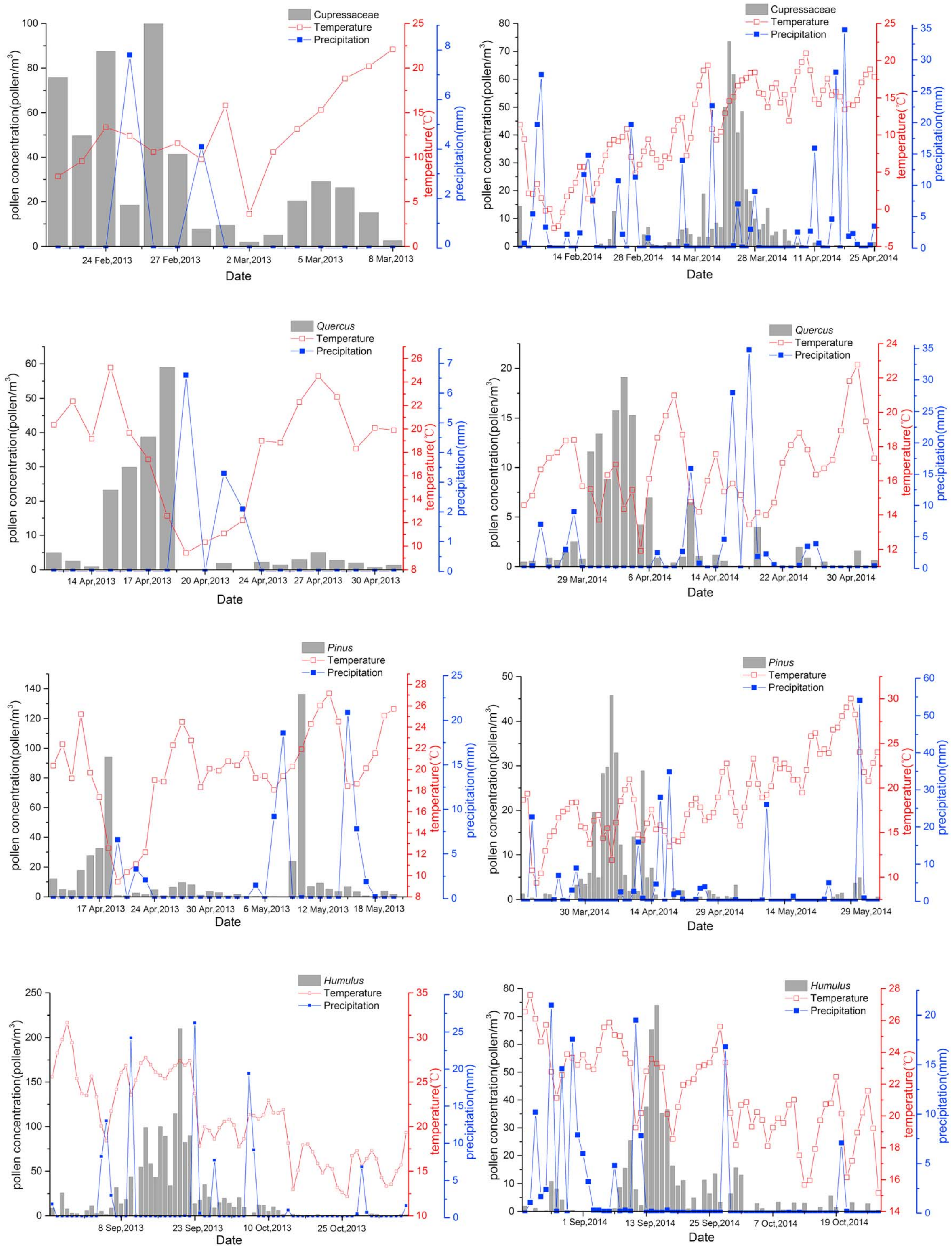

Figure 5. Daily pollen concentration of four selected taxa during their respective pollen seasons, plotted with temperature and precipitation. The left-hand column shows the 2013 pollen season, and the right-hand column shows the 2014 season.

5.2. Relationships Between Selected Pollen Types and Meteorological Factors

We selected four taxa for further exploration of the relationships between meteorological factors and daily pollen concentration (Figure 5). These are 3 arboreal taxa (Cupressaceae, *Quercus*, and *Pinus*) and a major herbaceous genus (*Humulus*) and have clear differences in the size of their pollen grains and the timing of their

Table 3
Characteristics of the Four Selected Pollen Types in the Atmosphere of Nanjing in 2013 and 2014 (SPI: Seasonal Pollen Index)

	Cupressaceae	*Quercus*	*Pinus*	*Humulus*
Concentrations				
SPI in 2013 (pollen d/m^{-3})	664	291	609	1902
SPI in 2014 (pollen d/m^{-3})	482	122	286	486
Ratio of SPI 2013:2014	0.73	0.42	0.47	0.26
Temporal patterns				
Start of pollen season in 2013	22 February	1 April	4 April	27 August
Start of pollen season in 2014	1 February	28 March	28 March	27August
Pollen peak in 2013	26 February	18 April	10 May	20 September
Pollen peak in 2014	22 March	3 April	5 April	15 September
End of pollen season in 2013	7 March	17 June	12 May	25 September
End of pollen season in 2014	30 March	19 April	31 May	1 October
Length of pollen season 2013 (days)	14	47	39	30
Length of pollen season 2014 (days)	58	22	65	36
Estimated fall speed (m/s)	0.035	0.016	0.046	0.013

pollen season. Cupressaceae is the main type detected in early spring, *Quercus* and *Pinus* are most common at the height of the spring overall pollen season, and *Humulus* is most abundant in the autumn pollen peak. Table 3 summarizes the temporal characteristics of the four types over the study period.

All four taxa had lower SPI in 2014 than 2013 (Table 3). *Humulus* was most strongly affected, with a fourfold decrease in recorded concentration from 2013 to 2014, *Quercus* and *Pinus* concentrations halved, and Cupressaceae showed only a moderate reduction in concentration. Figure 5 shows the data from the 2013 and 2014 pollen seasons for each taxon, with daily mean temperature and daily total precipitation plotted over pollen concentration, and Figure 6 shows the results of simple cross-correlation analysis comparing daily pollen concentrations with daily meteorological records (temperature, relative humidity, and precipitation) lagged from 0 to −30 days during the pollen seasons.

5.2.1. Cupressaceae

Cupressaceae is an important component of the pollen assemblage in early spring and is a pollen taxon with intermediate size and high to intermediate dispersal abilities (Galán et al., 1998). Peak concentration is observed earlier in 2014 than 2013, and the 2014 pollen season was longer. However, the SPI is higher in 2013 than in 2014. In European studies, minimum temperature and rainfall in the months prior to flowering season are identified as the two parameters that have the greatest effect on the presence of Cupressaceae pollen in the atmosphere (Galán et al., 1998). In a 6-year study from an Iberian site, Cariñanos et al. (2004) show that a decrease in temperature during the flowering period results in greater pollen presence of *Cupressus* in the atmosphere. In our data set, the temperature in early 2013 is lower than that in 2014 (Figure 3a), which suggests that the same relationship between cooler early flowering period temperatures and higher SPI may be seen in Chinese Cupressaceae (Figure 5).

Figure 6 shows the results of simple cross correlation between aerial pollen concentration and meteorological conditions on preceding days, which allow us to establish hypotheses about the effects of meteorological conditions on the development of flowering structures in the weeks before pollen release. Relatively few individual correlations are significant at the 95% level, but overall patterns emerge. Positive correlations with warmer temperatures at the start of the month before flowering (days −28 to −20 in 2013 and days −30 to −21 in 2014) are followed by negative correlations with mean temperature for a period of 2–3 weeks before flowering (−19 to 0 in 2013, −20 to −4 in 2014), which accord with the European findings (Cariñanos et al., 2004; Galán et al., 1998). There is no clear relationship with precipitation, contrary to the findings of Galán et al. (1998), nor with relative humidity.

5.2.2. *Quercus*

The *Quercus* pollen season began at almost the same time in both years, and the season was longer in 2013 than in 2014 (Table 3). Studies in the UK (Norris-Hill, 1998) and Spain (García-Mozo et al., 2006; Recio et al., 1997) indicate that temperature is the key factor influencing the start of *Quercus* pollen seasons. A study from southern Denmark suggests that *Quercus* pollen concentration is most strongly correlated with the average maximum temperature over the months from June to September of the previous year (Andersen, 1980). Figure 5 shows that comparatively warm mean daily temperatures did precede the main peak of *Quercus* pollen within the pollen season in both years in this study.

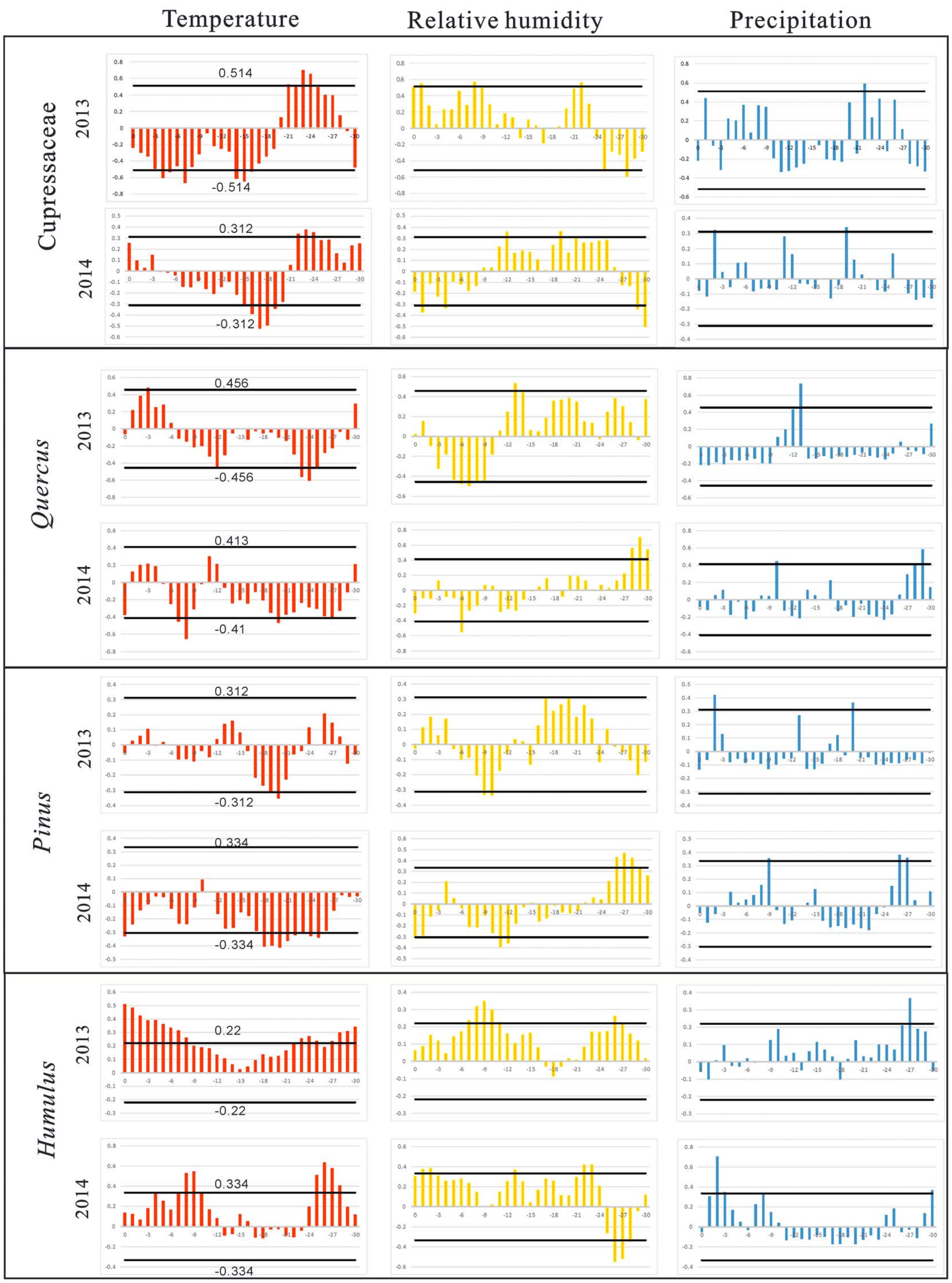

Figure 6. Cross correlation between mean daily pollen concentrations during the pollen season and daily meteorological parameters (temperature, relative humidity, and precipitation) at lags of 0–30 days. The *x* axis is number of days of lag; the *y* axis is correlation coefficient (*r*). The solid black lines show the critical values of *r* ($p = 0.05$).

However, simple cross correlation (Figure 6) suggests a different relationship with temperature, with negative relationships for most of the month before flowering, although few individual correlations are statistically significant. Only in the few days before flowering are cross correlations positive. Cross correlation with other factors show no clear pattern, and longer term relationships cannot be usefully investigated with this short data set.

5.2.3. *Pinus*

Like *Quercus*, the *Pinus* pollen season started on almost the same day in both years, but the *Pinus* season duration was longer in 2014 than 2013, with an earlier pollen peak (Table 3). *Pinus* has a much longer pollen season than Cupresseaceae or *Quercus*, and pollen grains of this type are recorded throughout the year, even in winter. *Pinus* is considered to be an overrepresented pollen type often transported over long distances (e.g., Campbell et al., 1999). Figure 5 shows two peaks in the 2013 pollen season and only one in the 2014 pollen season, with no clear meteorological connections.

Simple cross correlation (Figure 6) shows mainly negative correlations with precedent mean daily temperature, with statistically significant relationships around 3 weeks before flowering (e.g., days −20 and −19 in 2013). Relative humidity early in the month before pollen recording has some positive relationships with pollen production, with a switch to negative relationships around 10–12 days before flowering. No clear pattern of correlations is seen between pine pollen concentration and precipitation.

5.2.4. *Humulus*

Humulus is the most abundant herbaceous taxon in the data set. Potential source plants are widely found in grassland, abandoned fields and the edges of pathways in Nanjing, and a similar dominance of the airborne pollen herbaceous concentration was seen in Shanghai (Huang et al., 2013). *Humulus* peak production occurred almost 1 week earlier in 2014 than 2013 (Table 3). Figure 5 shows *Humulus* pollen concentration peaking at the start of a period of declining mean daily temperature, typical of autumn conditions, and in both years the peak is closely following a rainfall event.

Cross correlation (Figure 6) shows clear positive correlation with antecedent temperature, as expected in a species which flowers at the end of the summer. Apparent relationships with precipitation show opposite patterns in the two studied years, while there is a generally positive relationship with relative humidity with some statistically significant correlations in the couple of weeks before pollen concentrations are recorded.

5.2.5. Summary

Each of the four taxa selected shows different responses to meteorological conditions. The most obvious difference is between autumn-flowering, herbaceous *Humulus*, and the three spring-flowering arboreal taxa. This is expected, since as Figure 3 shows the temperature curve in particular has strong contrary trends in spring and autumn. Warmer temperatures during the last few weeks of flower development appear to lead to higher pollen production in *Humulus*, whereas the same pollen response occurs with cooler antecedent temperatures for the tree taxa. High relative humidity in the weeks before flowering is correlated with higher pollen concentrations in *Humulus*, while the three tree taxa have no clear relationship with humidity. None of the taxa seem to have a consistent response to precipitation in the month before flowering. The processes underlying assumed relationships may depend on multiday patterns or interactions between different factors and therefore not show up in simple cross correlation, or may act over longer time periods (e.g., the *Quercus*-precipitation relationship noted in Denmark; Andersen, 1980). Studies of multiple years of pollen trapping (which effectively record only SPI values) have shown clear relationships between total pollen concentration and climatic conditions during the previous growing season for tree taxa (e.g., Andersen, 1980; Huusko & Hicks, 2009; Nielsen et al., 2010).

5.3. Relationships Among Airborne Pollen Grains, Land Cover, and Wind Direction

Figure 7 summarizes the land cover and wind direction data, and the surface area of each land-cover community in each octant is shown in Table 1. The main communities present in the 10-km circle around the station are crops and orchards (48.2%), artificial landscape (25.3%), and *Pinus* and *Quercus* mixed forest (10.9%). The main pollen types in the airborne spectra (*Pinus*, *Quercus*, *Morus*, and some herbaceous types such as Poaceae, *Artemisia*, and *Humulus*) all have plentiful sources in these communities, suggesting that our choice of 10-km radius captures at least part of the pollen sources for these taxa.

The numbers of days of winds from each octant over the sampling years are shown in Figure 7b. 2013 winds blew mainly from the NE, SW, and SE, with a slight shift in 2014 to NE, E, and SE. Figures 7c and 7d show total pollen concentration recorded on days with wind coming from each octant in both years. Higher pollen concentrations generally occur in the octants with the highest number of wind days in 2014, as expected, but in 2013 pollen concentration totals are much higher for the SW octant days, reflecting wind conditions during the spring pollen peak.

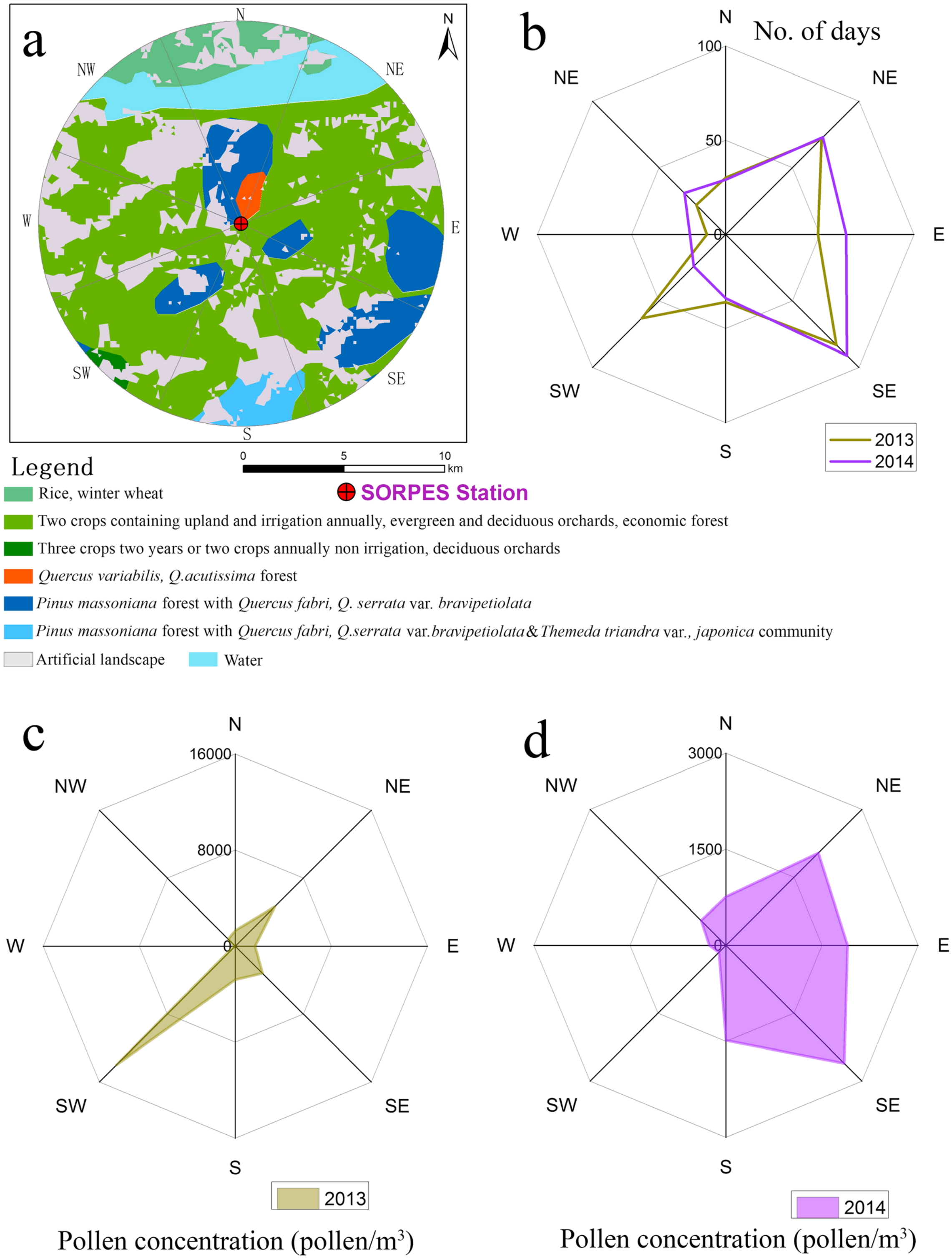

Figure 7. (a)Land cover map for 10-km radius around the SORPES station, (b) annual distribution of wind directions (number of days from each octant), (c) total pollen concentrations from days when the wind came from each octant in 2013, and (d) total pollen concentrations from days when the wind came from each octant in 2014.

5.4. Implications for Pollen Analysis

Airborne pollen is an important component of the pollen assemblages recovered from sediment samples and the fossil record (Royall et al., 1991), and understanding the controls on airborne pollen composition and abundance can contribute to reconstruction of past land cover from such pollen records (Rogers, 1993). Constructed pollen traps have an advantage over "natural" traps such as lake sediments or moss polsters since the time scale of pollen trapping is tightly controlled. Annual variations in pollen deposition have proved to be very large (Andersen, 1980; Hicks, 1994), and long-term averages have been used to develop criteria for interpreting pollen records in terms of the presence and density of species in the surrounding vegetation and thus reconstruct forest history (Hicks, 2001; Hicks & Hyvärinen, 1999). However, understanding possible causes of these interannual variations is also a potentially useful tool for reconstructing past environments (e.g., Huusko & Hicks, 2009). Plant species show individual resource allocation strategies in response to changing conditions, which affect reproductive biology including pollen production. Aeropalynological studies such as the data presented here enable scientists to consider relationships between pollen concentration and climate parameters at both interannual and intraannual time scales and therefore explore possible causes of the variation seen in the variations in totals between years, as well as contributing to pollen forecasting for air quality control and allergy management.

The data presented here cover 2 years in a city located within a monsoonal climate region. Two seasonal pollen peaks were identified, a spring one characterized by pollen taxa sourced from trees and shrubs (i.e., *Morus*, Cupressaceae, *Pinus*, *Pterocarya*, and *Quercus*) and an autumn one dominated by upland herbs (i.e., Compositae, Poaceae, *Humulus*, and Cruciferae). The two years have similar pollen spectra in terms of species composition, reflecting the surrounding landscape, but show clear differences in terms of both overall pollen concentration and timing of pollen release. Annual total pollen concentration was generally lower in 2014 than 2013. One possibility is that this reflects a lagged response of taxa to comparatively hot and dry conditions in 2013, which affected growth and reproductive success in the following year. Of the four taxa considered in detail, *Humulus* (an autumn flowering herb) showed a much greater proportionate reduction in total pollen concentration from 2013 to 2014 than the three tree taxa.

Simple cross-correlation analysis allows us to suggest some relationships between meteorological conditions in the month before flowering and daily pollen concentration. Negative correlations with temperature were seen in all three tree taxa, with relationships for *Quercus* switching to positive in the few days before flowering. *Humulus* showed clear positive correlation with antecedent temperature and a generally positive relationship with relative humidity. These differences suggest that pollen signal responses to climatic influences should be considered at a taxon level rather than an assemblage level. Once longer time series data are available, a more comprehensive analysis of both inter- and intraannual relationships between climate parameters and airborne pollen could be carried out on all the main pollen taxa recorded in a location, such as the analysis already carried out for the air pollution index in Nanjing (Shen et al., 2015). From this 2-year data set, it appears that such a study will provide valuable insights into the possible causes of variation observed in annual pollen trap data series, and thereby improved understanding of the possible mechanisms underlying longer term fluctuations in pollen concentration and influx seen in the sedimentary record.

Appendix A: Fall Speed of Pollen Grain

The settling velocity of a spherical particle (v_s) is calculated from Stoke's law:

$$v_s = \frac{2r^2 g(\rho_0 - \rho)}{9\mu}$$

where

v_s = spherical settling velocity (m s^{-1})

r = pollen grain radius (m)

g = acceleration due to gravity (m s^{-2}) taken as 9.81 m s^{-2}

ρ_0 = particle (grain) density (kg m^{-3}) taken as 10^3 kg m^{-3}

ρ = fluid (air) density (kg m^{-3}) taken as 1.27 kg m^{-3}

μ = dynamic viscosity (kg m^{-1} s^{-1}) taken as 1.8×10^{-1} kg m^{-1} s^{-1}

And for ellipsoid particles, Falck's correction is applied to calculate the settling velocity (v_e) as follows:

$$v_e = v_s \sqrt[3]{a/b}$$

where

v_e = ellipsoidal settling velocity (m s^{-1})

v_s = settling velocity of a sphere of the same volume as the ellipsoid of interest (m s^{-1})

a = major axis (m)

b = minor axis (m)

Mean radius (r) or major and minor axes (a and b) were measured from 30 randomly selected pollen grains on counting slides for each taxon type (e.g., Duffin & Bunting, 2008).

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References

An, S. Q., & Zhao, R. L. (1990). Characteristics analysis of secondary forest vegetation in Zijing Mountain. *Acta Phytoecologica et Geobotanica Sinica*, *14*(1), 13–22.

Andersen, S. T. (1980). Influence of climatic variation on pollen season severity in wind-pollinated trees and herbs. *Grana*, *19*(1), 47–52. https://doi.org/10.1080/00173138009424986

Andersen, T. B. (1991). A model to predict the beginning of the pollen season. *Grana*, *30*(1), 269–275. https://doi.org/10.1080/00173139109427810

Campbell, I. D., McDonald, K., Flannigan, M. D., & Kringayark, J. (1999). Long-distance transport of pollen into the Arctic. *Nature*, *399*(6731), 29–30. https://doi.org/10.1038/19891

Cariñanos, P., Galan, C., Alcázar, P., & Domınguez, E. (2004). Airborne pollen records response to climatic conditions in arid areas of the Iberian Peninsula. *Environmental and Experimental Botany*, *52*(1), 11–22. https://doi.org/10.1016/j.envexpbot.2003.11.008

China Meteorological Administration Data Service Center (1981–2010). http://data.cma.gov.cn/

Chuine, I., & Belmonte, J. (2004). Improving prophylaxis for pollen allergies: Predicting the time course of the pollen load of the atmosphere of major allergenic plants in France and Spain. *Grana*, *43*(2), 65–80. https://doi.org/10.1080/00173130410019163

Clot, B. (2003). Trends in airborne pollen: An overview of 21 years of data in Neuchâtel (Switzerland). *Aerobiologia*, *19*(3/4), 227–234. https://doi.org/10.1023/B:AERO.0000006572.53105.17

Comtois, P. (1998). Statistical analysis of aerobiological data, methods in aerobiology, Bologna. *Pitagora Editrice Bologna*, 217–259.

Ding, A. J., Fu, C. B., Yang, X. Q., Sun, J. N., Zheng, L. F., Xie, Y. N., et al. (2013). Ozone and fine particles in the western YangtzeRiverDelta: An overview of 1 yr data at the SORPES station. *Atmospheric Chemistry and Physics*, *13*(11), 5813–5830. https://doi.org/10.5194/acp-13-5813-2013

Ding, A. J., Nie, W., Huang, X., Chi, X., Sun, J., Kerminen, V. M., et al. (2016). Long-term observation of air pollution-weather/climate interactions at the SORPES station: A review and outlook. *Frontiers of Environmental Science & Engineering*, *10*(5), 1–15.

Duffin, K. I., & Bunting, M. J. (2008). Relative pollen productivity and fall speed estimates for southern African savanna taxa. *Vegetation History and Archaeobotany*, *17*(5), 507–525. https://doi.org/10.1007/s00334-007-0101-2

Dupont, L. M., & Wyputta, U. (2003). Reconstructing pathways of aeolian pollen transport to the marine sediments along the coastline of SW Africa. *Quaternary Science Reviews*, *22*(2-4), 157–174. https://doi.org/10.1016/S0277-3791(02)00032-X

Editorial Board of Vegetation Map of China (2007). *Vegetation map of the People's Republic of China (1:1,000,000)* (pp. 192–257). Beijing: The Geological Publishing House.

Gagnon, L., & Comtois, P. (1989). Urban aeropalynology: Is one sampling station representative of the pollen rain. In P. Comtois (Ed.), *Aerobiology Health Environment, Asymposium* (pp. 43–54). Montréal: Université de Montréal Press.

Galán, C., Cuevas, J., Infante, F., & Domínguez, E. (1989). Seasonal and diurnal variation of pollen from Gramineae in the atmosphere of Córdoba Spain. *Allergologia et Immunopathologia*, *17*(5), 245–249.

Galán, C., Fuillerat, M. J., Comtois, P., & Domínguez, E. (1998). A predictive study of Cupressaceae pollen season onset, severity, maximum value and maximum value date. *Aerobiologia*, *14*(2–3), 195–199. https://doi.org/10.1007/BF02694206

García-Mozo, H., Galán, C., Gomez-Casero, M. T., & Dominguez, E. (2000). A comparative study of different temperature accumulation methods for predicting the start of the *Quercus* pollen season in Córdoba (south West Spain). *Grana*, *39*(4), 194–199. https://doi.org/10.1080/00173130051084322

García-Mozo, H., Galán, C., Jato, V., Belmonte, J., de la Guardia, C. D., Fernández, D., et al. (2006). *Quercus* pollen season dynamics in the Iberian Peninsula: Response to meteorological parameters and possible consequences of climate change. *Annals of Agricultural and Environmental Medicine*, *13*(2), 209–224.

Gregory, P. H. (1973). *Themicrobiology of the atmosphere* (2nd ed.). New York: John Wiley.

Haberle, S. G., Bowman, D. M., Newnham, R. M., Johnston, F. H., Beggs, P. J., Buters, J., et al. (2014). The macroecology of airborne pollen in Australian and New Zealand urban areas. *PLoS One*, *9*(5), e97925. https://doi.org/10.1371/journal.pone.0097925

Hicks, S. (1994). Present and past pollen records of Lapland forests. *Review of Palaeobotany and Palynology*, *82*(1-2), 17–35. https://doi.org/10.1016/0034-6667(94)90017-5

Hicks, S. (2001). The use of annual arboreal pollen deposition values for delimiting tree-lines in the landscape and exploring models of pollen dispersal. *Review of Palaeobotany and Palynology*, *117*(1), 1–29.

Hicks, S., & Hyvärinen, H. (1999). Pollen influx values measured in different sedimentary environments and their palaeoecological implications. *Grana*, *38*(4), 228–242. https://doi.org/10.1080/001731300750044618

Hjelmroos, M. (1991). Evidence of long-distance transport of Betula pollen. *Grana*, *30*(1), 215–228. https://doi.org/10.1080/00173139109427802

Huang, J. H., Wang, Y. F., Shen, C. L., & LYu, S. L. (2013). Monitoring of the airborne pollen grains in Shanghai [in Chinese with English abstract]. *Journal of East China Normal University (Natural Science)*, *2*, 56–62.

Huusko, A., & Hicks, S. (2009). Conifer pollen abundance provides a proxy for summer temperature:Evidence from the latitudinal forest limit in Finland. *Journal of Quaternary Science*, *4*, 522–528.

Jäger, S., Spieksma, E. T. M., & Nolard, N. (1991). Fluctuations and trends in airborne concentrations of some abundant pollen types, monitored at Vienna, Leiden, and Brussels. *Grana*, *30*(2), 309–312. https://doi.org/10.1080/00173139109431985

Jato, V., Rodríguez-Tajo, F. J., Alcázar, P., De Nuntiis, P., Galán, C., & Mandrioli, P. (2006). May the definition of pollen season influence aerobiological results? *Aerobiologia*, *22*(1), 13–25. https://doi.org/10.1007/s10453-005-9011-x

Latorre, F. (1999). Differences between airborne pollen and flowering phenology of urban trees with reference to production, dispersal and interannual climate variability. *Aerobiologia*, *15*(2), 131–141. https://doi.org/10.1023/A:1007523316024

Latorre, F., Romero, E. J., & Mancini, M. V. (2008). Comparative study of different methods for capturing airborne pollen, and effects of vegetation and meteorological variables. *Aerobiologia*, *24*(2), 107–120. https://doi.org/10.1007/s10453-008-9090-6

Mandrioli, P., Di Cecco, M., & Andina, G. (1998). Ragweed pollen: The aeroallergen is spreading in Italy. *Aerobiologia*, *14*(1), 13–20. https://doi.org/10.1007/BF02694590

Maya-Manzano, J. M., Sadyś, M., Tormo-Molina, R., Fernández-Rodríguez, S., Oteros, J., Silva-Palacios, I., & Gonzalo-Garijo, A. (2017). Relationships between airborne pollen grains, wind direction and land cover using GIS and circular statistics. *Science of the Total Environment*, *584*, 603–613.

Mesa, J. A. S., Smith, M., Emberlin, J., Allitt, U., Caulton, E., & Galan, C. (2003). Characteristics of grass pollen seasons in areas of southern Spain and the United Kingdom. *Aerobiologia*, *19*(3/4), 243–250. https://doi.org/10.1023/B:AERO.0000006597.44452.a3

Nielsen, A. B., Møller, P. F., Giesecke, T., Stavngaard, B., Fontana, S. L., & Bradshaw, R. H. W. (2010). The effect of climate conditions on interannual flowering variability monitored by pollen traps below the canopy in Draved Forest, Denmark. *Vegetation History and Archaeobotany*, *19*(4), 309–323. https://doi.org/10.1007/s00334-010-0253-3

Norris-Hill, J. (1998). A method to forecast the start of the *Betula*, *Platanus*and *Quercus* pollen seasons in North London. *Aerobiologia*, *14*(2–3), 165–170. https://doi.org/10.1007/BF02694201

Qiao, B. S. (2005). *Color Atlas of air-borne pollens and plants in China* (p. 385). Beijing: Peking Union Medical College Press.

Ranzi, A., Lauriola, P., Marletto, V., & Zinoni, F. (2003). Forecasting airborne pollen concentrations: Development of local models. *Aerobiologia*, *19*(1), 39–45. https://doi.org/10.1023/A:1022626107746

Recio, M., Cabezudo, B., Trigo, M. D. M., & Toro, F. J. (1997). Accumulative air temperature as a predicting parameter for daily airborne olive pollen (*Oleaeuropaea* L.) during the pre-peak period in Málaga (Western Mediterranean area). *Grana*, *36*(1), 44–48. https://doi.org/10.1080/00173139709362589

Rogers, C. A. (1993). Application of aeropalynological principles in palaeoecology. *Review of Palaeobotany and Palynology*, *79*(1-2), 133–140. https://doi.org/10.1016/0034-6667(93)90043-T

Rousseau, D. D., Schevin, P., Duzer, D., Cambon, G., Ferrier, J., Jolly, D., & Poulsen, U. (2006). New evidence of long distance pollen transport to southern Greenland in late spring. *Review of Palaeobotany and Palynology*, *141*(3-4), 277–286. https://doi.org/10.1016/j.revpalbo.2006.05.001

Royall, P. D., Delcourt, P. A., & Delcourt, H. R. (1991). Late Quaternary paleoecology and paleoenvironments of the Central Mississippi alluvial valley. *Geological Society of America Bulletin*, *103*(2), 157–170. https://doi.org/10.1130/0016-7606(1991)103<0157:LQPAPO>2.3.CO;2

Shen, C., Li, C., & Si, Y. (2015). A detrended cross-correlation analysis of meteorological and API data in Nanjing, China. *Physica A*, *419*, 417–428. https://doi.org/10.1016/j.physa.2014.10.058

Sugita, S., Gaillard, M. J., & Broström, A. (1999). Landscape openness and pollen records: A simulation approach. *The Holocene*, *9*(4), 409–421. https://doi.org/10.1191/095968399666429937

Tormo-Molina, R., Maya-Manzano, J. M., Silva-Palacios, I., Fernández-Rodríguez, S., & Gonzalo-Garijo, Á. (2015). Flower production and phenology in *Dactylisglomerata*. *Aerobiologia*, *31*(4), 469–479. https://doi.org/10.1007/s10453-015-9381-7

Wang, F. X., Chen, N. F., Zhang, Y. L., & Yang, H. Q. (1995). *Pollen flora of China* (2nd ed.). Beijing: Science Press.

Wei, J. S., Liu, M., Gu, Y. J., Zhang, J., & Zhang, J. (2008). Study on pollen concentration change rule and forecast method in Nanjing City. *Journal of Anhui Agricultural Science*, *36*(22), 9368–9371.

Yan, C. H., Zhang, S., & Song, Y. C. (1995). A preliminary study on the nature of the forest in Nanjing. *Chinese Journal of Plant Ecology*, *19*(3), 280–285.

Zhang, J., Xu, X., Zhang, Z. X., Zhang, Q., & Yan, S. F. (2009). Allergic pollen characteristics in air and its relationship with meteorological factors in Nanjing. *Journal of Meteorology and Environment*, *25*(5), 67–71.

Zhao, K., Zhang, B. W., Xu, Y., & Tan, K. (2009). A preliminary analysis on the seed plants flora of Nanjing. *Journal of Anqing Teachers College (Natural Science Edition)*, *15*(2), 81–84.