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An assessment of predictive forecasting of *Juniperus ashei* pollen movement in the Southern Great Plains, USA

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Abstract *Juniperus ashei* pollen, a significant aeroallergen, has been recorded during December and January in Tulsa, Oklahoma, over the past 20 years. The nearest upwind source for this pollen is populations growing in southern Oklahoma and central Texas, at distances of 200 km and 600 km respectively. Long-distance dispersal of *J. ashei* pollen into the Tulsa area shows a strong correlation with the trajectories of wind blowing across southern populations before traveling north towards eastern Oklahoma. The strong tie between climatic conditions and the occurrence of this aeroallergen within the Tulsa, Oklahoma, atmosphere provided a unique opportunity to forecast the dispersal, entrainment, and downwind deposition of this significant aeroallergen. Forecasts of long-distance *J. ashei* pollen dispersal began during the winter of 1998/1999. Each forecast uses defined climatic parameters to signal pollination at each source site. Coupled to these estimates of pollen release, forecast weather conditions and modeled wind trajectories are used to determine the threat of dispersal to downwind communities. The accuracy of these forecasts was determined by comparing the forecast “threat” to aerobiological records for the same period collected in the “Tulsa region”. Analysis of the two seasons revealed only a single occurrence of “high” or “very high” pollen concentrations in Tulsa not directly linked to “moderate” or “severe” forecast threats from the southern source areas.

Keywords *Juniperus ashei* · Pollen · Forecasting · Great Plains, USA · Wind trajectories

Introduction

Wind-pollinated plants depend on the air stream to provide pollen grains for fertilization. Once pollen is entrained in the atmosphere, however, the distance that it travels becomes unlimited, the final deposition being dependent on changing atmospheric conditions. This phenomenon of pollen as a “regional component” (Faegri et al. 1989) or the “escape fraction” (Gregory 1961) can result in significant concentrations being deposited at some distance from the source area (Van de Water and Levetin 2001). For example, atmospheric concentrations of *Juniperus ashei* pollen as high as 2,000 grains/m³ have been recorded over the past 20 years during December and January in Tulsa, Oklahoma, approximately 600 km from the dominant upwind source (Levetin and Buck 1986; Rogers and Levetin 1998; Levetin 1998). The incursion of allergenic pollen, such as *J. ashei*, into distant areas can pose serious health risks and can trigger severe respiratory symptoms in sensitized individuals (Hjelmroos 1991; Wallin et al. 1991).

Identification of conditions leading to the release of pollen or spores from a source area coupled with environmental controls on particle entrainment, transport, and deposition can be used to forecast downwind dispersal (Davis and Main 1984, 1986; Main and Davis 1989). In the case of aeroallergens, if forecasts are available then allergic individuals living along the dispersion path can take prophylactic measures to mitigate exposure. Such a pollen forecasting system has been operational in the southern Great Plains, USA, for the prediction of the entrainment and dissemination of highly allergenic *J. ashei* pollen from populations growing in southern Oklahoma to central Texas.

Juniperus ashei begins pollination in early December and ends in late January to early February, a period distinct from that of other co-occurring juniper species; *J.*

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pinchotii, for examples pollinates during the fall and *J. virginiana* in the early spring. The densest and most extensive *J. ashei* populations grow along the dissected slopes of Cretaceous limestone on the Edwards Plateau of central Texas. Van Auken (1993) found that mean vegetation densities in this area of central Texas are highest in the evergreen woodlands at $2,568 \pm 973$ plants/ha, of which approximately 40%–70% are *J. ashei*. As a measure of the pollen potential of this source, Hidalgo et al. (1999) reported that pollen production in individual trees of the Cupressaceae family ranges from 6.4×10^9 to 1×10^{12} pollen grains/year, a value that breaks down to approximately 4.0×10^5 pollen grains/male cone (Nilson and Praglowski 1992; Hidalgo et al. 1999).

The *J. ashei* population inter-grades to the east with *J. virginiana* and to the west with *J. pinchotii*. Isolated outlier communities of *J. ashei* grow to the south in northern Mexico and to the north in the Arbuckle Mountains of south central Oklahoma and the Ozark Mountains of northwest Arkansas and southeast Missouri (Little 1971; Adams 1975). The *J. ashei* population in the Arbuckle Mountains covers approximately 130 km² and is confined to areas with exposed limestone bedrock and shallow carbonate-rich soils. The distribution and density of the Mexico and Ozark Mountain populations are currently unknown. The dominant weather pattern, however, results in the Mexican population being upwind of the main central Texas population, the Ozark Mountain trees being the furthest downwind outlier.

Winter weather patterns in the southern Great Plains, USA, are dominated by dry, cold air that moves east out of the Rocky Mountains and south from the Canadian Arctic. These air masses collide with warmer, more humid air of the tropical Atlantic region to the southeast. The clash between these weather patterns results in region-wide atmospheric instability (Borchert 1950) that can entrain and carry microscopic particles over long-distances. Specific weather patterns can be coupled to atmospheric models of particle dispersal to forecast particle concentration movements both forwards (Davis and Main 1984, 1986; Main and Davis 1989; Yao et al. 1997) and backwards in time (Mandrioli et al. 1980, 1984; Cabezudo et al. 1997; Van de Water and Levetin 2001). In the southern Great Plains, *J. ashei* pollen concentrations in Tulsa, Oklahoma, correlate with regional southerly winds associated with south to north pressure gradients from mesoscale weather systems that move across the region (Levetin and Buck 1986; Rogers and Levetin 1998; Levetin 1998).

Recognition of the relationship between regional weather conditions and pollen dispersal was used to forecast the threat of *J. ashei* pollen influx into communities downwind from the main source areas in central Texas and southern Oklahoma. The success of this, as for any forecasting system, is dependent upon providing accurate assessments of future conditions. In this case, forecast accuracy depends upon estimating *J. ashei* pollen release, entrainment into the atmosphere, movement, and ultimately downwind deposition. The forecast system

predicts regional *J. ashei* pollen transport throughout the south central U.S.; however, this study specifically addresses the forecasting of the influx of *J. ashei* pollen from southerly source areas into the Tulsa, Oklahoma, area. More specifically, this paper addresses the accuracy of the forecasting effort during the first 2 years, the 1998/1999 and 1999/2000 pollination seasons.

Materials and methods

Five point-sources were chosen to represent the distribution of *J. ashei* in Texas (Austin: 30.27°N, 97.70°W; Junction: 30.47°N, 99.75°W; San Angelo: 31.40°N, 100.50°W), Oklahoma (Arbuckle Mountains: 34.45°N, 97.12°W), and Arkansas (Ozark Mountains: 36.50°N, 93.50°W). These locations were used to model pollen dispersal from local *J. ashei* populations. Each forecast was a multi-step process that included the review of current synoptic weather conditions in the southern Great Plains, analysis of evolving regional weather patterns, and the forward calculation (48 h) of air-mass trajectories from each point source. Once made, each forecast was posted on the internet (<http://pollen.utulsa.edu>) and included a regional weather summary, estimated release conditions for each source population, the forward-projected air-mass trajectories, and the threat of significant downwind deposition of pollen concentrations.

Pollination within each *J. ashei* population is spatially and temporally variable, therefore release conditions were estimated by comparing historical data with real-time field observations made by volunteers living throughout the region. Once the cones mature and pollen grains are released, entrainment and dispersal through the atmosphere are dependent upon local weather conditions. Environmental parameters were used as estimates of release. They include sunshine levels greater than 65%, air temperatures above 5 °C, relative humidity levels less than 50% with dry conditions for the previous 24 h, and wind speeds greater than 1.8 m/s. Ongoing research is investigating the applicability of these parameters as predictors. The potential for release in each source area was categorized as “favorable,” “mixed,” or “unfavorable.” Additional categories were initially used during the instigation of the forecasting effort, but have been reclassified from “mostly favorable” to “mixed,” and from “quite favorable” to “favorable” conditions.

Once pollen is released and entrained within the atmosphere, the movement of the air mass determines the location and concentration of potential downwind deposition. Each air-mass trajectory was estimated using an atmospheric model of particle deposition (HYSPLIT-4: <http://www.arl.noaa.org>). The HYSPLIT-4 (HYbrid Single-Particle Lagrangian Integrated Trajectory) model computes dispersion, assuming advection of a fixed number of initial particles, by use of the mean wind field combined with turbulent components. Results are reported with respect to central standard time (CST) to reflect the daily rhythm of pollen dissemination within the study populations and make interpretations of environmental conditions easier to follow. Each model run was calculated for 1100 hours (CST) at five sites from a starting height of 200 m above ground level. The starting time was chosen as a representative of the mean period of pollen release during each given day. It is recognized, however, that environmental conditions greatly affect daily pollen release. The model predicted air-mass trajectory pathways along which climatic conditions were evaluated to estimate conditions of travel and deposition. The evaluation process integrated weather patterns associated with past high-influx levels, current weather conditions, and forecast changes. Also taken into account were the duration of the favorable conditions, the duration of the flight path, and the projected pathway of each trajectory over densely populated areas. The forecast threat to downwind regions was categorized as “low”, “moderate”, or “severe.”

Air sampling

Aerobiological samplers were used throughout the region to record atmospheric pollen concentrations for model validation. Aerobiological monitors were stationed in the southern source areas in Texas at Austin and Junction, along with the Arbuckle Mountains population in southern Oklahoma (see Van de Water and Levettin 2001 for specific site information; Fig. 1). Three stations were deployed in the Tulsa region to record the influx of *J. ashei* pollen into the area. The sites were stationed at the University of Tulsa (36.18°N, 95.88°W) and the communities of Bixby (35.97°N, 95.87°W) and Hectorville (35.85°N, 96.00°W), Oklahoma. The last two are associated with sites of the Oklahoma Mesonet, an integrated network of over 110 environmental monitoring stations positioned across Oklahoma, providing real-time weather conditions (<http://www.okmesonet.ocs.ou.edu/overview>).

Each sampling station was equipped with a Burkard spore trap containing a 7-day sampling head. The samplers were changed weekly and the sampling drums sent for processing to the aerobiology laboratory at The University of Tulsa. In the laboratory, the Melenex tape on which the pollen is captured was removed, divided into 24-h periods, mounted onto glass slides, and the number of Cupressaceae pollen grains microscopically determined. Each slide was analyzed at 400× along 12 transverse transects representing each even-numbered hour. Raw counts were converted to hourly concentrations (pollen grains/m³), using a relationship that assumes a constant pumping rate of 10 l/m atmosphere.

Assessment of forecast accuracy

A total of 334 forecasts were developed during the period of this study. Forecasting began during the 1998/1999 pollination season on 4 December and continued until 31 January. The following season, 1999/2000, began on 6 December and continued until 12 February. To assess forecast accuracy, the timing of each forecast trajectory passing over northeastern Oklahoma was compared to pollen concentrations recorded within the Tulsa region. Periods in which northerly wind fields dominated were identified by the use of posted forecasts from each season. Each identified forecast period was then re-run using the HYSPLIT-4 model, but with archived model data to retrieve hourly positions (latitude, longitude, and elevation above ground level) for each trajectory as they moved away from their source area. A trajectory was considered to have crossed the Tulsa region if it passed through the area defined as a box centered on the city. The area encompassed within the Tulsa region is approximately 120 km east to west (95.33°W to 96.67°W) and 150 km north to south (35.55°N to 36.67°N). The east–west width is perpendicular to the mean southerly wind-flow direction and approximately 20% of the travel distance from the central Texas source area, a value that approximates the stated error of the modeled trajectories (Draxler 1991, 1996). Travel-time from the source area to the Tulsa region was recorded to help identify trajectories contributing to the pollen registration.

J. ashei does not grow in the Tulsa region, therefore Cupressaceae pollen registrations during December and January must represent pollen carried from distant sources. Average hourly pollen concentrations throughout the study were categorized according to the guidelines of the National Allergy Bureau (NAB), in which 1–15 pollen grains/m³ is “low”, 15–90 grains/m³ is “moderate”, 90–1500 grains/m³ is “high”, and more than 1,500 pollen grains/m³ is “very high.” The registration of moderate, high, and very high pollen concentrations during each season was based on the hourly aerobiological records. Registrations of low concentrations were excluded because they represent relatively minor concentrations, potentially from a variety of source locations, including re-entrainment of previously deposited pollen.

All forecasts that crossed the Tulsa region were compared to the aerobiological record. Forecasts were considered successful if moderate or severe threats to northeastern Oklahoma were identified for the source location within the forecast and if high or very

high pollen concentrations were registered in the Tulsa region after travel time had been taken into account. Modeled trajectories are for a single hour during each day and pollen release is thought to occur throughout the daylight hours; therefore, a forecast was judged successful if high or very high concentrations were recorded in Tulsa, Oklahoma, during a period corresponding to the potential release period at the source plus travel time. Successful forecasts record high to very high concentrations in at least two of the three sampling stations in the Tulsa area. For example, pollen traveling from central Texas forecast at 1100 hours CST represents pollen entrained and carried between 0800 hours and 1600 hours on that day. Therefore, a successful forecast would encompass high or very high pollen concentrations in a majority of the Tulsa samplers 3 h prior to or 5 h past the modeled 1100 hours air-mass arrival.

Results and discussion

Forecast results

Analysis of the 1998/1999 forecasts show that air-mass trajectories from source areas crossed the Tulsa region 25 times on 15 different days (Table 1). Of these, 14 emanated from the Arbuckle Mountains (56%) with most arriving within 12 h of release, 5 trajectories (20%) came from Austin, and 3 each (12%) from Junction and San Angelo. Two of the Austin trajectories traveled the distance quickly, in 8 h (17 January 1999) and 4 h (12 January 1999), respectively, whereas the west Texas trajectories took 25–36 h to reach the Tulsa region. The Arbuckle Mountain forecasts listed “unfavorable” release conditions with a low threat to northeastern Oklahoma in 5 of the 14 trajectories. At the Texas sites, “favorable” release conditions and a “severe” threat to northeastern Oklahoma were forecast in all but 2 cases. Climatic conditions in Junction on 26 December 1998 and in Austin on 4 January 1999 resulted in “mixed” or unfavorable forecast release conditions and a low threat to downwind areas.

The transmission of pollen into the Tulsa region was registered by high and very high pollen concentrations on 11 days during 1998/1999 (Table 2). In only a single case (16 January) was the source of the elevated pollen concentrations unidentified. Trajectories from the Arbuckle Mountains correlated with high and very high pollen concentrations on 6 different days; air-mass pathways from Austin are associated with 4 influx events, and those from west Texas occur twice. In addition, each trajectory associated with high and very high pollen concentrations matched favorable forecast release conditions at the source, except in a single case. This case shows that pollen release conditions in the Arbuckle Mountains were forecast as unfavorable from 9 to 11 January, but became favorable on 12 January. The threat of pollen influx into northeastern Oklahoma was forecast as severe for each of the trajectories, except for low and moderate conditions at the Arbuckle Mountains between 9 and 11 January.

Severe drought during the 1999/2000 pollination season resulted in a reduction of trajectories traveling over the Tulsa region, with only 20 occurrences on 14

Table 1 Forecast trajectories crossing the Tulsa region during the 1998/1999 pollination season; release date and site indicate source area. Travel hours represents time for the trajectory to pass into and out of the Tulsa region using trajectories calculated at 1100 hours CST. *Ar* Arbuckle Mountains, Oklahoma; *Au* Austin, Texas; *Ju* Junction, Texas; *Sa* San Angelo, Texas

Tulsa arrival		Release date	Site	Release conditions	Threat	Travel time (h)
Date	Time (hour, CST)					
17/12/98	2000	17/12/98	Ar	Favorable	Severe	9–11
17/12/98	1900	17/12/98	Au	Favorable	Severe	8–9
18/12/98	1400	18/12/98	Ar	Unfavorable	Low	3–7
26/12/98	1800	25/12/98	Ar	Unfavorable	Low	19–29
27/12/98	1500	26/12/98	Ju	Mixed	Low	28–35
30/12/98	2300	29/12/98	Sa	Favorable	Severe	36–40
30/12/98	1500	30/12/98	Ar	Unfavorable	Low	4–9
6/1/99	1100	4/1/99	Au	Unfavorable	Low	48
5/1/99	1500	5/1/99	Ar	Favorable	Moderate	4–10
11/1/99	0300	9/1/99	Ar	Unfavorable	Low	40–48
11/1/99	0200	10/1/99	Ar	Unfavorable	Low	15–22
11/1/99	1100	10/1/99	Ju	Favorable	Severe	24–25
11/1/99	0600	10/1/99	Sa	Favorable	Severe	29–30
11/1/99	1500	11/1/99	Ar	Favorable	Moderate	4–6
12/1/99	1400	12/1/99	Ar	Favorable	Severe	3–6
12/1/99	1500	12/1/99	Au	Favorable	Severe	4–8
15/1/99	1500	15/1/99	Ar	Favorable	Severe	4–8
17/1/99	0900	15/1/99	Au	Favorable	Severe	46–48
18/1/99	2200	18/1/99	Ar	Favorable	Severe	11–16
19/1/99	1400	18/1/99	Ju	Favorable	Severe	27–32
19/1/99	1600	18/1/99	Sa	Favorable	Severe	29–33
19/1/99	1700	19/1/99	Ar	Favorable	Severe	6
20/1/99	0500	18/1/99	Ar	Favorable	Severe	42–48
20/1/99	1800	20/1/99	Ar	Favorable	Severe	7–8
22/1/99	0300	20/1/99	Au	Favorable	Severe	40

Table 2 Date, time and pollen concentration, sampler location of trajectory crossing the area, trajectory release time, release conditions and forecast threat of pollen deposition in Tulsa, Oklahoma, during 1998/1999. *Italicized and Bold values are high and very high concentrations respectively. Where multiple trajec-*

tories crossed Tulsa, each pathway is listed separately. Ar Arbuckle Mountains, Oklahoma; *Au* Austin, Texas; *Ju* Junction, Texas; *Sa* San Angelo, Texas. Threat to downwind communities: *L* low, *M* moderate, *S* severe. Release conditions: *U* unfavorable, *M* mixed, *F* favorable

Date	Peak time and pollen conc. (grains/m ³)						Site	Release date	Release conditions	Threat
	Tulsa	Bixby	Hectorville							
17/12	2400	7	2400	<i>130</i>	2400	<i>138</i>	Au	17/12	F	S
18/12	0200	225	0200	<i>370</i>	0400	<i>312</i>	Au	17/12	F	S
6/1	0600–0800	<i>145</i>	0200	14	0200	12	Ar	5/1	F	S
11/1	2400	<i>630</i>	2400	<i>580</i>	2400	<i>616</i>	Ar	9/1	U	L
							Ar	10/1	U	L
							Ar	11/1	F	M
							Ju	10/1	F	S
							Sa	10/1	F	S
12/1	2000	1,920	1600	2,573	1800	3,681	Ar	12/1	F	S
							Au	12/1	F	S
15/1	2400	87	2400	<i>174</i>	2400	<i>196</i>	Ar	15/1	F	S
16/1	0200	<i>384</i>	1600	<i>232</i>	1800	<i>319</i>				
19/1	1400	<i>181</i>	0800	<i>109</i>	1400	<i>123</i>	Ar	18/1	F	S
							Ju	18/1	F	S
							Sa	18/1	F	S
							Ar	19/1	F	S
20/1	1800	326	2000	<i>449</i>	1800	<i>210</i>	Ar	18/1	F	S
21/1	1000	<i>406</i>	1000	<i>217</i>	2400	<i>355</i>	Au	20/1	F	S
27/1	0200	<i>319</i>	1600	<i>188</i>	1600	<i>116</i>				

different days. As in the previous year, the majority of incursions, 11 days (55%), were from the Arbuckle Mountains (Table 3). Most of the trajectories show pollen traveling quickly, arriving within 12 h of release in 8 cases. The Texas sites contributed 5 (25%) from Austin and 2 (10%) each from Junction and San Angelo. Pollen

entrained in the majority of the southern trajectories took between 13 h and 24 h to arrive over the Tulsa region. Of the 11 trajectories from the Arbuckle Mountains, 3 were forecast as unfavorable conditions for release and a low threat of downwind dispersal to northeastern Oklahoma. Of the 5 trajectories from Austin, 2 were forecast as

Table 3 Forecast trajectories crossing the Tulsa region during 1999/2000. Explanation follows Table 2. *Ar* Arbuckle Mountains, Oklahoma; *Au* Austin, Texas; *Ju* Junction, Texas; *Sa* San Angelo, Texas

Tulsa arrival		Release date	Site	Release conditions	Threat	Travel time (h)
Date	Time (hour)					
29/12/99	1800	29/12/99	Ar	Favorable	Severe	7–8
2/1/00	0700	1/1/00	Ju	Favorable	Severe	20–24
2/1/00	0800	1/1/00	Sa	Favorable	Severe	21–26
2/1/00	1800	2/1/00	Ar	Unfavorable	Low	7–15
3/1/00	1500	2/1/00	Ar	Unfavorable	Low	28–29
3/1/00	0700	2/1/00	Au	Mixed	Moderate	20
5/1/00	1200	4/1/00	Ar	Unfavorable	Low	25–27
6/1/00	0200	5/1/00	Au	Favorable	Moderate	15–17
8/1/00	1100	6/1/00	Au	Unfavorable	Low	48
8/1/00	1000	7/1/00	Au	Unfavorable	Low	33–35
9/1/00	1500	9/1/00	Ar	Favorable	Moderate	4–5
10/1/00	1900	10/1/00	Ar	Favorable	Severe	8–9
11/1/00	1900	10/1/00	Ar	Favorable	Severe	32–34
12/1/00	1500	12/1/00	Ar	Favorable	Severe	4
15/1/00	1400	15/1/00	Ar	Mixed	Moderate	3–6
16/1/00	2000	16/1/00	Ar	Mixed	Moderate	9
17/1/00	0800	16/1/00	Ju	Mixed	Moderate	21
17/1/00	0700	16/1/00	Sa	Mixed	Moderate	20–21
17/1/00	1800	17/1/00	Ar	Mixed	Moderate	7
22/1/00	0300	20/1/00	Au	Favorable	Severe	40

Table 4 Date, time and concentration, sampler location of trajectory crossing the area, trajectory release time, release conditions and forecast threat of pollen deposition in Tulsa Oklahoma for 1999/2000. Descriptions follow Table 2. *Ar* Arbuckle Mountains,

Oklahoma; *Au* Austin, Texas; *Ju* Junction, Texas; *Sa* San Angelo, Texas. *S* severe, *L* low, *M* moderate; *F* favorable, *U* unfavourable, *M* mixed

Date 1999/2000	Peak time (hour) and pollen conc. (grains/m ³)						Release site	Date	Conditions	Threat
	Tulsa		Bixby		Hectorville					
2/1	0400	652	0200	645	0400	449	Ju	1/1	F	S
							Sa	1/1	F	S
							Ar	2/1	U	L
12/1	1000	790	1400	442	0800	1,044	Ar	12/1	F	S
15/1	2400	1,029	2400	348	2400	812	Ar	15/1	F	S
16/1	1000	4,333	1000	3,659	1000	2,065	Ar	15/1	F	S
							Ar	16/1	M	M
17/1	1000	268	1000	290	0600	246	Ju	16/1	M	M
							Sa	16/1	M	M
							Ar	17/1	M	M
22/1	1000	391	1600	232	1400	232	Au	20/1	F	S

unfavorable release conditions with a low threat for deposition in northeastern Oklahoma. Forecast for all other sites indicated mixed to favorable conditions for release with, moderate to severe threats of pollen entrainment, travel, and deposition to the north (Table 3).

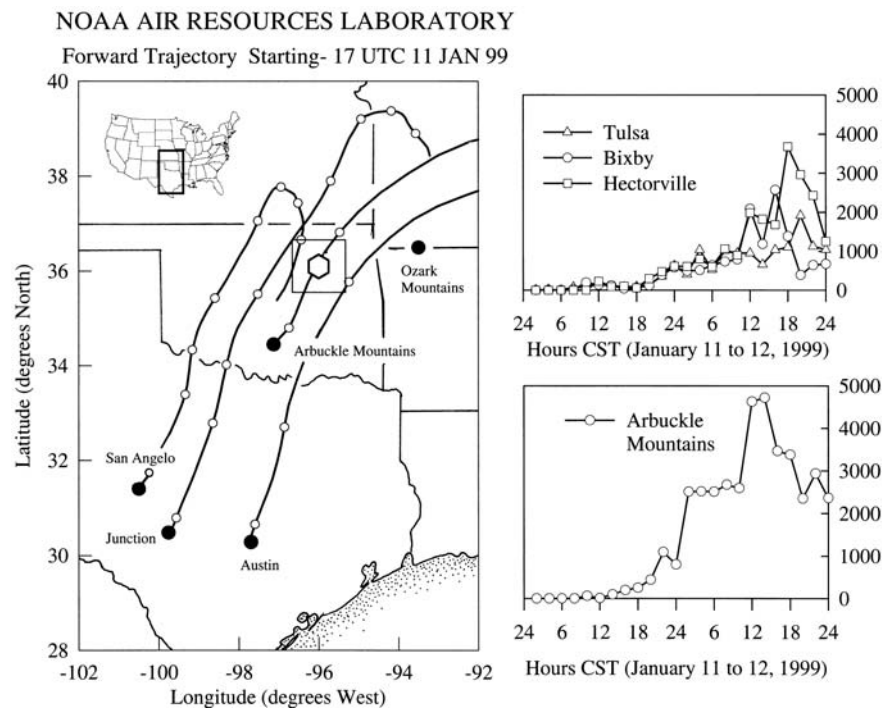
Analysis of the Tulsa region aerobiological samplers for 1999/2000 registered high and very high pollen concentrations on 6 days during the pollination season (Table 4). Trajectories from the source areas were identified for all influx events during the season. Significant pollen concentrations, high and very high, were associated with 5 trajectories from the Arbuckle Mountains, 2 each from Junction and San Angelo, and 1 from Austin. Release conditions were forecast as mixed or favorable and the threat to downwind communities moderate to severe in all but a single case, i.e. the Arbuckle Mountains on 2 January 2000 (Table 4). Note that mixed forecast release conditions and a moderate

threat of dispersal occurred later in the pollen season after 15 January as the number of pollen cones ready for dissemination from source areas began to be reduced.

A successful forecast description

To illustrate a successful forecast of pollen deposition in the Tulsa region, the event of 11 and 12 January 1999 is described in detail (Fig. 1). Weather conditions throughout the southern Great Plains were generally warm and pollen release was favorable in Texas, but in southern Oklahoma colder weather initially resulted in unfavorable release conditions (Tables 1, 2). On 11 January 1999, an approaching cold front began to draw pollen-laden air to the north and east with increasingly strong winds from the south. The forecast for 11 and 12 January noted a serious threat of dispersal throughout northern Texas and eastern

Fig. 1 Air-mass trajectories for five source locations for 11 January 1999 along with aerobiological records for the Tulsa region and Arbuckle Mountains. The box surrounding Tulsa (black hexagon) defines the Tulsa region. White circles along each trajectory mark a 6-h period starting at noon (CST), 1 h after trajectory initiation (1100 hours CST)



Oklahoma from sources in central Texas. Pollen sources from the Arbuckle Mountains were forecast to present a moderate threat on 11 January then a serious threat by 12 January.

Significant concentrations of *J. ashei* pollen were deposited throughout the Tulsa region (Fig. 1, Table 2). The Tulsa aerobiological records show concentrations beginning to rise on 11 January, and then peak during midday. Pollen levels decreased in the afternoon, but returned to high concentrations by approximately 2000 hours that evening. Elevated levels continued into 12 January with higher concentrations registered at areas south of the University of Tulsa site at Bixby and Hectorville. Very high concentrations were achieved during the afternoon and evening hours of 12 January. A cold front passed over northeastern Oklahoma during the late evening and early morning of 12 and 13 January, shifting winds from the south to the northwest. Across the Tulsa region, pollen concentrations fell rapidly during the morning of 13 January passing from moderate to low levels, where they remained for the rest of the day.

The 11 January trajectory from the Arbuckle Mountains shows the air mass moving quickly to the north-northeast over the Tulsa region (Fig. 1). By 1800 hours, pollen entrained at 1100 hours CST in southern Oklahoma was positioned along the Oklahoma-Kansas border. Assuming pollination and entrainment at the source only occurs during daylight hours and taking the distance to the Tulsa region into account, this suggests that pollen from the Arbuckle Mountains passed over the Tulsa region from 1500 hours on 11 January to 0100 hours on 12 January. The air masses continued to track north-northeast, passing out of northeastern Oklahoma. Pollen

registration from the Arbuckle Mountains in the Tulsa region, however, is ambiguous because of the source's position along the flight path of air masses moving north from the larger southern source areas (Van de Water and Levetin 2001). For example, wind trajectories emanating from the Arbuckle Mountains on 12 January correlate with the influx of high and very high pollen concentrations in the Tulsa region (Fig. 1). Analysis of the Arbuckle Mountains pollen registrations, however, shows very high concentrations beginning after midnight on 12 January, at a time when local pollination should be minimal. This suggests a significant concentration of pollen moved north from the more southern source areas. Pollen influx to the Arbuckle Mountains from Texas is a common occurrence during the *J. ashei* pollination season (Van de Water and Levetin 2001).

Air-mass trajectories from the three Texas source areas also track over Oklahoma during this period. The trajectory from Austin moved rapidly with the regional flow to the north and east. The trajectory barely crossed the southeastern tip of the Tulsa region (Fig. 1). Strong winds moved the air mass rapidly, within 4–8 h, from Austin over the Tulsa region. To the west, the Junction trajectory followed a trend towards the north and east similar to the direction of the Austin trajectory, but passing west of the Arbuckle Mountains and crossing the northwest corner of the Tulsa region. Northerly wind velocities decreased from the east to west in central Texas, therefore the 1100 hours air mass from Junction took 24–25 h compared to the 4–8 h that it took from Austin. The two trajectory pathways, however, bracket the Tulsa region when they arrive over the area (Fig. 1). This suggests that the *J. ashei* population growing

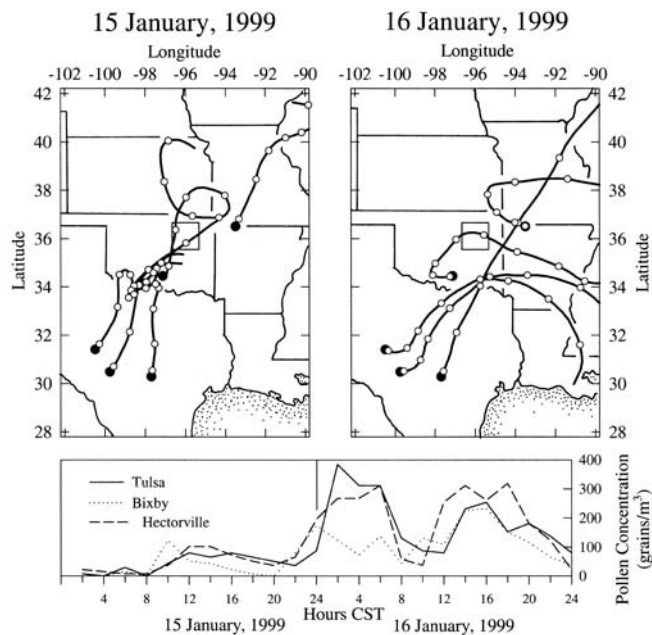


Fig. 2 Air-mass trajectories from the five source sites in relation to the Tulsa region and *J. ashei* registrations in the Tulsa region on 15 and 16 January 1999

between Austin and Junction contributed significantly to the down-wind pollen concentrations. In fact, the east-to-west wind-velocity gradient across central Texas should have resulted in the entrained pollen cloud shearing towards the east as it moved northward. Higher pollen concentrations registered at the aerobiological samplers from the southern portion of the Tulsa region (Bixby and at Hectorville) may correlate with the greater wind velocity, increased turbulence and a greater capacity to keep pollen aloft during travel that would typify stronger wind conditions. Trajectories from San Angelo parallel those from Junction, but travel further to the west, then turn southward ahead of the cold front, and enter the Tulsa region on 13 January. Low atmospheric pollen concentrations throughout the Tulsa region on 13 January indicate that the air mass deposited entrained pollen as it passed southward into Oklahoma.

The 11 and 12 January forecast thus successfully predicted favorable conditions for pollen release within the source populations and signaled a serious threat of long-distance transport into the northeast Oklahoma area. Forecast accuracy was confirmed through the detection of high and very high pollen concentrations at all three Tulsa samplers. Analysis of the air-mass trajectories suggests that the sources of the pollen recorded in Tulsa were the Arbuckle Mountains and the area between Austin and Junction, Texas (Table 2).

An unsuccessful forecast and potential sources of an error

The Tulsa region aerobiological samplers registered high and very high pollen concentrations from the morning of

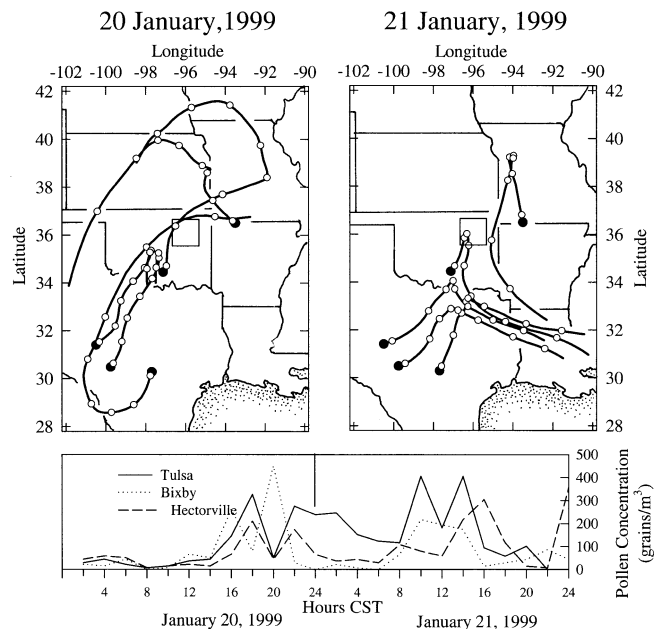


Fig. 3 Air-mass trajectories from the five source sites in relation to the Tulsa region and *J. ashei* registrations in the Tulsa region on 20 and 21 January 1999

15 January until after midnight on 16 January (Fig. 2). Analysis of the air mass trajectories during this period shows that winds from the Arbuckle Mountains crossed the Tulsa region on 15 and 17 January, but that no forecast trajectory crossed the area during the elevated pollen concentrations of 16 January. Peak pollen concentrations on 15 January were recorded at midnight at each sampler; levels continued to build during the morning and again after noon and into the evening of 16 January.

On 15 January, wind trajectories from Austin, Junction, and San Angelo all converged over southern Oklahoma. Release conditions in these areas were all favorable and presented a severe threat along their travel path. These conditions probably resulted in a substantial pool of entrained pollen building in the atmosphere over southern Oklahoma. The trajectories for the southern sites did not continue north over the Tulsa region, but a general south-to-north flow in the Arbuckle Mountain trajectory probably brought these heightened pollen concentrations to the Tulsa region resulting in the high registrations on 16 January. This example shows the difficulty in determining the actual contribution of pollen to the atmosphere, the complexity of forecasting these movements, as well as the interplay of a changing three-dimensional atmosphere.

One possible source of error results from the use of single trajectories to predict air movement throughout the day. This was especially clear during 20 and 21 January 1999, when concentrations at the three aerobiological samplers showed significantly different values during a portion of an influx event (Fig. 3). Pollen concentrations rose after noon on 20 January to high concentrations until just before midnight. Analysis of the air trajectories

shows that the Arbuckle Mountain pathway passed over the northwest corner of the Tulsa region. As occurred on 15 January, the air masses from the southern sites stalled in south-central Oklahoma. The aerobiological record shows that high concentrations were maintained throughout the evening and early morning at the Tulsa site, but much lower readings occurred in Bixby and Hectorville. If the 1100 hours trajectory from the Arbuckle Mountains continued to flow northward, as suggested by the 21 January pathway, then pollen in the atmosphere in south-central Oklahoma may have moved over the western side of the Tulsa region. This could account for the differentiation of pollen registration. However, with only a single trajectory plotted, the ultimate movement of entrained pollen is uncertain.

Finally another source of error in the forecasting system results from inherent variability in the HYPLIT model. Each modeled air-mass trajectory is estimated to vary in position by 10% to 20% of the source distance after 24 h (Draxler 1991, 1996). Therefore the width of the Tulsa area is generally perpendicular to most air-mass flight paths and was defined as 120 km or 20% of the distance to the Texas sites (600 km). The majority of the trajectories that crossed the Tulsa region show travel times of 25–36 h from release at the southern source sites. Therefore the potential exists for trajectories that cross into the Tulsa region to be, in reality, outside the area shown on the calculated trajectories.

Over two forecasting seasons the threat of long-distance transport into Tulsa was still accurately predicted. Timing is also important to keep pollen entrained. Analysis of pollen deposition in the Arbuckle Mountains shows that significant concentrations are greatly diminished after the first 24-h travel period (Van de Water and Levetin 2001). However, a limited number of Cupressaceae pollen grains have been identified along air-mass trajectory pathways at significant distances. For example, juniper pollen has been identified during the winter as far away as southern Canada (James Anderson, unpublished data) and can be correlated to air-mass trajectories initiated over central Texas days earlier.

Conclusions

Analysis of 2 years of forecasting pollen dispersal shows success in the determination of the conditions leading to release and prediction of the downwind air-mass pathways. Uncertainties inherent to the forecasting procedure continue to be studied. Forecast improvement relies upon a better understanding of pollination phenology within the populations, as well as the behavior of pollen within the atmosphere during entrainment and travel. These factors of uncertainty are present in the forecasting process and warrant additional study. The ability to provide accurate forecasts of the dispersal of this highly allergenic particle will prove useful in the alleviation of potentially serious medical conditions.

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References

- Adams RP (1975) Gene flow versus selection pressure and ancestral differentiation in the composition of species. Analysis of populational variation of *Juniperus ashei* Buch. using terpenoid data. *J Mol Evol* 5:177–185
- Borchert JR (1950) The climate of the central North American grassland. *Ann Assoc Am Geogr* 40:1–39
- Cabezudo B, Recio M, Sánchez-Laulhé JM, Del Mar Trigo M, Toro FJ, Polvorinos F (1997) Atmospheric transportation of marihuana pollen from north Africa to the southwest of Europe. *Atmos Environ* 31:3323–3328
- Davis JM, Main CE (1984) A regional analysis of the meteorological aspects of the spread and development of blue mold on tobacco. *Boundary-Layer Meteorol* 28:271–304
- Davis JM, Main CE (1986) Applying atmospheric trajectory analysis to problems in epidemiology. *Plant Dis* 70:490–497
- Draxler RR (1991) The accuracy of trajectories during ANATEX calculated using dynamic model analyses versus rawinsonde observations. *J Appl Meteorol* 30:1446–1467
- Draxler RR (1996) Boundary layer isentropic and kinematic trajectories during the August 1993 North Atlantic Regional Experiment Intensive. *J Geophys Res* 101:29,255–29,268
- Faegri K, Iversen J, Krzywinski K (1989) Textbook of pollen analysis. Wiley, Toronto, p 328
- Gregory PH (1961) The microbiology of the atmosphere. Interscience, New York, p 251
- Hidalgo PL, Galán C, Domínguez E (1999) Pollen production of the genus *Cupressus*. *Grana* 38:296–300
- Hjelmroos M (1991) Evidence of long-distance transport of *Betula* pollen. *Grana* 30:215–228
- Levetin E (1998) A long-term study of winter and early spring tree pollen in the Tulsa, Oklahoma atmosphere. *Aerobiologia* 14:21–28
- Levetin E, Buck P (1986) Evidence of mountain cedar pollen in Tulsa. *Ann Allergy* 56:295–299
- Little EL Jr (1971) Atlas of United States trees, vol 1. Conifers and important hardwoods. U.S. Department of Agriculture Miscellaneous Publications, Washington DC, p 1146
- Main CE, Davis JM (1989) Epidemiology and biometeorology of tobacco blue mold. In: McKean WE (ed) Blue mold of tobacco APS, St Paul, Minn, p 196
- Mandrioli P, Negrini MG, Scarani C, Tampieri F, Trombetti F (1980) Mesoscale transport of *Corylus* pollen grains in winter atmosphere. *Grana* 19:227–233
- Mandrioli P, Negrini MG, Cesari G, Morgan G (1984) Evidence for long range transport of biological and anthropogenic aerosol particles in the atmosphere. *Grana* 24:43–53
- Nilson S, Pragłowski J (1992) Erdtman's handbook of palynology. Munksgaard, Copenhagen, p 580
- Rogers CA, Levetin E (1998) Evidence of long-distance transport of mountain cedar pollen into Tulsa, Oklahoma. *Int J Biometeorol* 42:65–72
- Van Auken OW (1993) Woody vegetation of the southeastern escarpment and plateau. In: Amos BB, Gehlbach FR (eds)

- Edwards Plateau vegetation: plant ecological studies in central Texas. Baylor University Press, Waco, Texas, pp 43–55
- Van de Water PK, Levetin E (2001) The contribution of upwind pollen sources to the characterization of *Juniperus ashei* phenology. *Grana* 40:133–141
- Wallin JE, Segerström U, Rosenhall L, Bergmann E, Hjelmroos M (1991) Allergic symptoms caused by long-distance transported birch pollen. *Grana* 30:265–268
- Yao C, Arya SP, Davis JM, Main CE (1997) A numerical model of the transport and diffusion of *Peronospora tabacina* spores in the evolving atmospheric boundary layer. *Atmos Environ* 31:1709–1714