

Transport pathway and source area for *Artemisia* pollen in Beijing, China

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Abstract *Artemisia* pollen is an important allergen responsible for allergic rhinitis in Beijing, China. To explore the transport pathways and source areas of *Artemisia* pollen, we used Burkard 7-day traps to monitor daily pollen concentrations in 2016 in an urban and suburban locality. Backward trajectories of 24- and 96-h and their cluster analysis were performed to identify transport pathways of *Artemisia* pollen using the HYSPLIT model on $0.5^\circ \times 0.5^\circ$ GADS meteorological data. The potential source contribution function (PSCF) and concentration weighted trajectory (CWT) were calculated to further identify the major potential source areas at local, regional, and long-range scales. Our results showed significant differences in *Artemisia* pollen concentration between urban and suburban areas, attributed to differences in plant distribution and altitude of the sampling locality. Such differences arisen from both pollen emission and air mass movements, hence pollen dispersal. At local or regional scales, source area of northwestern parts of Beijing City, Hebei Province and northern and northwestern parts of Inner Mongolia influenced the major transport pathways of *Artemisia* pollen. Transport pathway at a long-range scale and its corresponding source area extended to northwestern parts of Mongolia. The regional-scale transport affected by wind and altitude is more profound for *Artemisia* pollen at the suburban than at the urban station.

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Introduction

The genus *Artemisia* which is an important source allergen (Mucciaccelli and Mattei 2002) is widely distributed in north temperate regions, such as Asia, North America, and Europe (Grewling et al. 2012). *Artemisia* pollen contains approximately 40 extractable proteins of which 10 appear to be allergens (Ipsen et al. 1985), and shows a strong cross-reactivity within species (Katial et al. 1997). In Beijing, *Artemisia* pollen is an important and widely distributed pollen type (Sun and Song 2006; Li et al. 2009; Yao and Zhang 2009b; Liu et al. 2010; Hao et al. 2013), and a major component of total pollen counts from August to September (Ye et al. 1991; Yao and Zhang 2009a; Liu et al. 2010; Xu and Zhang 2011; Xu et al. 2012; Meng et al. 2013). *Artemisia* sensitizations are strongly associated with the development and severity of rhinitis (Li et al. 2009; Li et al. 2011). A strong association between pollen level and the number of consultations for allergic rhinitis (AR) (Zhang et al. 2012) as well as the linear exposure-response relationships (Li et al. 2008) have been observed. However, self-reported prevalence of local residents for AR was only 8.7% (Zhang et al. 2009). Skin tests showed that 88.5% of outpatients suffering from hay fever or asthma in autumn were allergic to *Artemisia* pollen (Yao and Zhang 2009b). As reported by 471 monitoring stations in European Aeroallergen Network (EAN), mean value of annual *Artemisia* pollen index is estimated to be 245 grains m^{-3} (Sofiev et al. 2013a). By contrast, however, annual pollen index of *Artemisia* in Beijing recorded by Yao and Zhang (2009b) is estimated to be much higher and may be as much as 250 times higher. This emphasizes the importance of

understanding the seasonal variations, sources, and transport pathways of *Artemisia* pollen, which until now have remained largely unknown.

Transport of airborne pollen can be considered at three scales: local, regional, and long-range. According to Seinfeld and Pandis (2006), local-scale transport refers to the initial dispersion of grains that occurs within the nearest kilometers from the plants. Transport at regional scales includes the dispersion of pollen grains at distances of up to 100 km, while long-range scale corresponds to transport distances beyond 100 km.

Weather dominates the processes of release, transport, and deposition at multiple scales (Laursen et al. 2007). Many studies used different atmospheric dispersion models to analyze the spatial and temporal variability of allergenic pollen, such as *Betula* (Veriankaitė et al. 2010; Siljamo et al. 2013; Izquierdo et al. 2015), *Fagus* (Belmonte et al. 2008), *Olea* (Hernández-Ceballos et al. 2014b), *Quercus* (Maya-Manzano et al. 2016), *Artemisia* (Estrella et al. 2006; Grewling et al. 2012; Drzeniecka-Osiadacz et al. 2015), and *Ambrosia* (Makra et al. 2010). Table S1 summarizes some previous studies on herbaceous pollen using different atmospheric transport models. To examine long-distance transport of *Ambrosia* pollen, Zink et al. (2012) used the COSMO-ART model by incorporating pollen grains into numerical weather forecast systems and explicitly calculating their dispersal. In order to forecast ragweed pollen concentrations in the air, Prank et al. (2013) used the SILAM emission model to investigate ragweed flowering season and pollen release. A number of recent studies have proved high effectiveness of the HYSPLIT model in tracing the pathway and possible long-distance transport of aerosols and air pollutants in Europe (Izquierdo et al. 2011; Šikoparija et al. 2013; Maya-Manzano et al. 2016). Furthermore, the combination of WRF-ARW model and cluster analysis has enhanced the precision and accuracy of air mass trajectories (Prtenjak et al. 2012; Hernández-Ceballos et al. 2014a; Izquierdo et al. 2015). More recently, Makra et al. (2016) have used the potential source contribution function (PSCF) and concentration weighted trajectory (CWT) that provided more information from different aspects to explicitly illustrate the sources and pathways of *Ambrosia* pollen in Hungary. A number of studies involving the comparison of airborne pollen between the urban and suburban/rural areas have been conducted in France (Bosch-Cano et al. 2011), Poland (Rodríguez-Rajo et al. 2010; Kruczek et al. 2017), Switzerland (Monn et al. 1999), and Spain (Hernández-Ceballos et al. 2015). However, only a few studies focus on transport pathway and source area of *Artemisia* pollen, as well as their differences between the urban and suburban areas. In this study, our main aim is to identify the major transport pathways and potential source areas of *Artemisia*

pollen in Beijing using HYSPLIT model and its derived algorithms which include PSCF and CWT methods at different scales.

Materials and methods

Study sites and pollen collection

Beijing (39.4°–41.6°N, 115.7°–117.4°E) is the largest metropolitan area in northern China (Table S2). A continental monsoon climate prevails in the region with hot rainy summers and cold dry winters. Two sampling sites which were set at the same height (3 m above ground level), over 40 km part, were employed to compare pollen levels and their sources between the urban and suburban areas (Fig. 1). The suburban site (40°16'11"N, 116°16'38"E, 638 m above sea level) is located at the top of Mangshan Mountain in Changping District. The urban site was settled at Beijing Teaching Botanical Garden station (39° 52' 22"N, 116° 25' 38"E, 38 m above sea level) in Dongcheng District.

Pollen data were collected from 1 January to 31 December 2016 using Hirst-type (Hirst 1952) Burkard 7-day recording volumetric spore-traps. Air is sucked into the trap at a rate of 10 l min⁻¹ and pollen grains adhere to the tapes mounted on a rotating drum that moves at 2 mm h⁻¹. Twenty-four-hour segments were cut from the 7-day samples. Then pollen was identified at ×400 magnification. The start (end) of pollen season was identified as the date on which one pollen grain per cubic meter of air is recorded and one or more pollen grains per cubic meter have been recorded for at least five consecutive (preceding) days.

Meteorological data collection

Meteorological data for backward trajectory computation were obtained from NOAA and downloaded with HYSPLIT (version 4). The GDAS used in this work has a temporal resolution of 3 h and a spatial resolution of 0.5° × 0.5° with vertical information on 23 pressure levels. Local meteorological data, including monthly minimum temperature and average wind speed, were provided by the Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences.

Data processing

Backward trajectories and cluster analysis

Backward trajectories were computed using the HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) model (Draxler and Hess 1998). Here, backward air mass movements arriving at two sampling sites were generated for each day during the pollen season at a 3-h intervals starting at

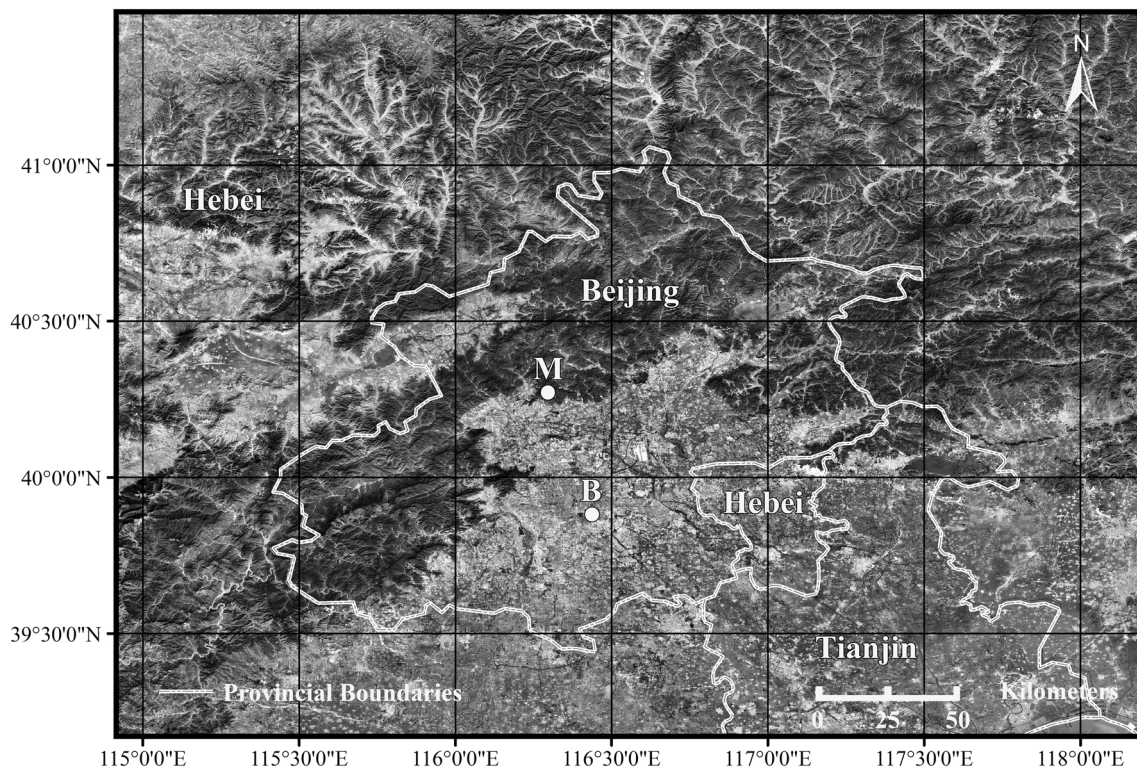


Fig. 1 Mangshan National Forest Park station (M: 40°16'11"N, 116°16'38"E, 638 m. a. s. l.) is located in the suburban area. Beijing Teaching Botanical Garden station (B: 39° 52' 22"N, 116° 25' 38"E, 38 m. a. s. l.) is located in the urban area

UTC 00:00. Backward trajectories arrive at two sites at a height of 500 m above ground level, ensuring that each trajectory starts in the near ground atmospheric boundary layer (Karaca et al. 2009; Makra et al. 2011; Dimitriou and Kassomenos 2014).

INDEX 1 and INDEX 2

The influence of long-range transport was examined by analyzing cluster occurrence on days when a 24-h mean *Artemisia* pollen concentration exceeded a threshold. For that purpose, two simple statistical indices related to the probability (INDEX 1) and frequency (INDEX 2) of daily *Artemisia* pollen episodes associated with different trajectory clusters were calculated as in Borge et al. (2007). The threshold of *Artemisia* pollen concentration is the 90th percentile of daily *Artemisia* pollen concentration in the whole year (Mangshan, 23 grains m⁻³; Beijing Teaching Botanical Garden, 5 grains m⁻³).

For a given monitoring station and cluster, INDEX 1 is defined as

$$INDEX\ 1_i(\%) = \frac{D_{(x > x_{0.90})i} \times 100}{D_i},$$

where D_i is the number of days for which a back trajectory belonging to cluster i is present (i.e., number of occurrences of cluster i), and $D_{(x > x_{0.90})i}$ is the number of 24-h *Artemisia*

pollen exceedance with occurrence of cluster i . This index expresses the likelihood of an exceedance occurring for a given cluster. For a given monitoring station and cluster, INDEX 2 is defined as

$$INDEX\ 2_i(\%) = \frac{D_{(x > x_{0.90})i} \times 100}{E},$$

where E is the total number of 24-h *Artemisia* pollen exceedances recorded at the specific monitoring station. For a given cluster i , INDEX 2 expresses the likelihood of certain trajectory being present on a pollen exceedance day.

Potential source contribution function

The PSCF has been used to identify the source of air pollutants and airborne pollen transport (Kavouras et al. 2013; Makra et al. 2016; Dimitriou and Kassomenos 2016). In each cluster, air mass residence time is distributed within the cells of a $0.5^\circ \times 0.5^\circ$ resolution grid, and the PSCF value for the ij th cell of the study area is defined as:

$$PSCF = \frac{m_{ij}}{n_{ij}},$$

where n_{ij} is the total number of trajectory points included in the ij th cell, and m_{ij} is the number of trajectory points contained in the ij th cell on the time that had an *Artemisia* pollen concentration at receptor site exceeding the threshold

value (Kavouras et al. 2013; Dimitriou and Kassomenos 2016). In order to enhance statistical reliability, an arbitrary weight function $W(i, j)$ was multiplied with PSCF results, $W(i, j)$ is defined as:

$$W(i, j) = \begin{cases} 1.00 & (3n_{ave} < n_{ij}) \\ 0.70 & (1.5n_{ave} < n_{ij} < 3n_{ave}) \\ 0.42 & (n_{ave} < n_{ij} < 1.5n_{ave}) \\ 0.17 & (n_{ij} < n_{ave}) \end{cases}$$

where n_{ave} is the average number of trajectory points of all grid cells without zero air mass residence time values (Polissar et al. 2001).

Contribution weighted trajectory

In the CWT method, each grid cell is assigned a weighted concentration by averaging the sample concentrations that have associated trajectories which crossed the grid cell as follows:

$$C_{ij} = \frac{1}{\sum_{k=1}^N n_{ijk}} \cdot \sum_{k=1}^N C_k \cdot n_{ijk},$$

where C_{ij} is the average weighted concentration in the ij th cell, k is the index of the trajectory, N is the total number of trajectories, C_k is the concentration observed on arrival of trajectory k , and n_{ijk} is the number of trajectory point in trajectory k in the ij th cell (Wang et al. 2006). PSCF and CWT computations were performed using TrajStat software (Wang et al. 2009).

Results

Artemisia pollen season

High variability of *Artemisia* pollen from late-July to mid-October is shown in Fig. 2. Daily pollen concentrations in most of the time were several times lower in the urban area than in the suburban area (Fig. 2). At the suburban station, the *Artemisia* pollen season comprised 71 days, starting on 7 August and ending on 16 October (Table S2). The annual pollen index of *Artemisia* was 5745 grains m^{-3} with a mean daily pollen concentration of 80 grains m^{-3} . Peak value was 854 grains m^{-3} occurring on 25 August. At the urban station, *Artemisia* pollen season started 9 days earlier and ended 14 days earlier than at the suburban station. Here, the annual pollen index of *Artemisia* was 842 grains m^{-3} with a mean daily pollen concentration of 12 grains m^{-3} and the peak of 88 grains m^{-3} occurred on 8 September.

Transport pathway identified by back trajectory analysis

Suburban area

At Mangshan station, 568 back trajectories were generated and eight clusters were retained (Fig. 3a, b). Identified by distance, slow-moving air masses cluster M1s probably originated from the coastal region of Tianjin City and Hebei Province, and cluster M3s originated from southwestern Hebei Province. The cluster results of 24-h trajectories indicated that cluster M2s and M8s air masses originated from the middle part of Inner Mongolia over the northwestern part of Hebei Province. Air masses of cluster M4s came from the northern part of Inner Mongolia at a higher speed and traveled nearly parallel to a longitude from the north before arriving at the receptor site. Cluster M5s, a fast-moving air mass, originated from southern Mongolia, passing through Inner Mongolia. Cluster M6s represented typical air masses originating from the northeastern regions and passing over Liaoning Province and Hebei Province. Slow-moving air mass cluster M7s comprised the shortest trajectories and was considered as purely local air masses within Beijing City.

Daily *Artemisia* pollen concentration for 24-h back trajectories exceeded the threshold altogether on 76 days (Table 1). Cluster M1s was characterized by the highest exceedance resulting in the highest INDEX 2, which was consistent with this cluster having the second highest mean daily pollen level. The air mass associated with cluster M4s obtained the highest INDEX 1 and carried the highest mean pollen concentration from Inner Mongolia, indicating the highest probability of *Artemisia* pollen exceedance. However, the second lowest INDEX 1 and the lowest INDEX 2 occurred with cluster M6s coming from a northeasterly direction, which is consistent with the lowest mean daily pollen level carried by this cluster.

Ninety-six-hour back trajectories are shown in Fig. 3b. Air masses of cluster M1l included the shortest distance, hence the slowest air mass coming from eastern regions of inland. Originating from the middle and southern parts of Russia, air masses associated with cluster M2l and M3l arrived at Beijing following the same route at different speeds. Cluster M4l air mass only comprised the back trajectories coming from the northeastern regions. Air masses associated with cluster M5l, M6l, and M8l, which can be distinguished by distance, all originated from northwestern regions, including northern part of Kazakhstan, the northeastern part of Inner Mongolia, and southwestern part of Russia, respectively. Cluster M7l represented the only pathway originating from the eastern coastal region and penetrated the inland from the southeast.

The total number of 96-h back trajectories exceedance was 69 (Table 1). Air masses corresponding to cluster M1l were characterized by the shortest distance and showed a very high frequency of daily pollen exceedance indicated by the second

Fig. 2 Daily *Artemisia* pollen concentrations at Mangshan National Forest Park station and Beijing Teaching Botanical Garden station from 1 July to 31 October in 2016

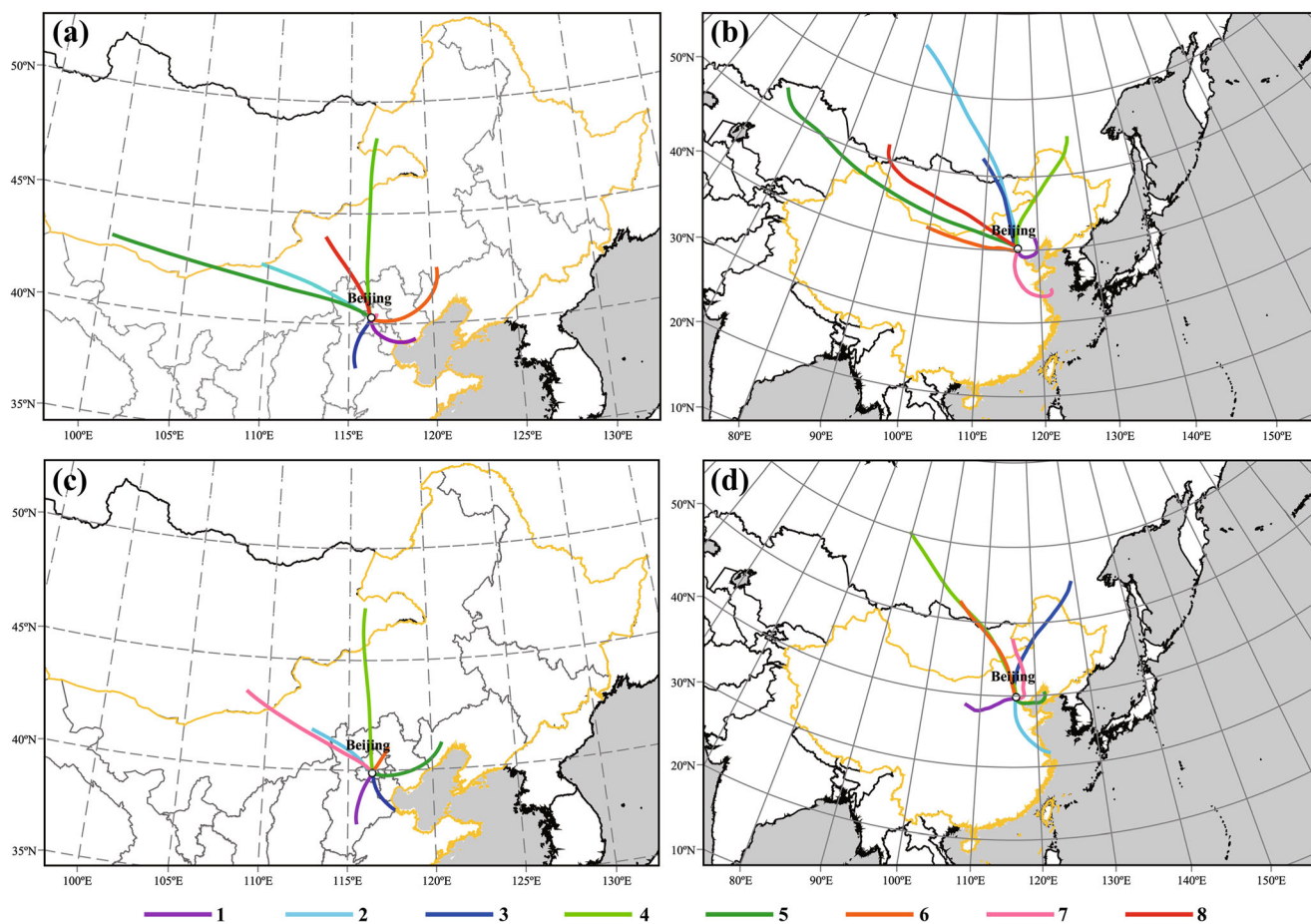
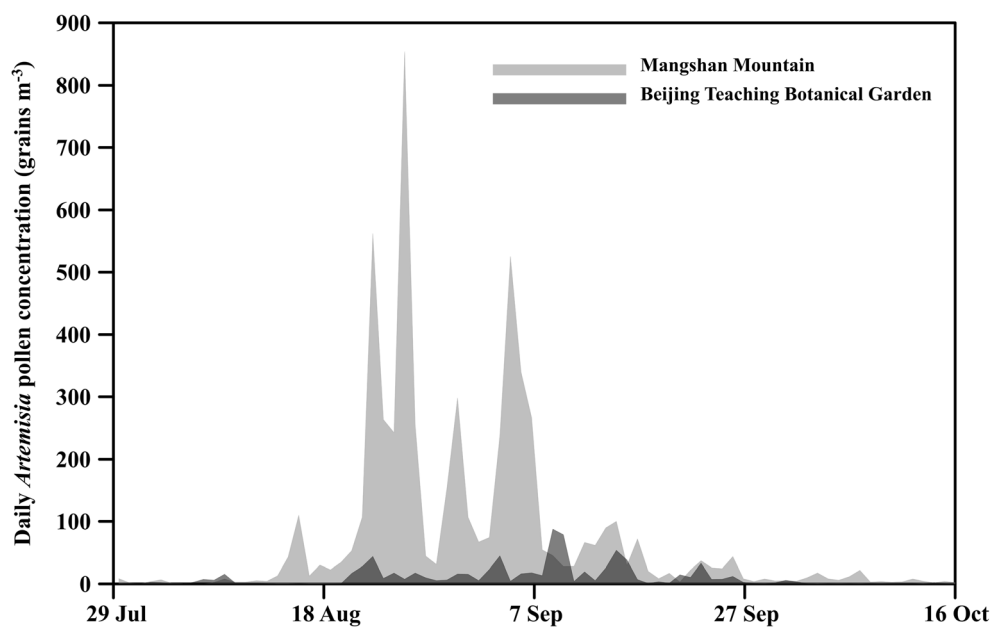


Fig. 3 Cluster analysis of 24-h (a, c) and 96-h (b, d) back-trajectories at Mangshan National Forest Park station and Beijing Botanical Teaching Garden station. Cluster 1: purple; cluster 2: light-blue; cluster 3: dark-blue; cluster 4: light-green; cluster 5: dark-green; cluster 6: orange; cluster

7: pink; cluster 8: red. The world map is painted in black. The map of China is painted in yellow and the map of each province in China is painted in gray

Table 1 Twenty-four- and 96-h back trajectory statistics and the corresponding parameters of daily *Artemisia* pollen concentration at Mangshan National Forest Park station

Clusters	Number of trajectories	Percentage of trajectories (%)	ArtC ^a mean values	ArtC maximum values	Number of ArtC exceedances	INDEX 1 (%)	INDEX 2 (%)
24-h							
M1s	106	18.7	113.5	562.2	17	53.1	19.8
M2s	43	14.4	91.5	339.9	8	42.1	9.3
M3s	154	26.9	40.1	525.3	12	38.7	14.0
M4s	30	6.3	256.6	853.8	7	87.5	8.1
M5s	59	3.7	76.6	853.8	9	47.4	10.5
M6s	48	6.9	39.6	255.5	6	42.9	7.0
M7s	77	7.8	79.4	298.0	17	56.7	19.8
M8s	51	15.3	62.5	266.4	10	62.5	11.6
96-h							
M1l	156	27.5	80.5	562.2	16	45.7	23.2
M2l	34	6.0	218.7	853.8	6	66.7	8.7
M3l	120	21.1	103.4	562.2	22	57.9	31.9
M4l	48	8.5	73.9	238.4	4	44.4	5.8
M5l	24	4.2	42.4	853.8	1	11.1	1.4
M6l	74	13.0	59.4	562.2	11	37.9	15.9
M7l	74	13.0	18.3	72.0	5	33.3	7.2
M8l	38	6.7	75.1	853.8	4	30.8	5.8

^a ArtC, daily *Artemisia* pollen concentration (grains m⁻³)

highest INDEX 2 as well as the largest percentage of all back trajectories. On the contrary, cluster M5l moved the longest distance but had the lowest INDEX 1 and INDEX 2 due to a low mean value of daily *Artemisia* pollen concentration. The highest INDEX 1 values occurred in cluster M2l and cluster M3l that followed the same route from a northwesterly direction, although they covered different distances. Cluster M2l and cluster M3l also carried the highest mean levels of *Artemisia* pollen.

Urban area

At Beijing Teaching Botanical Garden station, 528 back trajectories were generated and seven clusters remained (Fig. 3c, d). Clusters B1s and B3s, relatively slow-moving air masses, originated from southwestern and southeastern parts of Hebei Province, respectively. The air masses of cluster B2s and B7s moved in the same direction but covered different distances from middle Inner Mongolia. Cluster B4s came straight from the northern parts of Inner Mongolia, as was the case for cluster B4s in the suburban area. Cluster B5s followed the same pathway as cluster B6s in the suburban area originating from the northeastern part of Hebei Province and western part of Liaoning Province, respectively. Cluster B6s represented the slowest air masses that originate from the northeastern direction that are not local pathways.

Daily pollen levels in the urban area exceeded the threshold altogether on 83 days (Table 2). Accounting for 28.4% of all

back trajectories, cluster B1s also showed the highest frequency of exceedance. Going along with the same pathway from the northwestern regions, cluster B2s and cluster B7s were featured by the highest mean pollen level and INDEX 1. The lowest INDEX 1 as well as mean and maximum pollen level occurred with cluster B3s that was the only pathway from the southeastern regions.

Cluster analysis of 96-h trajectories revealed that air masses associated with cluster B1l, B2l, and B7l indicated the only pathways from the western, southeastern, and northern direction, originated from southern Inner Mongolia, the eastern Jiangsu Province, and eastern Mongolia, respectively (Fig. 3d). Cluster B3l comprised the air masses coming only through northeastern regions of China. Originating from southern Russia, cluster B4l and B6l air masses arrived at Beijing following the same route and can be distinguished by distance. Air masses of cluster B5l came from the Bohai Bay passing over the eastern and coastal China.

The total number of exceedance days for every cluster of 96-h trajectories was 75 (Table 2). Air masses corresponding to cluster B6l carried a very high mean level of *Artemisia* pollen concentration, and arrived at Beijing following the same path as cluster B4l (faster northwest). Moreover, the highest probability of high pollen levels occurred with cluster M6l due to the highest INDEX 1 and INDEX 2. Compared with cluster B6l, cluster B4l sustained a lower INDEX 1 and INDEX 2, although cluster B4l obtained the highest mean

Table 2 Twenty-four- and 96-h back trajectory statistics and the corresponding parameters of daily *Artemisia* pollen concentration at Beijing Teaching Botanical Garden station

Clusters	Number of trajectories	Percentage of trajectories (%)	ArtC ^a mean values	ArtC maximum values	Number of ArtC exceedances	INDEX 1 (%)	INDEX 2 (%)
24-h							
B1s	150	28.4	12.4	87.7	19	59.4	22.9
B2s	45	8.5	17.9	87.7	13	72.2	15.7
B3s	91	17.2	5.4	33.2	12	41.4	14.5
B4s	54	10.2	10.3	78.7	9	64.3	10.8
B5s	81	15.3	10.7	44.0	11	50.0	13.3
B6s	80	15.2	10.4	45.0	13	54.2	15.7
B7s	27	5.1	35.1	87.7	6	66.7	7.2
96-h							
B1l	42	8.0	13.0	87.7	9	56.3	12.0
B2l	86	16.3	6.1	53.9	6	37.5	8.0
B3l	53	10.0	16.6	45.0	7	63.6	9.3
B4l	60	11.4	18.1	87.7	8	61.5	10.7
B5l	137	26.0	10.4	53.9	17	53.1	22.7
B6l	79	15.0	15.0	78.7	15	65.2	20.0
B7l	71	13.5	10.1	45.0	13	48.1	17.3

^a ArtC, daily *Artemisia* pollen concentration (grains m⁻³)

pollen level. The cluster B5l air masses traveled the shortest distance but has accounted for the largest part of all back trajectories and showed the highest frequency of exceedance. The lowest pollen level and INDEX 1 and INDEX 2 occurred with cluster B2l, which came through southeastern regions.

Potential source area detected by PSCF and CWT models

Cluster analysis of air mass trajectories can provide the transport pathways of air parcels and particulates, but locating their source regions is more challenging (Stohl 1996). A comparison of results of the PSCF and CWT in both sites helps to determine the source areas of the *Artemisia* pollen in the urban and suburban area of Beijing City.

Suburban area

Weighted PSCF values of 24-h back trajectories at Mangshan station ranged from 0 to 0.78 (Fig. 4a), and weighted CWT values varied from 0 to 230.3 (Fig. 4b). Three major potential source regions were identified by the PSCF and CWT models. The PSCF values were high in the northern part of Inner Mongolia and a small part of Mongolia, as were the CWT values. Therefore, on average these potential source regions were associated with the highest concentrations at the receptor site. This is consistent with cluster analysis results, whereby M4s had the highest INDEX 1. Another potential source region is the northwestern region of Hebei Province extending

through to northwestern Inner Mongolia, since the PSCF values here were found to be the highest, although not so high for CWT. In addition, this source region corresponded to the air mass movements of cluster M2s whose INDEX 1 or INDEX 2 were only moderate. The third possible source region includes the southern part of Beijing City and Hebei Province. This result concurs in part with a very high INDEX 2 for corresponding cluster M3s.

Weighted PSCF values of 96-h back trajectories varied from 0 to 0.89 (Fig. 4c), and weighted CWT values ranged from 0 to 334.2 (Fig. 4d). The northern region of Beijing was the most likely source area due to its highest PSCF values. The northwestern region was an important source area but extended to the north of Mongolia, in relation to the pathways taken by cluster M2l and cluster M3l which showed the highest probability of high pollen level. Compared with the 24-h back trajectory at the same site, the southern source region stretched to Shandong and Jiangsu Province. However, this potential source area was not detected by the CWT method. We attribute this difference to the lowest pollen level of the relevant cluster M7l.

Urban area

Weighted PSCF values of 24-h back trajectories at Beijing Botanical Teaching Garden station ranged from 0 to 0.95 (Fig. 5a) and weighted CWT values varied from 0 to 29.7 (Fig. 5b). The highest values of the PSCF and CWT were both grouped in the western areas of Hebei Province, thus this area was identified as a major source area west of Beijing. Another

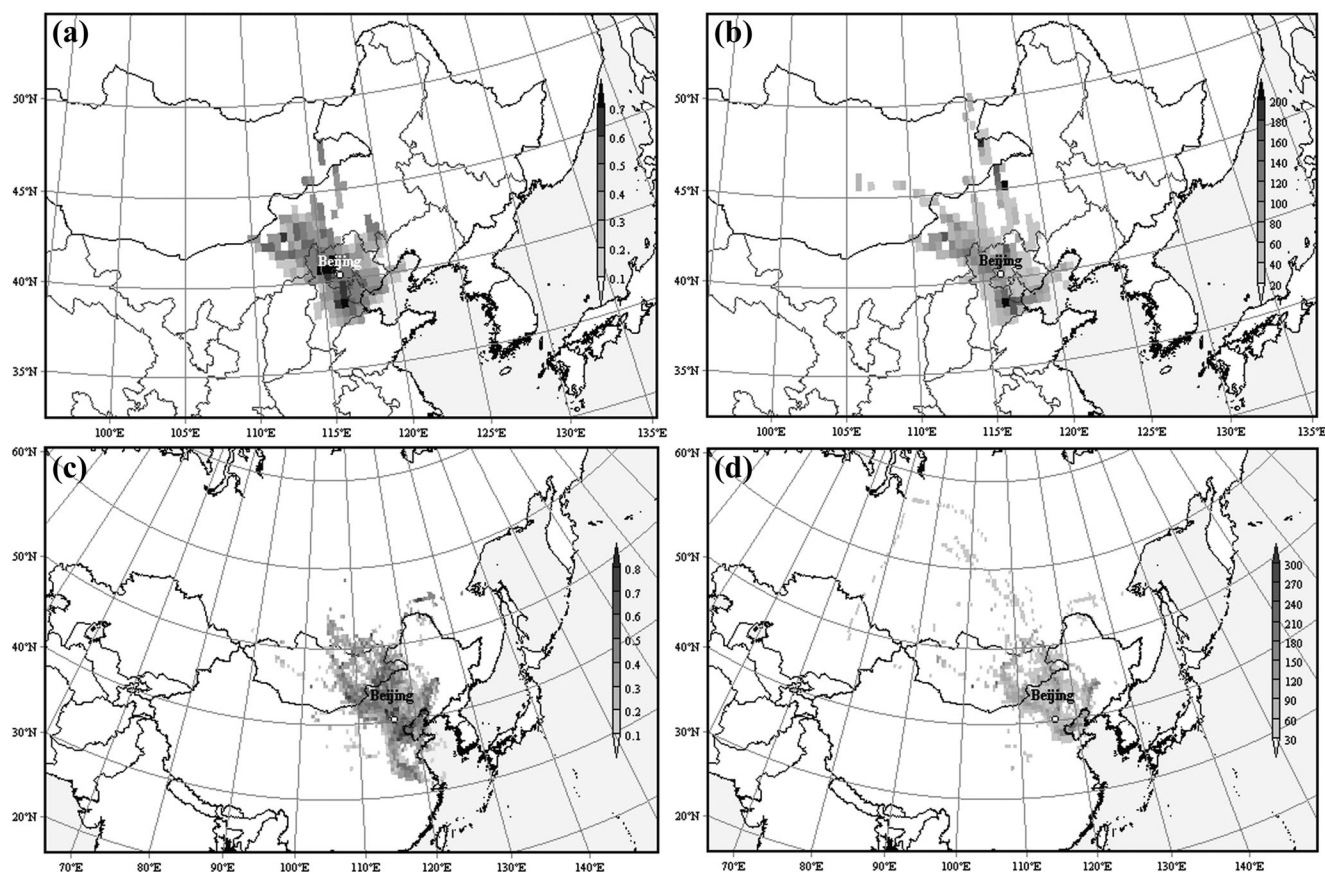


Fig. 4 Potential source contribution function (a, c) and concentration weighted trajectory (b, d) results of 24-h (a, b) and 96-h (c, d) back-trajectories at Mangshan National Forest Park station. Dark colors represent greater source potential

major source region, including middle Inner Mongolia and the northwestern Hebei Province, was detected in these two approaches, since CWT values here were more pronounced than in any of the other areas. Corresponding air mass cluster B2s and cluster B7s carried the highest daily pollen concentrations to the urban site in Beijing, a finding that is supported by the statistical analysis. The third source region was observed in the southern areas in Hebei Province, given that the highest values of the PSCF and CWT were centered upon this area. This is consistent with the corresponding pathway covered by cluster B1s of which INDEX 2 was the highest.

Weighted PSCF values of 96-h back trajectory at the urban station ranged from 0 to 0.99 (Fig. 5c) and weighted CWT values varied from 0 to 33.2 (Fig. 5d). Consistent with 24-h analysis at the same site, northwestern source areas located in middle Inner Mongolia and Mongolia were easy to identify using the CWT method due to its significantly high values. This accords with the highest INDEX 1 and INDEX 2 of the relevant cluster B4/ and cluster B6/ which extended source areas to the middle of Russia. Unexpectedly, one major southern source region, including the southern Hebei and northwestern Shandong, was only identified by the PSCF approach and not identified in the cluster analysis. The corresponding air masses cluster B2/ carried the lowest pollen level and showed the lowest probability and frequency of

daily *Artemisia* pollen exceedance (INDEX 1 = 37.5%, INDEX 2 = 8.0%). This difference may be interpreted as due to the shortcomings of the PSCF method. For example, the “trailing effect” may be caused by the weights being evenly distributed along the trajectories’ paths, which frequently leads to the identification of potential source directions rather than locations (Hsu et al. 2003) or even incorrect source regions (Lai et al. 2007). Even though each modeling approach has been found to have some advantages compared to the others, more comprehensive information on source areas may be obtained using them in combination (Hsu et al. 2003).

Discussion

Generally speaking, local transport can be described by a single observation station, while long-range transport requires more than one station distributed over the area (Sofiev et al. 2013b). Here, observed *Artemisia* pollen levels as well as local and regional transport of *Artemisia* pollen are compared between the urban and suburban areas using 24-h air mass movements at each site. Moreover, long-range transport of *Artemisia* pollen in Beijing is further explored by 96-h back trajectories at both the urban and suburban sites.

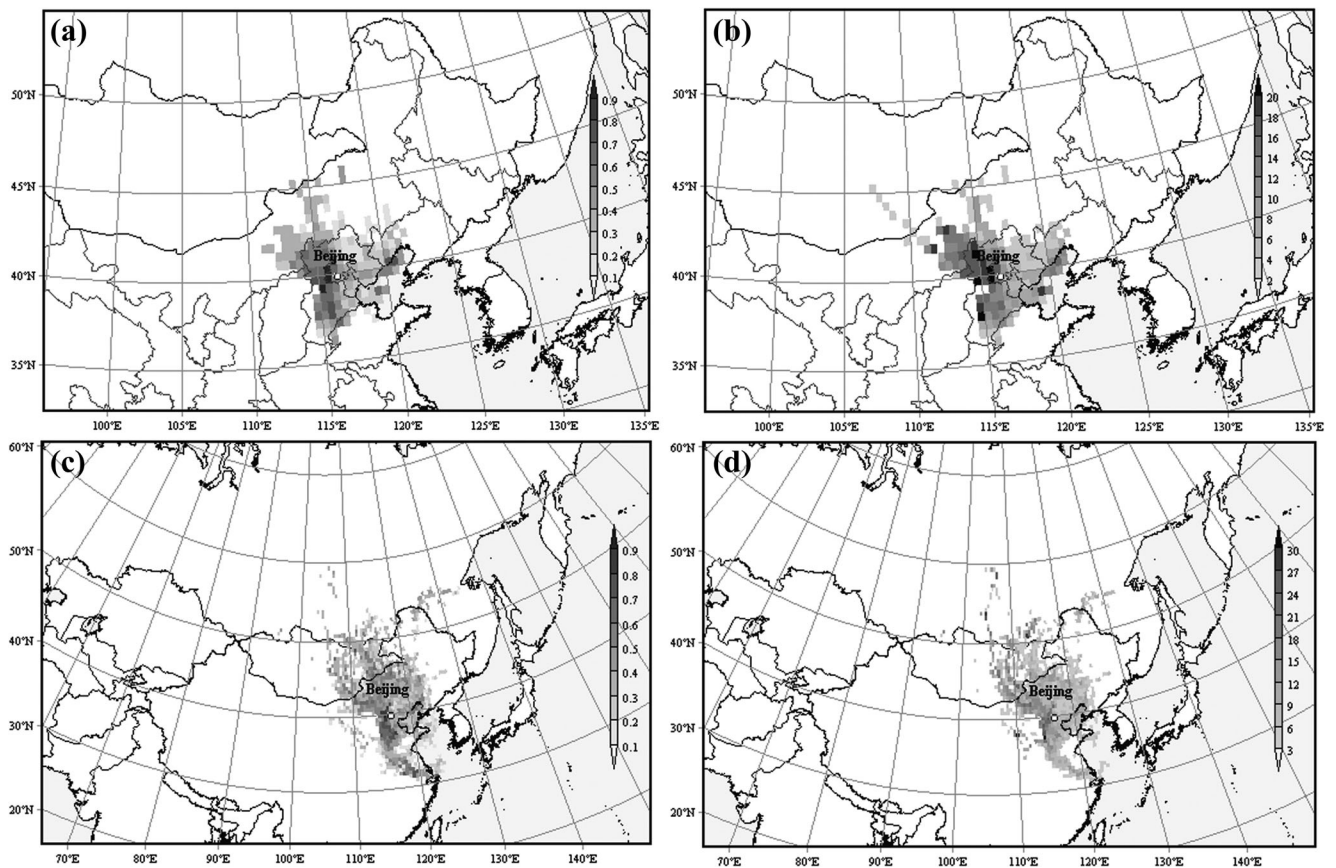


Fig. 5 Potential source contribution function (a, c) and concentration weighted trajectory (b, d) results of 24-h (a, b) and 96-h (c, d) back-trajectories at Beijing Botanical Teaching Garden station. Dark colors represent greater source potential

Comparisons of daily *Artemisia* pollen levels and local/regional transport between the urban and suburban areas

Observed *Artemisia* pollen levels in Beijing were significantly higher in the suburban area than in the urban area. Evidenced by some previous studies in European countries, the sensitization (Burr et al. 2003) and quantities (Unger 1999; Ziska et al. 2003; Rodríguez-Rajo et al. 2010; Bosch-Cano et al. 2011; Kruczek et al. 2017) of allergenic pollen in the air were found to be significantly higher in the rural/suburban areas than in the urban areas, resulting from the differences in local and distant pollen sources, local weather conditions as well as degree of urbanization. In our study, this difference probably arises due to two major causes, one being local *Artemisia* pollen emission associated with local transport, and the other being altitude, in turn influencing *Artemisia* pollen transported at regional scales.

Artemisia is considered to be a pioneer species of disturbed in both urban and rural environments, especially on agricultural fields, roadside verges, abandoned places, and where building activities take place (Spieksma et al. 2003). Abandoned fields provide suitable environments for the growth of *Artemisia* (Table S2). Therefore, local plants that released *Artemisia* pollen

into the air near the volumetric trap are likely to be more abundant in the suburban area than in the urban area. At local scales, cluster M7s characterized by shortest distance from the local regions displayed a major role in the pathway by local transport process (Fig. 3a). Furthermore, cluster M7s showed the highest frequency of exceedance and carried a moderate mean pollen level to the receptor. On the contrary, at the urban site, the shortest trajectory that was relevant to cluster B6s was a less “polluted” pathway among all clusters (Table 1).

One key factor that needs to be considered when discussing regional transport is the elevation altitude above sea level, strong evidences for which is presented by Aguilera and Valenzuela (2012). The pollen sampler located at the suburban site standing in an absolutely higher altitude is more likely to capture transported *Artemisia* pollen from other source regions at a regional scale. On the contrary, the city site is surrounded by tall buildings at a lower altitude and has a greater chance to capture pollen from local plants within the nearest few kilometers. At regional scales, common potential source regions, including northwestern part of Beijing City and Hebei Province, as well as Inner Mongolia, were identified in two sampling sites (Figs. 4 and 5). Furthermore, plants of the Asteraceae family, especially *Artemisia*, are widely distributed in Inner Mongolia and

Mongolia (Sun and Song 2006), thus validating the plant sources for regional transport. However, divergence of source areas at a regional scale between these two sites may partly explain the difference in pollen levels. Pathway cluster M4s covered by the northern part of Inner Mongolia carried the highest pollen concentrations to the suburban receptor site. By contrast, in the urban area, the corresponding path cluster B4s from northerly direction had a very low pollen level.

According to Katelaris et al. (2004) and Avolio et al. (2008), validity range for pollen grains is based on the average distance traveled during 1 day. Thus the validity range for *Artemisia* pollen grains is 155–181 km on average estimated by monthly mean wind speed at the suburban station (Table 3). In contrast, the validity range of *Artemisia* pollen grains at the urban station is only around 35 km. In addition, mean wind speeds of $1.8\text{--}2.1\text{ m s}^{-1}$ and monthly minimum temperatures of $7.6\text{--}20.3\text{ }^{\circ}\text{C}$ at the suburban station provide favorable conditions which are associated with temperatures above $5\text{ }^{\circ}\text{C}$ and wind speeds exceeding 1.8 m s^{-1} for regional-scale transport (Sofiev et al. 2013b). On the other hand, the mean wind speed at the urban station was less than 0.6 m s^{-1} which would favor only local transport. Under these circumstances, differences in transports of pollen grains at these two sites are largely determined by wind speed. Threshold values of temperature for the emission of *Artemisia* pollen lie in the range $10\text{--}14\text{ }^{\circ}\text{C}$ (Wahl and Puls 1989, Grewling et al. 2012). Pollen emissions from local sources are likely to decrease in October, since mean minimum October temperatures at these two sites were lower than this threshold value (Table 3). However, a number of *Artemisia* pollen grains were still in the air and captured at the suburban site until late-October, indicating that a proportion of pollen is carried by large-scale transport. Meanwhile, the pollen season at the urban site ended as early as 2 October, suggesting that pollen collected in October were most likely from distant sources. On the basis of the argument outlined here, we come to the conclusion that the influence of regional-scale transport is more profound for *Artemisia* pollen at the suburban station than at the urban station.

In practice, the impacts of allergenic pollen on human health cannot be ignored in spite of a relatively low level of *Artemisia* pollen observed in central part of Beijing City. Studies on *Artemisia* pollen suggested that even just a few pollen grains in

the atmosphere can be sufficient to initiate high pollinosis rates (Spieksma et al. 1980; Spieksma 1986). Epidemiological evidences obtained from Beijing Hospital in Dongcheng district (near the urban sampling site) confirmed that numbers of outpatients diagnosed with AR (allergic rhinitis) increased with pollen concentrations (Zhang et al. 2012). The population density in Dongcheng District is approximately 15 times larger than in suburban Changping District, indicating a much greater potential population who may present with symptoms of AR.

Long-range transport of *Artemisia* pollen

The combined influence of local production and long-range transport must be considered when explaining pollen dispersal (Skj  th et al. 2007; Zink et al. 2012; Hern  ndez-Ceballos et al. 2015). Pollen grains maintain the potential to cause allergic reactions in regions very remote from their source due to long-range transport (Grewling et al. 2016). Pollen grains in the atmosphere may remain suspended for 2- or 3-day deposition velocities of about 0.01 m s^{-1} (Sofiev et al. 2006). These figures are comparable to some atmospheric aerosols, implying that about one half of the emitted mass of pollen grains could be transported to distances beyond 100 km (Aylor 2002).

At long-range scales, the most heavily “polluted” pathways, cluster M2I and cluster M3I in the suburban station as well as cluster B4I and cluster B6I at the urban station, make up the transport component that lies beyond 100 km (Fig. 3b, d). Four clusters are the most likely possible pathways that carried the highest mean pollen concentrations along with a very high INDEX 1 or INDEX 2 (Tables 1 and 2). Beyond that, northwestern regions (northwestern Hebei Province, northern Inner Mongolia, and northwestern Mongolia) covered by these four clusters (Figs. 4c, d, 5c, d) are considered to be common potential source areas for long-range transported *Artemisia* pollen. Moreover, even longer pathways are identified by the CWT method that extended through the middle of Russia, although it was not apparent using the PSCF model.

Although previous studies about long-range transport of airborne pollen indicate high degrees of variation, depending on the specific taxa of pollen and target study areas, they all conclude that long-range transport contributes a smaller part to the observed pollen concentrations than local and regional transport (Rousseau et al. 2005; van der Knaap et al. 2012). The HYSPLIT model and its derived algorithms, such as PSCF and CWT used in this paper, are routinely deployed to identify the pathway and source area of atmospheric particles, including the biogeographical estimates of allergenic pollen transport (Makra et al. 2016). Atmospheric pollutants are subject to several processes during dispersion: transport via air masses, turbulent mixing, dry and wet deposition, and chemical and physical transformation (Sofiev et al. 2006). Further studies aiming to explicate both the biological and meteorological mechanisms which combine pollen release from plants with the subsequent dispersion of

Table 3 Monthly mean values of minimum temperature (Tmin) and average wind speed (WS) from July to October at the suburban station and urban station

Month	Suburban		Urban	
	Tmin	WS	Tmin	WS
July	19.8	2.1	23.0	0.4
August	20.3	1.9	22.3	0.4
September	15.1	1.8	16.6	0.4
October	7.6	1.8	9.2	0.4

pollen grains at a large scale are still required (Sofiev et al. 2006; Sofiev et al. 2013c). In the near future, the SILAM models will also be used to forecast and quantify the amount of allergenic pollen in long-range transport in Beijing.

Conclusion

The *Artemisia* pollen season in Beijing in 2016 started in late-July and ended in mid-October. *Artemisia* annual pollen index of this study (842–5745 grains m⁻³) was found to be higher than that in many areas across Europe (245 grains m⁻³). Significant differences in the observed annual pollen index and the mean daily pollen concentration during the pollen season were observed between suburban (5745, 81 grains m⁻³) and urban areas (842, 13 grains m⁻³). We attribute these differences to *Artemisia* plant distribution and pollen emission together with air mass movements at local scales, and altitude influence associated with transported *Artemisia* pollen at regional scales. Cluster analysis revealed that cluster M7s (originated from the northeast) and cluster M4s (originated from the north) were the most relevant local and regional air masses in the suburban area, respectively. Cluster B2s and cluster B7s originated from the northwest and were major the pathways responsible for regional transport in the urban area. At a regional scale, the northwestern parts of Beijing City and Hebei Province, as well as Inner Mongolia, were common potential source regions in both the urban and suburban areas. Source areas in the northern part of Inner Mongolia were only detected at the suburban station. At long-range scales, potential source areas extended to the northwestern part of Mongolia besides above-mentioned regional source areas. The influence of large-scale transport on *Artemisia* pollen is more profound at the suburban station than at the urban station. In the future, forecasting and quantification of the amount of allergenic pollen in Beijing at long-range scales will be further explored using the SILAM models.

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Table S1 Previous studies on modelling transport of allergenic pollen

Pollen taxa	Study			Dispersion Model	Reference
	Area	No of Sites	Year	Module (and its reference)	
<i>Ambrosia</i>	Hungary	43	2006	COSMO-ART	Zink et al. (2012)
<i>Ambrosia</i>	Europe	NA	2005-2011	SILAM (Sofiev et al. 2013, 2008)	Prank et al. (2013)
<i>Casuarina, Olea, Quercus, Artemisia, Chenopodiaceae/ Amaranthaceae, Poaceae</i>	Spain	2	2006-2007	Backward trajectory; cluster analysis (HYSPLIT) (Draxler and Rolph 2003); Source-receptor model (Belmonte et al. 2008)	Izquierdo et al. (2011)
<i>Ambrosia</i>	Croatia	2	2002-2009	Backward trajectory; WRF-ARW (HYSPLIT) (Skamarock and Weisman 2009)	Prtenjak et al. (2012)
<i>Ambrosia</i>	Serbia, Poland, Sweden, Denmark	16	2011	Backward trajectory (HYSPLIT) (Draxler and Hess 1998).	Šikoparija et al. (2013)
<i>Ambrosia</i>	Hungary	8	2009-2013	Backward trajectory (HYSPLIT), PSCF, CWT (Draxler and Hess 1998; Polissar et al. 2001; Wang et al. 2006)	Makra et al. (2016)

NA, not available.

Table S2 Characteristics of geographic conditions and *Artemisia* pollen season in suburban and urban stations

Monitoring station	Suburban	Urban
	Mangshan National Forest Park	Beijing Teaching Botanical Garden
Geographic conditions		
Latitude	40°16'11"N	39° 52' 22"N
Longitude	116°16'38"E	116° 25' 38"E
Altitude (m. a. s. l.)	638	38
District name	Changping	Dongcheng
District area (km ²) ^a	1344	42
Population density in the district (individuals km ⁻²) ^a	1461	21620
Housing construction area (km ²) ^b	14.3	2.2
<i>Artemisia</i> pollen season		
Pollen peak date	25th August	8th September
Pollen start date - end date	7th August - 16th October	29th July - 2nd October
Pollen season duration (days)	71	66
Annual pollen index (grains m ⁻³)	5745	842
Mean daily pollen concentration (grains m ⁻³) ^c	80	12
Maximum daily pollen concentration (grains m ⁻³)	854	88

a Urbanization data is from the latest annual report of Beijing transport development.

b Housing construction data is obtained from the Statistic Yearbooks of Changping district and Dongcheng district in 2016.

c Mean daily *Artemisia* pollen concentration is the total pollen count during the pollen season divided by season duration.