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Pollen count forecasting

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Since the late 19th century, air sampling has been used to determine the bioaerosol composition of the atmosphere [1–3], and for many years allergists have used the data generated from air sampling to aid in the diagnosis and treatment of patients. Air sampling provides information on what was in the air over a period of time, typically the previous 24 hours. When daily samples are collected for several years, the data can be used to generate a pollen calendar for a specific geographic area. With this information, allergists and patients have a reasonably good idea of when specific allergens can be expected. Pollen calendars cannot predict the severity of the pollen season, exactly when the pollen season will start, how weather conditions will affect pollen release on a specific day, or if regional or long-distance sources contribute to the local pollen record. Investigators have attempted to make the shift from descriptive aerobiology to predictive aerobiology by producing pollen forecasts. A pollen forecast is a prediction of the anticipated atmospheric pollen concentration over a short or long period of time. Accurate forecasts help physicians develop treatment plans for their patients and enable sensitive individuals to avoid exposure to high pollen levels or prompt them to take prophylactic medication. Forecasts also can help the medical community to plan clinical trials and help the healthcare industry in marketing and stocking pharmaceutical products [4]. This article provides information on the status of pollen forecasting efforts.

Forecasting requires knowledge of the aerobiology along with meteorology, plant phenology, and plant ecology. For a particular pollen type, the aerobiologic data from several years are needed to determine the variations possible in seasonal pollen characteristics, such as the earliest and latest start dates, end dates, peak periods, and cumulative season pollen totals. The characteristics for oak pollen and ragweed pollen seasons in Tulsa, Oklahoma, are shown (Tables 1,2). Once

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Table 1
Characteristics of *Quercus* (oak) pollen season

Year	Start[a] date	End[b] date	Season length (d)	Peak level (pollen grains/m^3)	Date of peak	Average daily level (pollen grains/m^3)	Cumulative season total
1987	Mar 16	Apr 18	34	186	Mar 23	39	1312
1988	Apr 2	Apr 23	22	903	Apr 8	316	6954
1989	Apr 2	Apr 22	21	723	Apr 16	231	4849
1990	Mar 31	May 4	35	525	Apr 22	88	3088
1991	Mar 31	Apr 15	16	1420	Apr 5	554	8862
1992	Mar 8	Apr 25	49	257	Apr 9	45	2190
1993	Apr 12	Apr 30	19	1477	Apr 18	474	9003
1994	Mar 23	Apr 19	28	1045	Apr 1	273	7656
1995	Mar 26	Apr 16	22	604	Apr 9	207	4554
1996	Apr 12	Apr 28	17	2225	Apr 20	604	10,271
1997	Mar 24	Apr 28	35	1903	Mar 31	445	15,580
1998	Apr 2	Apr 24	23	2490	Apr 11	707	16,251
1999	Apr 1	Apr 30	30	2312	Apr 7	617	18,518
2000	Mar 23	Apr 23	32	1008	Apr 7	421	13,476

[a] Date of 5% of cumulative season total.

[b] Date of 95% of cumulative season total.

pollen release has begun, airborne pollen concentrations typically show a Gaussian distribution, although day-to-day meteorologic factors can influence release. Daily pollen concentrations for a single year reflect the influence of weather (Fig. 1A); however, averaging the daily pollen concentrations for several years typically shows a smoother seasonal pattern (Fig. 1B). A 3- or 5-day running

Table 2
Characteristics of *Ambrosia* (ragweed) pollen season

Year	Start[a] date	End[b] date	Season length (d)	Peak level (pollen grains/m^3)	Date of peak	Mean daily level (pollen grains/m^3)	Cumulative season total
1987	Aug 30	Oct 8	40	2332	Sep 8	295	23,028
1988	Aug 28	Oct 13	47	1129	Sep 12	216	16,835
1989	Aug 27	Oct 13	48	1318	Sep 9	214	16,729
1990	Aug 26	Oct 13	49	980	Sep 27	193	15,060
1991	Aug 28	Oct 16	50	840	Sep 11	163	12,741
1992	Aug 24	Oct 12	50	1079	Sep 6	272	21,244
1993	Sep 2	Oct 5	34	1521	Sep 14	206	16,082
1994	Aug 22	Oct 5	45	724	Sep 6	154	10,295
1995	Aug 30	Oct 20	52	663	Sep 13	137	10,720
1996	Aug 30	Oct 13	45	712	Sep 12	93	7005
1997	Aug 29	Oct 3	36	937	Sep 7	196	15,298
1998	Aug 28	Oct 10	44	542	Sep 7	97	7594
1999	Aug 31	Oct 16	47	623	Sep 8	119	9338
2000	Aug 19	Oct 10	52	498	Sep 20	92	7297

[a] Date of 5% of cumulative season total.

[b] Date of 95% of cumulative season total.

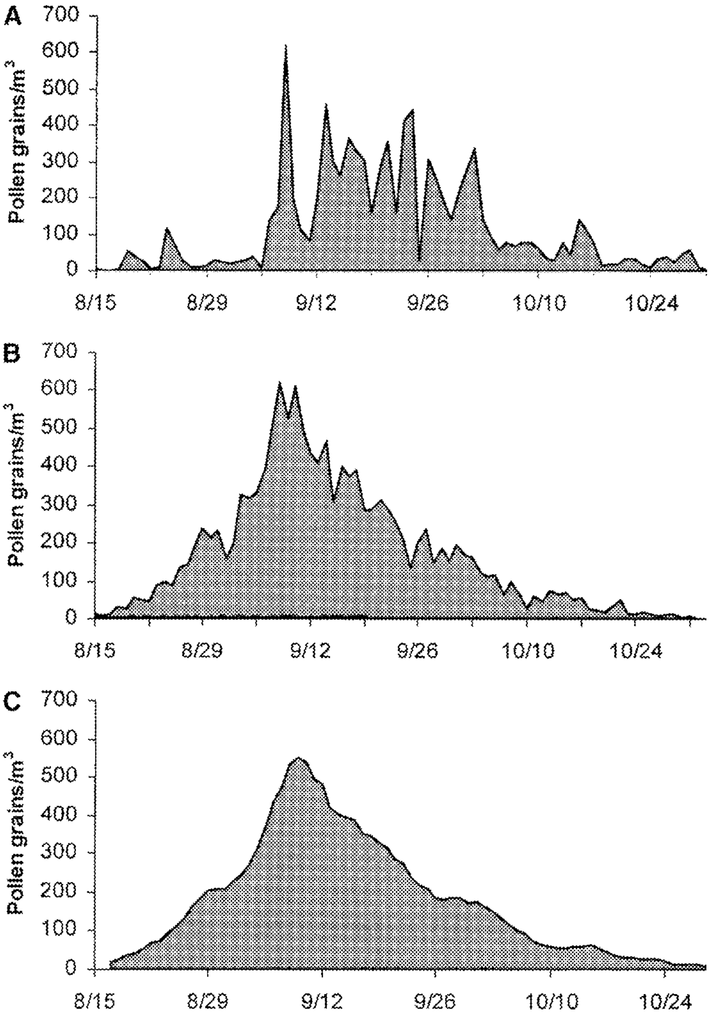


Fig. 1. Daily *Ambrosia* (ragweed) pollen levels in the atmosphere of Tulsa, Oklahoma, showing data from a single year (1999; *A*), daily averages from 14 seasons (1987–2000; *B*), and 5-day running means from 14 seasons (1987–2000; *C*).

mean also can produce a smoother curve (Fig. 1C). Rogers and other investigators have suggested that aligning the peaks for each year develops a better approximation of the average seasonal pollen release [5].

Plant phenology is the study of seasonal plant cycles and their connection to environmental variables [6]. The flowering of many trees in the spring is regulated by temperature, whereas the photoperiod determines the flowering of many weeds in late summer. As a result, start dates of the spring tree season show greater variability than those for the fall weed season. From 1987 to 2000, the mean start date for the oak pollen season in Tulsa, Oklahoma, (defined as the day when the pollen level reached 5% of the cumulative season total) is March 28; however, there was a 35-day range in start date from March 8 to April 12 (see Table 1). The ragweed pollen season showed only a 14-day range from August 19 until September 2, with the mean start date of August 27. In 9 of these years, the ragweed season began between August 27 and August 31 (see Table 2). Ecologic literature and plant distribution maps can provide information on the occurrence of specific allergy plants in a local geographic area [7]. In many areas, however, long-distant transport can introduce other allergenic pollen types when winds are favorable [8–11]. Knowledge of upwind sources is also important.

Types of pollen forecasts

Pollen forecasting can have various objectives relative to time (eg, short-term, seasonal, or long-term forecasts). Short-term forecasts address day-to-day changes of pollen levels. During the main pollen season, these changes largely are governed by daily meteorologic conditions and need to be updated daily or every few days. Correlation of daily (and hourly, if available) pollen concentrations from previous years with archived meteorologic data can generate the meteorologic parameters needed for optimum pollen release. These factors, along with knowledge of the seasonal pollen characteristics, are the starting points for daily pollen forecasts.

Seasonal forecasts address characteristics of the pollen season, such as start date, pollen season severity (seasonal totals), and peak levels [12]. These characteristics are governed by phenology and preseason climate, although day-to-day weather during the pollen season may alter the seasonal potential. For trees that flower in the spring, a low-temperature period of dormancy is necessary before bud maturation [13]. For some species, several hundred hours of low temperature may be required before this dormancy is broken [14]. In addition to the cold requirement, completion of reproductive development occurs in response to warming temperatures above a threshold value [6]. For many spring-flowering trees, the severity and duration of the winter control the timing of the spring pollen season [15]. Because of differences in temperature, the flowering for a certain species in a given area may vary significantly from year to year. To forecast the beginning of the pollen season, it is necessary to know when the chilling requirement has been satisfied and when sufficient heat units have been accumulated. The chilling and heat-unit requirements have been determined for many taxa, and several forecast models predict the pollen-season start date based on these factors [13,14,16–20]. The pollen season severity also may be influenced by climatic conditions from the previous year when flower buds are initiated [13,21–23].

Long-term forecasts address possible trends in seasonal pollen levels caused by global climate change. They generally require an aerobiology database for many years in a given area. Several studies have shown earlier start dates for various types of tree pollen during the past 10 to 20 years; even earlier dates have been projected for dates in the future. Although several researchers have suggested that global warming will continue the trend of early flowering, Partenen and colleagues pointed out that a photoperiod requirement is necessary for many plants, and this factor may offset the temperature cues and prevent premature onset of growth [24].

Examples of pollen forecasting

Forecasting models have been developed for various hay fever plants by researchers around the world. Although some models date back to the 1970s, most have been developed within the past decade as pollen databases have increased and archived meteorologic data have become more widely available. The development of the Internet has expanded the usefulness of these forecasts. This article is limited to a select group of examples and is focused on the authors' forecasting efforts for the mountain cedar pollen season in the southern Great Plains.

Grass pollen forecasts

Pollen from the family Poaceae is a significant cause of allergic rhinitis in North America, Europe, and Australia [4,25–27]. Norris-Hill used various models for predicting daily grass pollen concentrations in London [25]. The model that explained the greatest amount of variance used accumulated average temperature combined with maximum temperature, relative humidity, and rainfall. This model was 71% accurate in predicting the 1991 grass pollen season. Schäppi and co-workers developed a model to estimate daily grass pollen concentrations in Melbourne, Australia [26]. They found that the average daily pollen concentration was correlated significantly ($r = 0.69$; $P<0.001$) to the average daily temperature. Rainfall and northerly winds were also important variables that affected pollen levels; however, these parameters were autocorrelated with temperature in that region of Australia. Temperature could be used as the sole meteorologic parameter for their forecasting model. They also determined that the severity of the grass pollen season was correlated significantly with the cumulative rainfall from the previous year. They concluded that their model can be useful for the prediction of potential rhinitis symptoms during the grass pollen season in Melbourne.

The longest continuous databases for airborne pollen concentrations are found in the United Kingdom, extending back to 1954 in Cardiff (Wales), 1961 in London, and 1969 in Derby (central England). Using these databases, Emberlin et al developed models for forecasting the severity of the grass pollen season at these sites [4]. The models were developed through multiple regression analysis using preseason temperature and rainfall variables. They made use of 10-day aggregates of meteorologic data; however, different preseason aggregates were the significant variables for the season severity at the three cities. Overall, these models explained approximately 95% of the variability in cumulative season grass pollen levels, suggesting that they may be useful predictors of season severity.

Birch pollen forecasts

In northern Europe, *Betula* pollen is the leading aeroallergen, and in other areas of Europe, this pollen is second to grass pollen as the most important cause of allergic rhinitis. Much attention has been focused on forecasting the birch pollen season because of its year-to-year variability [17]. Laadi reported that the start date for the *Betula* pollen season varied as much as 25 days for a given location in France [17], and Clot reported a 28-day difference in start date in Neuchâtel, Switzerland [16]. Emberlin and colleagues summarized the *Betula* start dates for six European cities, covering 18 to 30 years [28]. Year-to-year variation ranged from 31 days in London to 72 days in Kevo, Finland. Investigators have reported differences in the start dates at different sites within the same region of the country [17,29]. Forecasting models have shown that preseason temperatures can be used to predict the season start date. Clot found that a cumulated temperature threshold of 270°C was necessary for *Betula* pollen release in Neuchâtel [16]. This threshold was reached by cumulating the average daily temperature starting on February 1. Once the threshold was reached, pollen release occurred whenever the temperature was above 10°C. Laadi used a similar model to predict season start date at various sites in France with a maximum error of 2 days [17]. He found that the temperature summation method provided more accurate predictions of season start date than a multiple regression model that used late fall and winter temperatures. Adams-Groom and co-workers used multiple regression models to predict birch season start dates at three sites in the United Kingdom [30]. The models used 10-day aggregates of preseason temperature and precipitation data and showed good correlation between predicted and actual start dates.

Birch pollen has been the focus of several studies of long-term changes in the pollen season start caused by global climate change. Clot showed that currently the birch pollen season starts 19 days earlier than it did in the 1980s in Neuchâtel, Switzerland [16]. Emberlin et al reported on the trends of birch pollen season start dates in six European cities over this same time period [28]. Four of the cities, London, Brussels, Zurich, and Vienna, showed clear trends toward earlier start dates, ranging up to 30 days earlier. Regression models suggest that start dates will continue to be earlier over the next 10 years, advancing by about 6 days if current temperature trends continue.

Dahl and Strandhede reported on significant differences in cumulative *Betula* pollen levels from year to year [21]. They showed that the most important factors for determining the seasonal pollen levels are temperatures during the spring and summer of the previous year and the cumulative pollen level during the previous year. In birch trees, the initiation of male catkins (pollen-bearing inflorescences or flower clusters) takes place 1 year before flowering. By early summer, male catkins are visible, and by autumn, the catkins are developed fully but are still short. The following spring, catkins elongate greatly; pollen grains complete their development and are released from the anthers. When catkins are elongating, considerable nutrient resources are used. If there are abundant catkins, the resources needed for elongation may draw from the resources needed for leaf development, shoot elongation, and the initiation of new catkins. As a result, the tree will have few catkins the following year. This change often results in oscillations in flowering abundance and pollen production and release. Whether a year with moderately good (but not abundant) flowering and pollen production can be followed by another good year is dependent on whether spring and summer meteorologic conditions are favorable. The regression model developed by Dahl and Strandhede for birch pollen season severity in Sweden used temperature sums from May 1 to July 20 of the previous year, the cumulative pollen level of the previous year, and temperature for current flowering season [21]. The model explained about 80% of the variance in annual birch pollen levels. The authors suggested that for practical use, the temperature sum and pollen level from the previous year are sufficient variables for the regression equation, enabling prediction of seasonal pollen severity well ahead of the season. Taira et al reported similar patterns in pollen production for *Cryptomeria japonia* (Japanese cedar), in which July temperatures were used as the predictive variable in the regression equation [22], and Fairley and Batchelder found that the amount of winter rainfall in the year before each oak pollen season was the determinate factor for oak pollen productivity [23].

Olive pollen forecasts

Galan and colleagues used regression analysis to predict the cumulative seasonal pollen level (pollen index), peak values, and date of peak for *Olea* (olive) pollen in southwest Spain [31], where sensitivity to olive pollen is one of the most important causes of rhinitis. The meteorologic variables that had the greatest predictive value for pollen index included March rainfall and preseason temperatures. For 1999, their model explained 74% of the variability in the pollen index and showed a less than 10% difference between observed and expected totals. The model was less successful for 2000. The investigators found a significant difference between observed and expected levels, which they suggested was caused by rainfall during the release period. The models for peak value and date of peak value showed significant differences between observed and expected values for both years. Additional years of data may help improve this forecasting model.

Several investigators have shown that preseason temperatures are the most important factors for flowering in olive trees, and several models have been developed for predicting season start date [14,18,19]. Moriondo and co-workers examined preseason temperatures but found that the number of chill events ($<5°C$) in January and February provided a better model for predicting the onset of the *Olea* pollen season [20].

Hidalgo et al published a preliminary report on an automated system for pollen forecasting, including *Olea* pollen [32]. The multinational European Advanced System of Teledetection for Health care Management of Asthma (ASTHMA) is being developed to furnish near real-time information on airborne allergens. This system will use neural network analysis to forecast the start of the *Olea* pollen season, the season severity, and the average daily pollen concentration. Several modules are used in the network: an emission module, a meteorologic module, and a dispersion module. Input data for these modules include topographic data, land-use data, flowering statistics for *Olea*, pollen season characteristics, pollen dispersion and emission factors, and meteorologic data. The system has been tested on archived data and will be used in forecasting mode. Hidalgo and colleagues suggested that the neural network seems to be a good tool for pollen forecasting, but more variables need to be added to enhance the system [32].

Ragweed pollen forecasts

Ragweed pollen is the most important cause of seasonal allergic rhinitis in North America, and various investigators have attempted to forecast ragweed pollen levels since 1970 [33–38]. As indicated earlier, flowering in ragweed is controlled by the photoperiod; ragweed a short-day plant in which flowers start developing as nights become longer. In most areas of North America, ragweed pollinates from August through October. The pollen season is earlier in northern areas and gets progressively later in the southern states [39]. Because the timing of the pollen season is predictable, efforts have focused on attempts to forecast the daily pollen levels and the season severity.

In an early attempt at ragweed forecasting, Raynor and Hayes used the mean pollen concentration curve for the region, the length of time since the start of the pollen season, and weather forecasts for the following day to predict the next day's pollen count [33]. Presence or absence of precipitation and wind direction were the most important meteorologic parameters for their location. Overall, the pollen forecasts achieved an accuracy of 67%, but when the meteorologic forecasts were correct, the pollen forecast accuracy improved to 75%. Farnham et al developed an empirical model for predicting daily counts using daily counts from the previous year, counts from the previous day, rainfall, relative humidity, wind speed, and temperature [35]. Application of this model gave good correlation between forecast predictions and patient symptoms and was 79% accurate at predicting the time of peak levels. These authors also described models produced through multiple regression analyses for three sites in New England. Stark and colleagues used Poisson regression analysis to develop a model for forecasting daily pollen levels [36]. The significant variables for the model included rainfall, wind speed, temperature, and day in season. They used the model and weather forecasts to predict the next day's pollen levels. Using data from Kalamazoo, Michigan, the investigators found that the model's predicted values were close to the observed values. The results improved when the model was used to predict relative pollen levels in categories of low, moderate, or high.

Comtois and co-workers developed a regression model for preseason forecasting of ragweed pollen season severity in Montreal, Canada, and Kansas City, Kansas [34]. Although spring temperature and precipitation were the explanatory variables in both locations, the parameters for these variables differed in the two areas. Studies in Tulsa, Oklahoma, found that summer temperature and precipitation were the significant variables for preseason forecasting of ragweed pollen season severity [40–42].

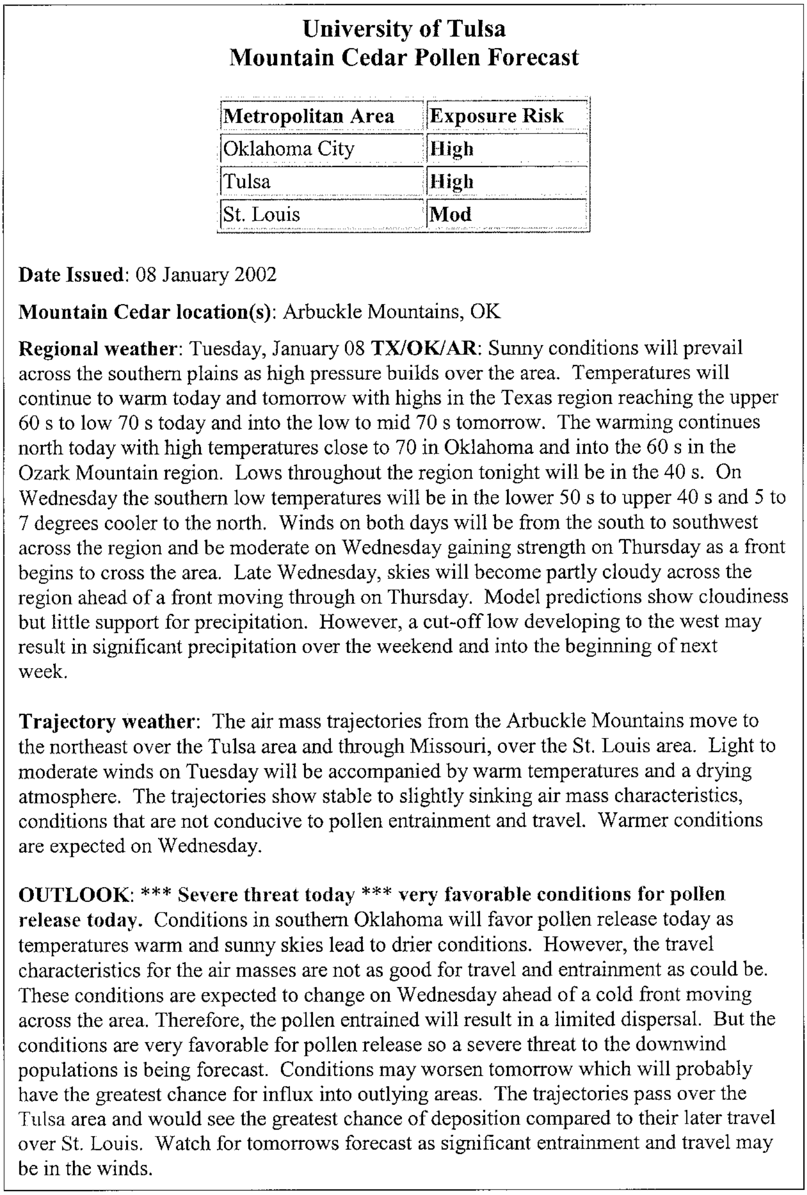
Several investigators have focused on future trends in ragweed pollen production [37,38]. Rising atmospheric CO_2 levels (the cause of global warming) are known to have direct effects on plants, and many species respond by increased growth or increased reproduction. When ragweed plants were grown at elevated CO_2 levels (up to 700 ppm, double the current atmospheric levels), pollen production increased, suggesting greater exposure to ragweed pollen if atmospheric CO_2 levels continue to increase [37,38].

Mountain cedar pollen forecasts

Juniperus ashei (mountain cedar) pollen is highly allergenic and affects a significant portion of patients with allergies in central Texas and other areas of the southern Great Plains. The *J ashei* system is unique, because pollination occurs at a time distinct from most other plants, including other juniper species. The occurrence of Cupressaceae pollen in the atmosphere can be ascribed to known pollinating populations of *J ashei.* Members of the Cupressaceae family, which includes *J ashei*, are prodigious pollen producers. Hidalgo et al reported pollen production in individual trees from 6.4×10^9 to 1×10^{12} pollen grains per year for species in this family; this production breaks down to approximately 400,000 pollen grains per male cone [43,44].

The most extensive population of *J ashei* occurs in the Edwards Plateau region of central Texas along the dissected slopes of Cretaceous limestone. This source area is ringed by and directly affects the urban centers of San Antonio, Austin, Waco, Dallas, and Fort Worth, with a combined population of more than 8.2 million. Outlier populations of *J ashei* can be found 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 southwest Missouri [45,46].

Over the past 4 years, daily dispersal forecasts of *J ashei* pollen have been posted on the Internet (http://pollen.utulsa.edu) during the winter months of December and January. The forecasting process integrates estimates of *J ashei* pollen release, conditions leading to entrainment into the atmosphere, predicted wind direction, and atmospheric buoyancy to track pollen cloud movement and estimate downwind deposition (Figs. 2 and 3). Successful forecasting begins with knowledge of the phenology of *J ashei.* As pollen dissemination from the male cones begins, controls on the daily release are estimated using environmental parameters from forecast weather conditions. Estimation of pollen release into the



University of Tulsa
Mountain Cedar Pollen Forecast

Metropolitan Area	Exposure Risk
Oklahoma City	**High**
Tulsa	**High**
St. Louis	**Mod**

Date Issued: 08 January 2002

Mountain Cedar location(s): Arbuckle Mountains, OK

Regional weather: Tuesday, January 08 **TX/OK/AR**: Sunny conditions will prevail across the southern plains as high pressure builds over the area. Temperatures will continue to warm today and tomorrow with highs in the Texas region reaching the upper 60 s to low 70 s today and into the low to mid 70 s tomorrow. The warming continues north today with high temperatures close to 70 in Oklahoma and into the 60 s in the Ozark Mountain region. Lows throughout the region tonight will be in the 40 s. On Wednesday the southern low temperatures will be in the lower 50 s to upper 40 s and 5 to 7 degrees cooler to the north. Winds on both days will be from the south to southwest across the region and be moderate on Wednesday gaining strength on Thursday as a front begins to cross the area. Late Wednesday, skies will become partly cloudy across the region ahead of a front moving through on Thursday. Model predictions show cloudiness but little support for precipitation. However, a cut-off low developing to the west may result in significant precipitation over the weekend and into the beginning of next week.

Trajectory weather: The air mass trajectories from the Arbuckle Mountains move to the northeast over the Tulsa area and through Missouri, over the St. Louis area. Light to moderate winds on Tuesday will be accompanied by warm temperatures and a drying atmosphere. The trajectories show stable to slightly sinking air mass characteristics, conditions that are not conducive to pollen entrainment and travel. Warmer conditions are expected on Wednesday.

OUTLOOK: ***** Severe threat today *** very favorable conditions for pollen release today.** Conditions in southern Oklahoma will favor pollen release today as temperatures warm and sunny skies lead to drier conditions. However, the travel characteristics for the air masses are not as good for travel and entrainment as could be. These conditions are expected to change on Wednesday ahead of a cold front moving across the area. Therefore, the pollen entrained will result in a limited dispersal. But the conditions are very favorable for pollen release so a severe threat to the downwind populations is being forecast. Conditions may worsen tomorrow which will probably have the greatest chance for influx into outlying areas. The trajectories pass over the Tulsa area and would see the greatest chance of deposition compared to their later travel over St. Louis. Watch for tomorrows forecast as significant entrainment and travel may be in the winds.

Fig. 2. Sample forecast for mountain cedar (*J ashei*) pollen. Each forecast includes one or more trajectory maps similar to the map shown in Figure 3. The complete forecast from the Arbuckle Mountains for January 8, 2002, can be viewed on the Internet at http://pollen.utulsa.edu.

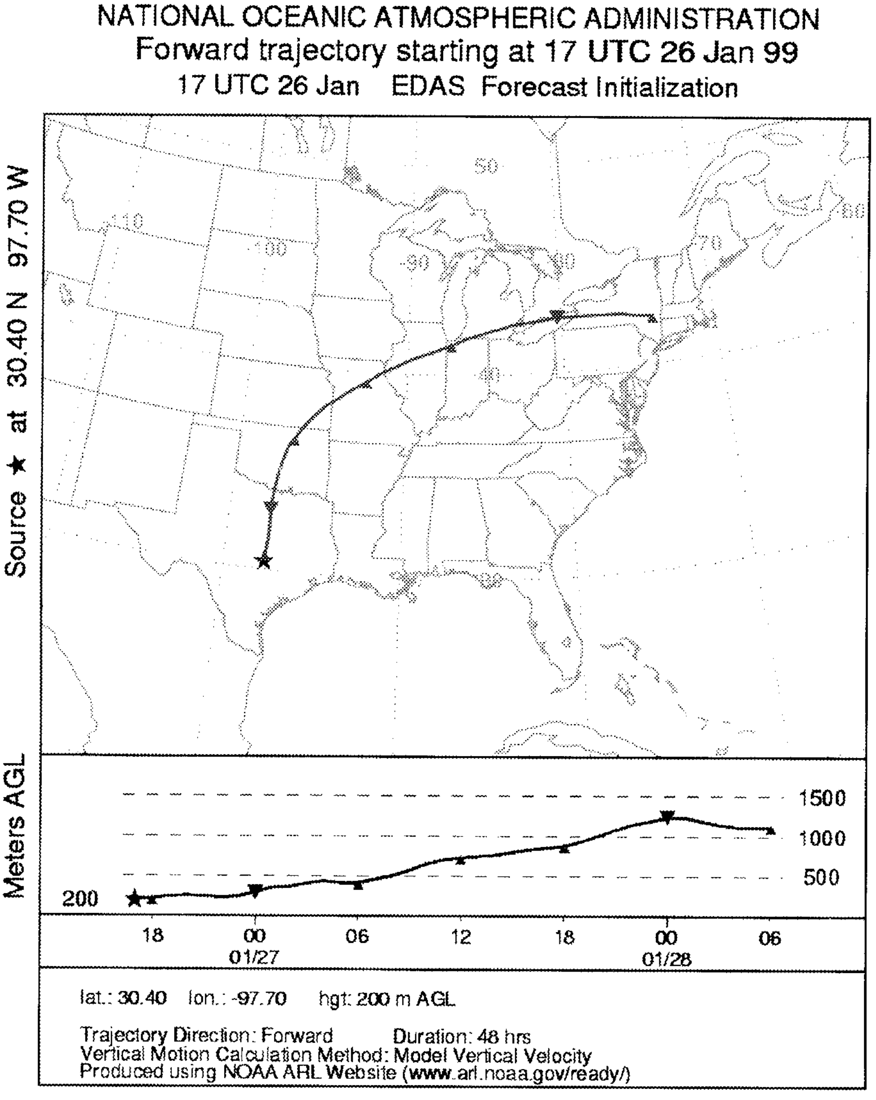


Fig. 3. Trajectory from Austin, Texas, on January 26, 1999, tracking the movement of a pollen-laden air mass as shown on the forecast for that day. The forecast outlook stated that "airborne pollen from eastern sections of the Plateau will get caught up in winds ahead of the low pressure system and has the potential to travel very long distances." The following day, airborne Cupressaceae pollen was registered in London, Ontario, at a concentration of 58 pollen grains/m^3. AGL, above ground level; ARL, Air Resources Laboratory; EDAS, Eta Data Assimilation System; hgt, height; lat., latitude; lon., longitude; UTC, Cooridinated Universal Time.

environment is coupled with forecast wind fields from weather models to determine the processes that are involved in pollen entrainment and downwind dispersal. The underlying factors used to formulate each forecast are detailed.

The start and stop of the forecast season is dependent on the determination of the phenologic characteristics of each population. The start time for the pollen season is variable in the region. Release conditions are estimated using past data and real-time field observations made by volunteers living throughout the region. Once pollen dispersal begins, production seems to follow a normal distribution but with an extended tail. Specific environmental conditions leading to cone maturation are unknown; however, as the forecasting effort continues, data showing the seasonal start and stop dates will continue to accrue, and underlying mechanisms will become clearer. Overall pollination has begun between December 10 and 25, depending on the year and specific population. As a general rule, pollination begins earlier in Texas than in the outlier in southern Oklahoma. Some southern Oklahoma trees have been observed to release pollen as early as the trees in Texas, however. Yearly climatic variability also influences pollination initiation. During 1999, Texas experienced an extreme drought, and pollination began only after a minor precipitation event moved through the area in late December. Although the season was shortened, the total amount of pollen released was similar to that released in the previous year.

Once cones mature and pollen release is active, entrainment and downwind dispersal becomes dependent on local and regional weather characteristics. During December and January, weather in the southern central United States is influenced by dry cold air moving east out of the Rocky Mountains and south from the Canadian Arctic. These air masses collide with the warmer, more humid air of the tropical Atlantic region to the southeast. The clash between weather patterns can result in region-wide atmospheric instability [47]. The prevailing westerly winds and the position of the jet stream sweep storms across the region, resulting in strong temperature and pressure gradients from north to south.

Because of the environmental diversity and spatial distribution of source populations, factors resulting in daily pollen release and entrainment were determined by comparing aerobiologic and meteorologic data. Environmental parameters that are used as estimates of daily release conditions include: sunshine, air temperatures above 5°C, relative humidity levels less than 50% with dry conditions for the previous 24 hours, and wind speeds greater than 4 mph. Ongoing research is investigating the applicability of these parameters as predictors of release.

Pollination initiation within the populations and estimated environmental parameters for daily release sets the stage to forecast potential downwind travel of entrained particles. Strong temperature and pressure gradients can move significant amounts of pollen over long distances and can have a significant impact on local, regional, and distant communities. In Tulsa, Oklahoma, regional southerly winds that are associated with north-to-south pressure gradients have resulted in *J ashei* pollen concentrations as high as 2000 grains/m^3 [8–10]. This finding illustrates that the distance pollen travels downwind is limited only by the maintenance of particle buoyancy in the atmosphere. As an extreme example, winter registration of Cupressaceae pollen in London, Ontario, Canada (J. Anderson, personal communication, 1999) can be backtracked to winds initiated over the Edwards Plateau of central Texas on the previous day (Fig 3). The direction and characteristics of the daily wind fields, along with evolving weather patterns, determine the areas and communities affected by *J ashei* upwind pollination. The ability to forecast evolving conditions determines the success or failure of the forecasting system.

The forecast process integrates current conditions and their duration, changes in forecast weather, and calculations of projected wind trajectories. Weather forecasts from the National Weather Service were consulted to determine local and regional atmospheric conditions. This information was coupled with wind trajectories that were generated using the hybrid single-particle Lagrangian integrated trajectory (HYSPLIT-4) model, an atmospheric particle-dispersion model available online from the National Oceanographic and Atmospheric Administration (NOAA) Air Resources Laboratory (http://www.arl.noaa.gov). The HYSPLIT-4 model computes particle dispersion by assuming advection of a fixed number of initial particles using the forecast mean wind field and turbulent components [48,49]. Forecasts are posted for Texas, southern Oklahoma, and the Ozark mountains populations of *J ashei.* Each population is represented by a limited number of point sources. The Texas populations include Austin, Junction, and San Angelo. The southern Oklahoma forecast tracks pollen from the Arbuckle mountains populations, and the Ozark mountains of Arkansas and southwest Missouri are represented in the Ozark mountains forecast [50]. Model runs were calculated from each source point at 11:00 AM central standard time from a starting height of 200 m above ground level; however, during the fourth season, this height was expanded to include 100 m, 250 m, and 500 m above ground.

Each forecast lists a review of the current and future synoptic weather conditions for the southern Great Plains. These reviews are combined to estimate the potential release conditions of the *J ashei* populations in the area. This potential for release is categorized and listed as favorable, mixed, or unfavorable. Each forecast describes the potential for pollen influx away from the local populations using the calculated air-mass trajectories. The threat of significant concentrations being deposited downwind is categorized as severe, moderate, or low (see Fig. 2). During the past two forecasting seasons, the potential influx into selected regional cities was listed at the top of each forecast page and listed as high, moderate, or low. Graphical representations are available for each of the calculated trajectories to show potential downwind influx zones.

Data from the authors' air samplers have been used to assess the accuracy of the forecast parameters and the predicted downwind pollen deposition. Samplers were stationed at select Texas and Oklahoma sites to compare predicted pollen release conditions with the actual atmospheric pollen concentrations. Burkard spore traps (Hirst-type air samplers) were installed in Austin and Junction, Texas, the Arbuckle Mountains of Oklahoma, and the Tulsa region. Each sampler provides a 24-hour, 7-day-a-week record of atmospheric particle concentration during the forecast season. It was recognized early in the forecasting process that atmospheric concentrations at each site consist of a local, regional, and long-distance component. Using the position of the smaller southern Oklahoma population, Van de Water and Levetin showed that the contribution of pollen from the larger Texas population to the downwind site was significant: 55% of all pollen registered in southern Oklahoma can be linked to winds initiated over the Edwards Plateau [11]. Wind conditions that brought the largest influx concentrations to the downwind site were at relatively low elevations over central Texas and increased as they moved northward, maintaining the buoyancy of the entrained particles.

The aerobiologic records from Texas allow an assessment of the release conditions listed on each of the daily forecasts. Absolute pollen concentrations for the 1998 to 1999, 1999 to 2000, and 2000 to 2001 seasons were compared against the forecast release conditions for each day and analyzed using the nonparametric Kruskal-Wallis analysis of variance test. Data were tested using atmospheric pollen concentrations and predicted release conditions from Junction and Austin, Texas, and from the combined data for all periods. Significant results ($P < 0.05$) occurred in all cases, except during the 2000 to 2001 season at Junction, Texas. The 2000 to 2001 season in Junction showed fewer heavy pollen concentration days, and mixed forecast release conditions carried greater weight and lowered the overall statistical significance. The mean concentration of airborne *Juniperus* pollen was 239 pollen grains/m^3 for all days with a forecast of unfavorable conditions for release, 727 pollen grains/m^3 with mixed conditions, and 1075 pollen grains/m^3 with favorable conditions (Fig 4). As an additional test, pollen concentrations were categorized into concentration levels for tree pollen according to the National Allergy Bureau (NAB) and were compared with forecast release conditions. The NAB categories for tree pollen are low (0–15 pollen grains/m^3), moderate (15–90 pollen grains/m^3), high (90–1500 pollen grains/m^3), and very high (> 1500 pollen grains/m^3). Comparison between the forecast conditions and NAB categories show that low and high concentrations are associated with unfavorable and favorable predictions, and a range of concentrations are associated with mixed release conditions (Table 3). The use of these environmental parameters as predictors has been successful, and additional data collection and analysis will allow further refinement of release conditions within the *J ashei* communities.

The ability to predict the release of pollen provides a powerful tool to predict where the pollen entrained in the atmosphere will travel before deposition. Modeled trajectories were compared against the aerobiologic record from Tulsa, Oklahoma, to determine forecast accuracy of downwind deposition. For the assessment, the timing of each forecast trajectory passing over northeastern Oklahoma was compared with pollen concentrations recorded by the three air samplers in the Tulsa area. A trajectory was considered to have crossed the Tulsa region if it passed over a rectangle centered on the city. The area encompassed by this rectangle is approximately 120 km east to west and 150 km north to south. The width is perpendicular to southerly wind flow and is approximately 20% of the distance from the Edwards Plateau source area, a value that estimates the approximate error associated with modeled trajectories [48,49].

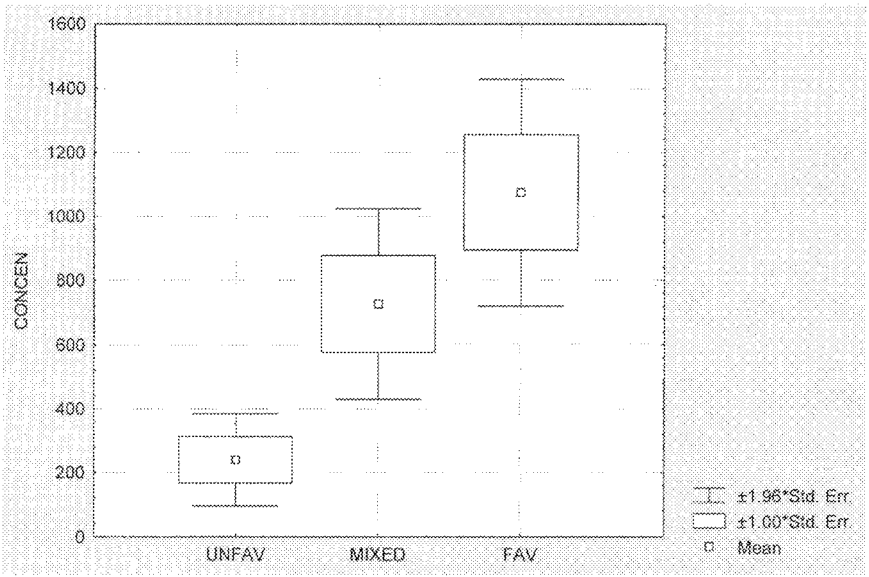


Fig. 4. Comparison of *J ashei* pollen levels grouped into categories based on pollen release forecast as unfavorable conditions for release (UNFAV), mixed conditions (MIXED), and favorable conditions (FAV). Mean concentrations (CONCEN) were 239 pollen grains/m^3 for all days with an unfavorable forecast, 727 pollen grains/m^3 with a mixed forecast, and 1075 pollen grains/m^3 with a favorable forecast. Std. Err., standard error.

Juniperus ashei does not grow in the Tulsa area; Cupressaceae pollen registrations during December and January represent pollen carried from distant sources. During each year of forecasting, Cupressaceae pollen was identified from the Tulsa atmosphere, although the downwind dispersal patterns were different each year. Figure 5 shows the concentration of airborne pollen in Tulsa during the first four winters of forecasting (1998–2002), and Table 4 summarizes these four seasons. The lowest number of incursions occurred during the winter of 2000 to 2001, a season that was characterized by unusually low tempera-

Table 3
Qualitative assessment of pollen release forecasts for Texas sites over 3 years using pollen levels from NAB

	Number of forecasts			
Forecast conditions	Low[a]	Moderate[b]	High[c]	Very high[d]
Unfavorable for release	57	36	29	4
Mixed conditions	19	28	33	13
Favorable for release	16	20	68	26

Abbreviation: NAB, National Allergy Bureau.

[a] 0–15 pollen grains/m^3.

[b] 15–19 pollen grains/m^3.

[c] 90–1500 pollen grains/m^3.

[d] >1500 pollen grains/m^3.

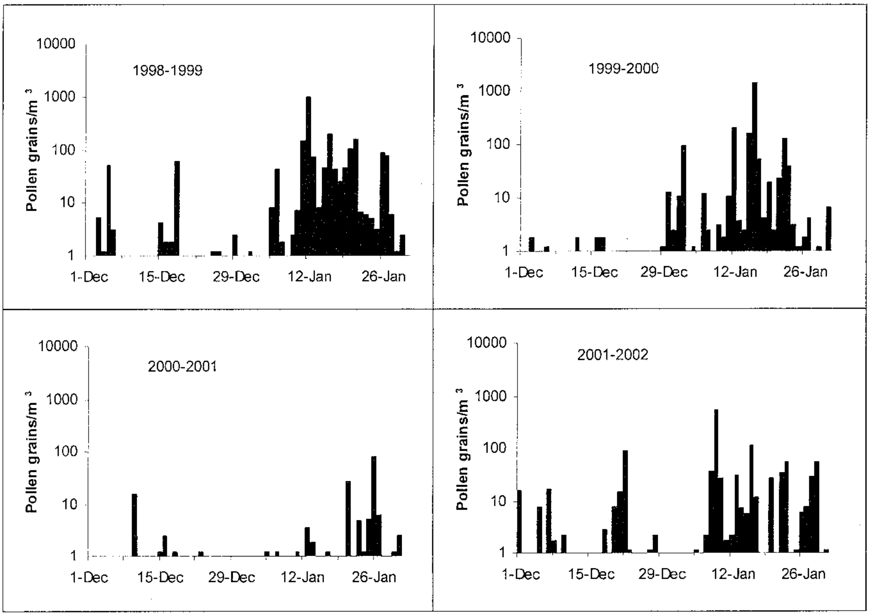


Fig. 5. *J ashei* incursions into the atmosphere of Tulsa, Oklahoma, during the Decembers and Januarys of 4 years.

tures and several snow and ice storms that dominated Oklahoma climate for approximately 5 weeks. The peak registration during this winter was 79 pollen grains/m^3, and the cumulative season total was 169. In contrast, the greatest registration was recorded in 1999 to 2000, with a peak of 1462 pollen grains/m^3 and a cumulative season total of 2283.

Days during which southerly winds dominated were identified using the forecasts. Air mass trajectories from source areas crossed the Tulsa area 131 times on these days during the forecasting seasons from 1998 to 2002. Most of these occurrences had conditions that were not favorable for pollen release and entrainment (ie, too early in the season, too late in the season, or meteorologic conditions did not meet the criteria). A significant number of trajectories had

Table 4
J ashei incursions in the atmosphere of Tulsa, Oklahoma, during December and January

Year	No. of days with pollen present	No. of trajectories crossing Tulsa	No. of days with moderate concentration	No. of days with high concentration	Peak concentration level (pollen grains/m^3)	Cumulative season total
1998–1999	49	40	10	5	984	2220
1999–2000	44	20	4	5	1462	2283
2000–2001	37	20	3	0	79	169
2001–2002	43	51	12	2	537	1159

favorable conditions for pollen release and showed severe exposure risk to downwind populations.

Average daily and hourly pollen concentrations from Tulsa area samplers were categorized using the NAB tree pollen levels (see Table 4). Forecast trajectories that crossed the Tulsa area were compared with the categorized registrations from the aerobiologic data. Forecasts were considered successful if moderate or severe threats to northeastern Oklahoma were identified within the forecast and if moderate, high, or very high pollen concentrations were registered by the Burkard samplers in the Tulsa area after travel time was taken into account. The HY-SPLIT trajectories were plotted for a single hour during each day, even though pollen release is believed to occur throughout the daylight hours. Therefore, a forecast also was judged successful if moderate-to-very high concentrations were recorded in Tulsa during a period corresponding to the potential release period at the source plus travel time.

Assessment of the first 4 years of forecasting (1998–2002) showed that 29 days had moderate pollen levels and 12 days had high levels (see Table 4). Although there were no days when the average daily concentration was very high, 3 days had very high hourly concentrations. The peak level recorded in Tulsa was 4333 pollen grains/m^3, which was registered at 10:00 AM central standard time on January 16, 2000.

Analysis of the successful forecasts showed that most of the trajectories emanated from the Arbuckle Mountains in southern Oklahoma; the eastern edge of the Edwards Plateau (Austin source area) in Texas was a close second. Each of these trajectories was associated with moderate or favorable forecast release conditions at the source, except in one case. The threat of pollen influx into northeastern Oklahoma was forecast as moderate or severe for each of the trajectories, except in one case. The downwind forecasting predicted all but two incursions into the Tulsa area during the 4 years of forecasting.

Analysis of past forecasting seasons shows that pollen dissemination and travel downwind is predictable within constraints. As the forecasting effort continues, the ability to accurately predict conditions leading to downwind pollen dissemination will continue to improve. More research will afford further means to assess the forecast accuracy and refine parameter estimates, improving the forecasts.

Summary

Pollen forecasting is becoming increasingly important to allergists as an adjunct to effective patient care. Forecasts allow patients to avoid exposure to high pollen levels and prompt them to take prophylactic medication and to plan outdoor activities for periods of low pollen levels. Investigators are making progress in developing effective models for daily and seasonal forecasts for important pollen allergens; however, current models are limited to specific geographic areas. Models for the onset of the season for spring tree pollen are based on the chilling and heat units that are required before flowering can occur.

Models for pollen season severity are based on regression analysis of preseason meteorologic conditions, and models for daily forecasts are based on the normal pollen curve and responses to day-to-day meteorologic conditions. When winds are favorable, long-distance transport can introduce allergenic pollen types into a local area. The Mountain Cedar Pollen Forecasting model, which combines day-to-day release forecasts at source areas and dispersion forecasts to downwind areas, has been reasonablly successful over the past 4 years. All pollen forecasting models are dependent on accurate meteorologic forecasts, and pollen forecasting will become more accurate as meteorologic forecasts improve.

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