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ORIGINAL ARTICLE

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Effects of meteorological conditions on spore plumes

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Abstract Fungal spores are an ever-present component of the atmosphere, and have long been known to trigger asthma and hay fever symptoms in sensitive individuals. The atmosphere around Tulsa has been monitored for airborne spores and pollen with Burkard spore traps at several sampling stations. This study involved the examination of the hourly spore concentrations on days that had average daily concentrations near 50,000 spores/m^3 or greater. Hourly concentrations of *Cladosporium*, *Alternaria*, *Epicoccum*, *Curvularia*, *Pithomyces*, *Drechslera*, smut spores, ascospores, basidiospores, other, and total spores were determined on 4 days at three sites and then correlated with hourly meteorological data including temperature, rainfall, wind speed, dew point, air pressure, and wind direction. On each of these days there was a spore plume, a phenomenon in which spore concentrations increased dramatically over a very short period of time. Spore plumes generally occurred near midday, and concentrations were seen to increase from lows around 20,000 total spores/m^3 to highs over 170,000 total spores/m^3 in 2 h. Multiple regression analysis of the data indicated that increases in temperature, dew point, and air pressure correlated with the increase in spore concentrations, but no single weather variable predicted the appearance of a spore plume. The proper combination of changes in these meteorological parameters that result in a spore plume may be due to the changing weather conditions associated with thunderstorms, as on 3 of the 4 days when spore plumes occurred there were thunderstorms later that evening. The occurrence of spore plumes may have clinical significance, because other studies have shown that sensitization to certain spore types can occur during exposure to high spore concentrations.

Keywords Spore plumes · Fungal spores · Asthma · Hay fever · Meteorological conditions

Introduction

Fungal spores are an ever-present component of our atmosphere and can be found in the air at almost any time throughout the year. Fungi require certain environmental conditions for their growth and reproduction, and associations with temperature and moisture have been well documented in the literature (Hasnain 1993). Weather variables such as wind (Hasnain 1993; Aylor 1990) and rainfall (Timmer et al. 1998) have been shown to affect the release and concentrations of spores in the air. Spore types such as *Cladosporium*, *Alternaria*, *Epicoccum*, and *Dreschlera* tend to be found in higher concentrations during warm, dry weather conditions, while ascospores and basidiospores tend to be more concentrated during wet or humid conditions, such as those late at night and before dawn. Precipitation is required for the release of many ascospores, and ascospore concentrations usually increase during and after rainstorms. Basidiospore concentrations are more directly affected by relative humidity and usually peak during the early morning. This diurnal periodicity of airborne spore concentrations has been shown in many different studies (Hirst 1953; Ingold 1971).

Tulsa, Oklahoma, has a mild, continental climate with ideal conditions for spore production during spring and fall. Increases in concentrations of dry-air spora as well as ascospores and basidiospores during spring and fall months have been documented by Levetin (1991). The majority of spores found in the air in Tulsa on most days are *Cladosporium*. Although studies have shown that *Cladosporium* concentrations are higher during periods of warm temperature and dry air (Hirst 1953), other studies have suggested that *Cladosporium* release is somehow related to rainfall and thunderstorms. For example, during a thunderstorm in June 1994 in London, transient peaks of *Cladosporium* conidia were observed before and after the rain (Allitt 2000).

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Routine analysis of airborne spores in Tulsa by a single-traverse method has shown days with very high average daily spore concentrations and dense clusters of spores on the slides. Days such as these may have a clinical significance for patients with asthma or rhinitis who are also sensitive to fungal spores. For example, a 1999 study showed that *Alternaria* spores are associated with severe asthma in a population of young adults (Neukirch et al. 1999). Also, admissions of children to hospitals in Mexico City and in Canada have been correlated with high outdoor fungal spore levels (Rosas et al. 1998; Dales et al. 2000).

The present study focused on 4 days with high spore levels (over 40,000 spores/m^3) in order to determine the hourly concentrations and the meteorological conditions that trigger these levels. A model predicting which meteorological conditions favor the release of large concentrations of these spores could provide a great benefit to patients with asthma or allergic rhinitis. Patients would be able to take prophylactic measures if they knew in advance which spores would be found in high concentrations on certain days.

Materials and methods

Four days were selected for study (18 September 1998, 21 September 1998, 30 September 1998, and 7 September 1999). In the Tulsa area, each of these days had average daily concentrations above 40,000 spores/m^3 air. (Fig. 1a, b). Air samples for these days from Tulsa as well as from two surrounding sites were examined for a total of 12 sampling periods. Burkard volumetric spore traps were in operation at the three sites to carry out the atmospheric sampling. One sampler was located at the University of Tulsa on the roof of a building, at 12 m above the ground and 252 m above sea level. The two other samplers were located outside Tulsa, Oklahoma, at Mesonet meteorological stations. One of these samplers was in an agricultural field in Bixby, Oklahoma, which is approximately 24 km southeast of the University of Tulsa and 184 m above sea level. The other sampler was located in a pasture in Hectorville, Oklahoma, which is approximately 40 km south of the University of Tulsa and 239 m above sea level. The intake orifice of both samplers was set 1.5 m above ground level. The samplers were set for 7-day sampling onto Melinex tape that was coated with a thin film of Lubriseal. The tape was changed weekly, cut into 24-h segments, mounted onto microscope slides, and stained with glycerin jelly containing basic fuchsin. Slides were counted at 1000 × magnification by the 12-traverse method (Sterling et al. 1999). Hourly concentrations of *Cladosporium*, *Alternaria*, *Epicoccum*, *Curvularia*, *Pithomyces*, *Dreschlera*, smut spores, ascospores, and basidiospores were determined and expressed in spores/m^3 air. Spores that did not fit into the above categories were categorized as “other”, and total spore levels were also determined. Spore concentrations were log-transformed to normalize data, and *Statistica* 4.0 was used to correlate meteorological data with spore data using a forward stepwise multiple-regression analysis.

Meteorological data were obtained from the Oklahoma Mesonet for temperature, rainfall, wind speed, relative humidity, air pressure, and wind direction for Bixby and Hectorville. Oklahoma Mesonet is a network of 115 meteorological stations located throughout Oklahoma. Meteorological parameters are measured every 5 min, and data are transmitted to a central computer at the University of Oklahoma and available on-line. Air pressure was not measured at Hectorville, so Bixby values were used in the analysis for both sites. This was the closest Mesonet station to Hectorville, approximately 16 km away. For the Tulsa sampler, meteorological data were obtained from the National Oceanic and Atmospheric Administration weather station located approximately 8 km from the sampler at Tulsa International Airport and included temperature, air pressure, rainfall, wind speed, dew point, and wind direction.

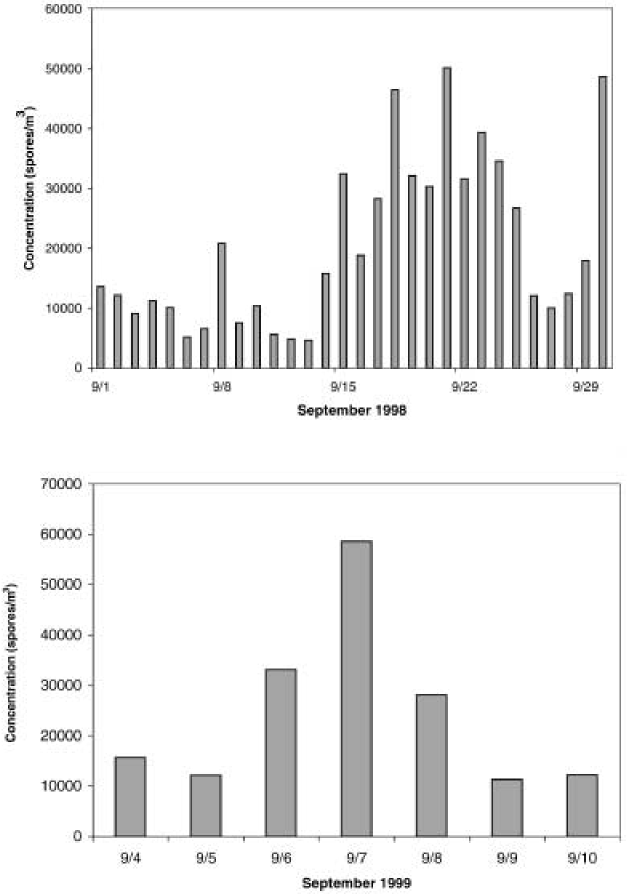

Fig. 1 Total spore concentrations for Tulsa on 1–30 September 1998 and 4–10 September 1999

Results

Comparisons of the hourly concentrations for each of the 4 days showed a similar pattern for spore release. The peak concentration for total spores occurred at 1000 or 1200 hours, with the exception of 7 September 1999 and 18 September 1998 at Bixby (Fig. 2). On 7 September there were two peaks, the first occurring at 0800 hours, and the second at 1800 hours. At Bixby on 18 September 1998, the peaks occur at 0200 and 1200 hours. The peaks for each day and each site occurred rather abruptly, the total concentrations for these hours rising to highs of over 200,000 spores/m^3 on 7 September 1999 from concentrations of near 45,000 spores/m^3 just a few hours before (Fig. 2). At Hectorville, on 7 September 1999, the peak hourly spore concentration was over 350,000 spores/m^3. The early morning showed typical patterns of high basidiospore and ascospore concentra-

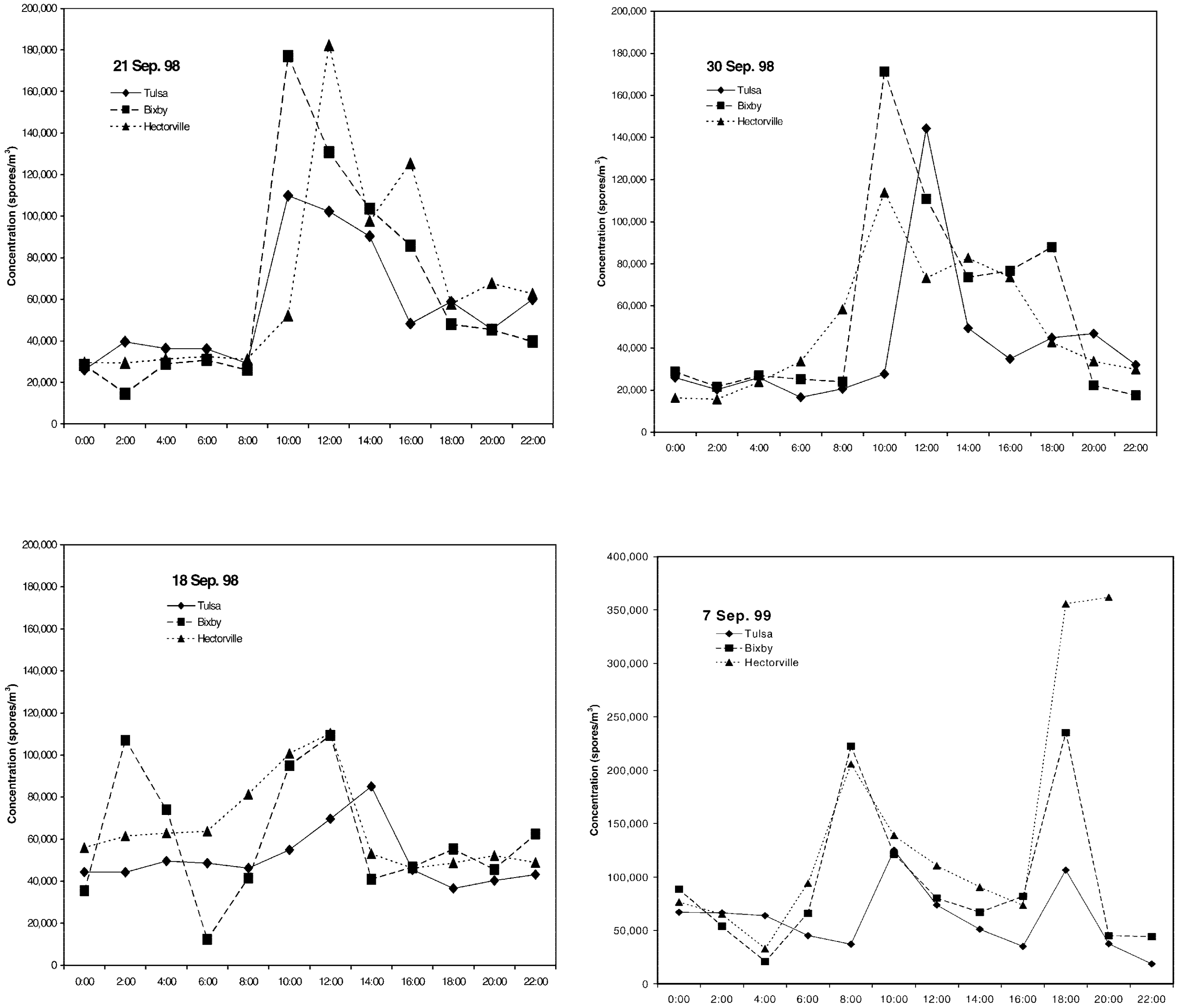

Fig. 2 Hourly spore concentrations for 18, 21, and 30 September 1998 and 7 September 1999 at all sampling sites

tions and low dry-air spore concentrations. The abrupt rise in spore concentration that occurred near midday was due to a huge spike in *Cladosporium* and *Alternaria* concentrations (Fig. 3).

The increase in spore concentrations on 21 September 1998 occurred at 1000 hours for all three sites (Fig. 2). At the Tulsa site, spore concentrations rose from over 20,000 spores/m^3 to over 110,000 spores/m^3 from 0800 to 1000 hours. Spore concentrations stayed very high until 1600 hours, when they dropped back to near 45,000 spores/m^3. Spore concentrations stayed at that level into the later evening because rainfall caused high concentrations of airborne ascospores. Although the hourly spore patterns seen for 30 September 1998 were very similar to those of 21 September 1998, the peak concentrations for each of these days did not occur at the same hour. Tulsa had a spike in total spore concentrations at 1200 hours, while Hectorville and Bixby showed large increases in total spore concentrations at 1000 hours. In contrast to 21 September 1998 at Tulsa, spore concentrations did not remain near the peak level; rather, concentrations fell to near-50,000 spores/m^3. Rainfall later in the evening also caused high ascospore concentrations at all sites on 30 September 1998, which was similar to 21 September 1998.

On 18 September the least pronounced rise in total spore concentrations of all of the days was recorded. Unlike the other days, concentrations stayed at high levels for most of the day. Peak total spore concentrations for this day occurred at 0200 and 1200 hours for Bixby and Hectorville, and at 1400 hours for Tulsa. Concentrations showed an increase of approximately 45,000 spores/m^3 at the peak times, which is lower than on the previous two days. Each of the three sites had a more gradual increase in total spore concentration than on the previous days, with the spike in total spore concentration gener-

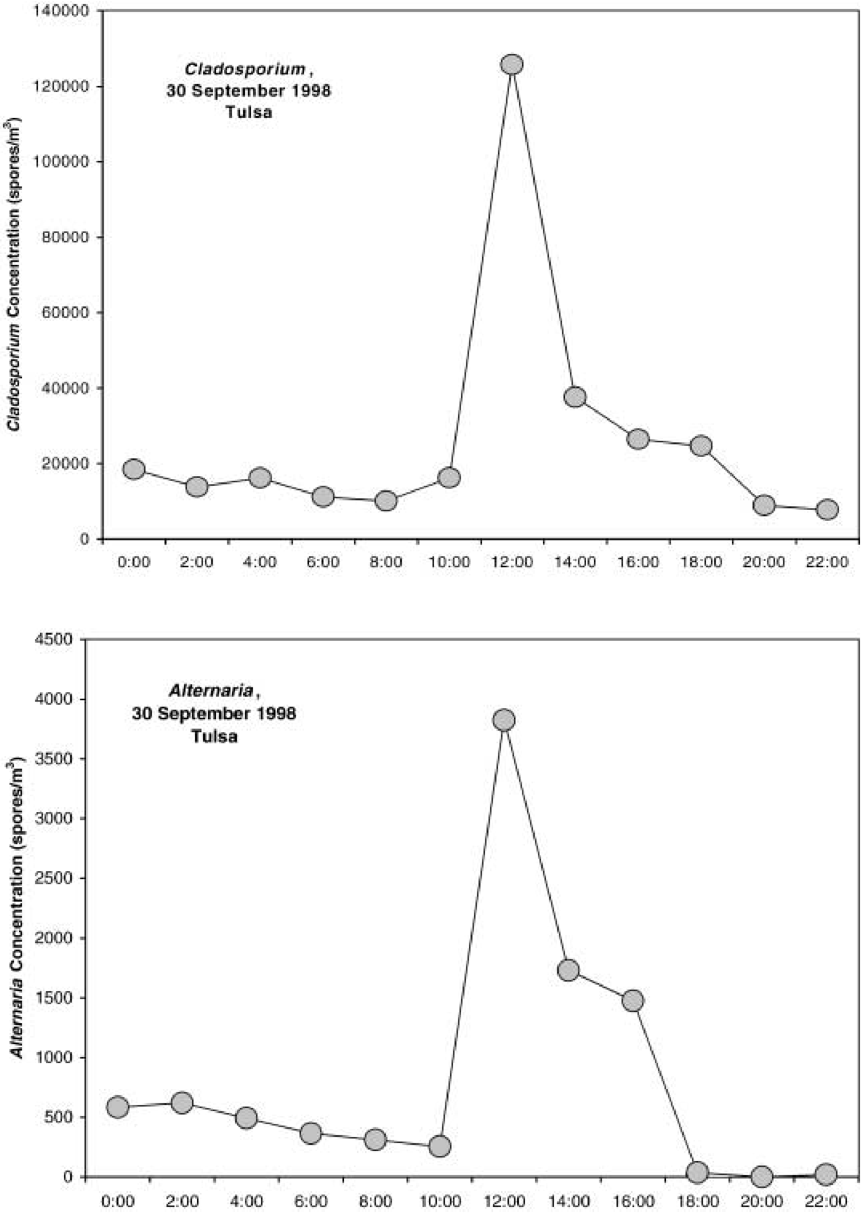

Fig. 3 Hourly *Cladosporium* and *Alternaria* concentrations for 30 September 1998 at Tulsa, Oklahoma

ally occurring over a period of 4 h instead of 2. This day also differed from the other two days, because there was no rain and no increase in ascospore concentrations.

The peak concentrations for 7 September 1999 were the highest of any of the days monitored. Unlike the other 3 days, 7 September 1999 had two distinct peaks. The first peak occurred at 0800 hours for Bixby and Hectorville, and at 1000 hours for Tulsa. The second peak occurred at 1800 hours at Tulsa and Bixby, and at 2000 hours at Hectorville. At Hectorville, the total spore concentrations rose from near 95,000 spores/m^3 at 0600 hours to approximately 205,000 spores/m^3 at 0800 hours. An even larger increase was seen between 1600 and 1800 hours, with total spore concentrations increasing from near 75,000 spores/m^3 to over 355,000 spores/m^3. No data were available after 2000 hours at Hectorville because high winds had disabled the sampler.

The percentage of each spore taxon for each day can be seen in Table 1. For each day, *Cladosporium* had the highest percentage of any spore type. On 18 September 1998 and 7 September 1999, *Cladosporium* spores accounted for over 85% of the total spore concentrations. Ascospores, basidiospores, and other spores generally showed the second highest percentages for any spore taxon. On 21 and 30 September 1998, ascospores, basidiospores, and other spores together accounted for over 23% of the total spore concentrations. Although peak hourly concentrations were extremely high on some days, *Alternaria* spores generally accounted for approximately 2% of the total spore concentrations for each day. The percentage of each spore taxon for the peak hour at the Tulsa site can be seen in Table 2. *Cladosporium* spores again accounted for the highest percentage of the total concentrations, while ascospores, basidiospores,

Table 1 Percentage of each spore taxon for each day at the Tulsa site

Spore type	Composition (%)			
	18 Sep. 1998	21 Sep. 1998	30 Sep. 1998	7 Sep. 1999
Cladosporium	85.2	68.7	65.3	88.8
Alternaria	1.8	2.1	1.9	3.3
Epicoccum	0.1	0.1	0.0	0.0
Curvularia	1.6	0.6	0.7	0.3
Pithomyces	0.5	0.8	0.5	0.2
Dreschlera	0.7	0.5	0.3	0.3
Smut spores	1.0	3.8	2.4	0.3
Ascospores	2.5	9.5	16.3	4.1
Basidiospores	3.9	9.5	6.7	0.6
Other	2.6	4.4	5.8	2.1

Table 2 Percentage of each spore taxon for each day for the peak hour at the Tulsa site

Spore type	Composition (%)			
	18 Sep. 1998	21 Sep. 1998	30 Sep. 1998	7 Sep. 1999
Cladosporium	90.30	76.90	87.20	95.50
Alternaria	1.30	1.50	2.60	1.90
Epicoccum	0.17	0.03	0.04	0.00
Curvularia	0.56	0.56	0.25	0.22
Pithomyces	0.34	0.48	0.40	0.00
Dreschlera	0.43	0.66	0.20	0.13
Smut spores	0.53	1.30	1.00	0.23
Ascospores	2.20	6.20	1.90	0.63
Basidiospores	1.20	3.20	1.90	0.47
Other	3.00	9.20	4.40	0.99

Table 3 Daily meteorological data for 18, 21, and 30 September 1998 and 7 September 1999

Parameter	18 Sep. 1998	21 Sep. 1998	30 Sep. 1998	7 Sep. 1999
Maximum temperature (°C)	32.2	30.0	30.0	35.6
Minimum temperature (°C)	19.4	21.7	21.1	20.6
Average temperature (°C)	26.1	26.1	25.6	28.3
Average dew point (°C)	19.4	21.7	18.3	20.0
Rainfall (mm)	0.0	50.6	5.3	26.7
Air pressure (mm Hg)	741.40	739.60	741.90	739.39
Wind direction (degrees from due north)	120	70	80	180
Average wind speed (m/s)	1.4	3.8	3.5	2.6
Time of thunderstorms (hours)	–	2100	2100	1800

other spores, and *Alternaria* spores all accounted for smaller percentages of the total.

For each of the 4 days, the average temperature, dew point, and air pressure were similar (Table 3). The average wind direction was from the east to northeast on 2 days, and from the south or southeast on the other days. The average wind speed varied from 1.4 m/s to 3.8 m/s for each day. Also, rainfall and thunderstorms occurred each day except for 18 September 1998. The thunderstorms occurring on the other days took place during the evening.

The effect of wind speed on *Cladosporium* concentrations during the midday increase in concentration can best be illustrated by result for 30 September 1998 at Bixby and for 21 September 1998 at Hectorville. Each day shows an increase in wind speed of about 4 m/s between the 1000 and 1200 hours, which is when the spike in spore concentrations occurred (Fig. 4). Wind speed showed significant positive correlations with *Cladosporium* at Hectorville ($r = 0.66$, $P < 0.05$) and Bixby ($r = 0.91$, $P < 0.05$).

Air pressures also seemed to correlate positively with peak *Cladosporium* concentrations, but this was not significant. On 21 and 30 September 1998 at Bixby, a gradual increase in air pressure throughout the morning peaked at 1000 hours when *Cladosporium* concentrations peaked (Fig. 5). The large air pressure increase near 2200 hours on both days does not correlate with a large increase in *Cladosporium* because rainfall from a thunderstorm washed spores from the atmosphere at 2100 hours.

The peak in *Cladosporium* also corresponds to increases in dew point on 30 September 1998 at Bixby and

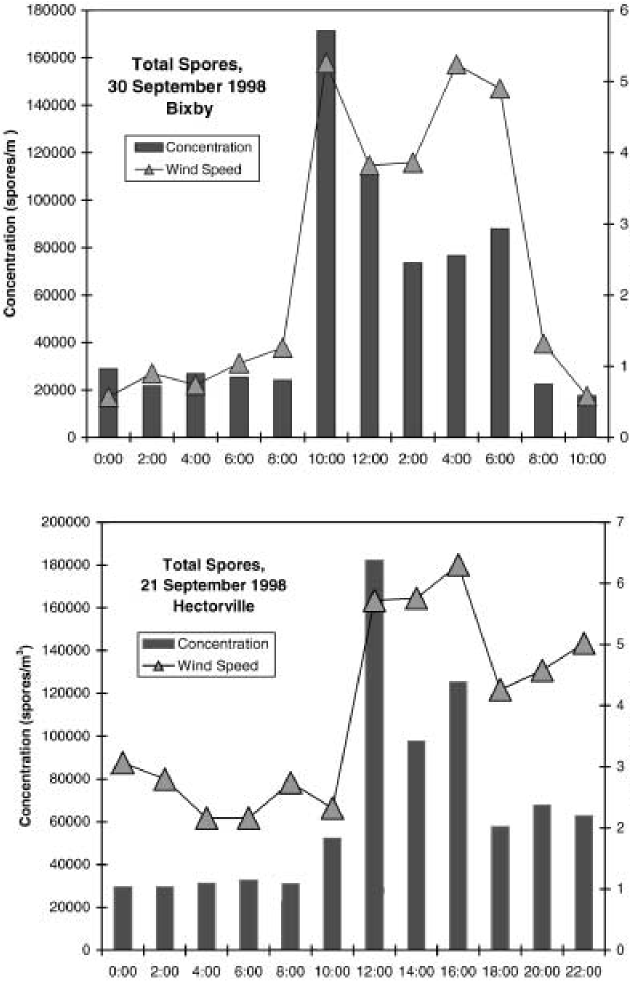

Fig. 4 Effects of wind speed on total spore concentrations on 21 and 30 September 1998 at Bixby and Hectorville

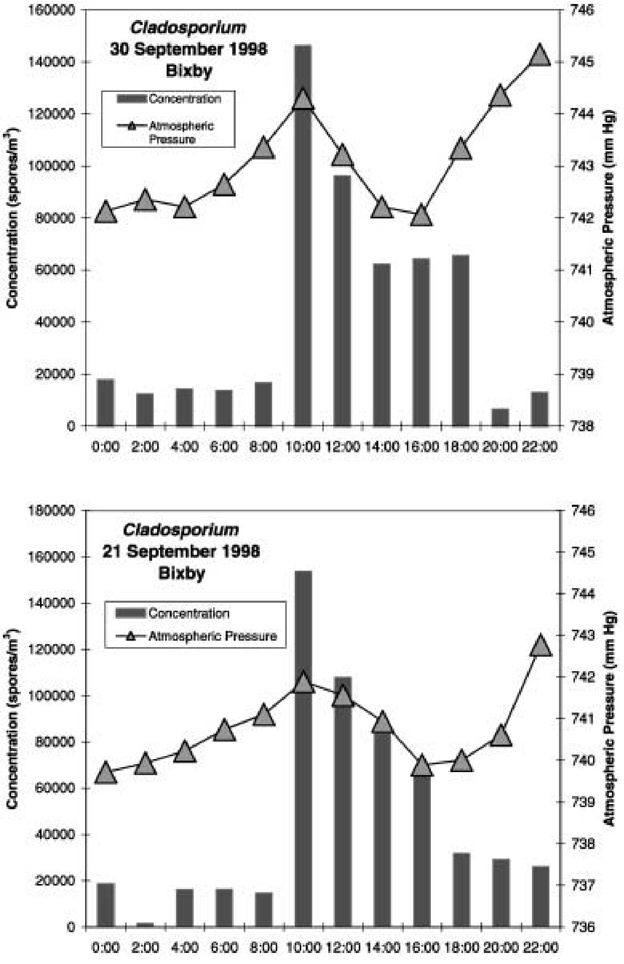

Fig. 5 Effects of air pressure on airborne *Cladosporium* concentrations on 21 and 30 September 1998 at Bixby

Hectorville. An increase in dew point of 2–3 °C began 4 h before the spore levels peaked at 1000 hours at Bixby and at 1200 hours at Hectorville (Fig. 6). Although the peak dew point occurred 2 h after the peak *Cladosporium* concentration at Hectorville, there is a significant correlation between dew point and total spore concentrations ($r = 0.83$, $P < 0.05$).

The total data from all of the 12 days were analyzed by a forward stepwise multiple-regression analysis (Table 4). Also, each day was analyzed individually (Table 5), and each site was analyzed individually (Table 6). Hourly temperature, dew point, and air pressure were the three weather variables that were significant predictors for total spore concentrations, and 30.4% of the variability is explained by all of the weather factors examined (Table 4). Dew point, temperature, and air pressure were three weather variables that seemed to be linked to spore concentrations on days with spore plumes. Dew point showed significant positive correlations with *Alternaria* ($r = 0.26$, $P < 0.05$), ascospores ($r = 0.18$, $P < 0.05$), basidiospores ($r = 0.37$, $P < 0.05$), and total spores ($r = 0.23$, $P < 0.05$), and was positively, but not significantly correlated with the concentrations of other spores. *Cladosporium* concentrations were significantly correlated with air pressure and temperature in a regression analysis that explained 30.5% of the variation. Similarly, *Alternaria* had significant relationships with temperature, dew point, and air pressure, and 36.6% of the variation was explained in this model. Each member of the dry-air spora in this model had significant positive relationships with temperature, while ascospores and basidiospores had negative correlations with temperature. Air pressure was a significant predictor of *Cladosporium* and total spore concentrations, and dew point was significantly correlated with *Alternaria*, ascospores, basidiospores, other spores, and total spores.

Table 5 shows multiple statistical models in which data for each day are grouped together. For 21 September 1998, 68.0% of the variability of the total spore concentrations was explained by the weather variables examined. The models also showed *Cladosporium*, *Alternaria*, *Curvularia*, smut spores, other spores, and total spore concentrations to be significantly affected by temperature and air pressure. Wind direction and precipi-

Table 4 Results from forward stepwise multiple regression analysis correlating log-transformed hourly spore concentrations with meteorological parameters from all days and all sites

Spore type	r^2	*df*	Beta values					
			T	Dew pt.	Air pressure	Wind direction	Wind speed	Precip.
Cladosporium	**0.305***	3, 139	**0.594**	0.116	**0.242**			
Alternaria	**0.366**	3, 139	**0.494**	**0.197**		**0.161**		
Epicoccum	**0.222**	4, 138	**0.418**		0.161	**–0.26**		–0.10
Curvularia	**0.215**	3, 139	**0.497**			–0.12	–0.11	
Pithomyces	**0.294**	5, 137	**0.431**	0.106		**–0.34**	0.100	0.116
Dreschlera	**0.232**	3, 139	**0.427**		–0.13	–0.11		
Smut spores	**0.244**	5, 137	**0.333**	0.223	0.138	–0.21	**0.185**	
Ascospores	**0.446**	6, 136	**–0.34**	**0.249**	0.089	**–0.30**	**0.272**	**0.228**
Basidiospores	**0.346**	4, 138	**–0.34**	**0.419**		**–0.22**	–0.07	
Other	**0.158**	5, 137		**0.172**	0.130	–0.15	**0.289**	0.132
Total	**0.304**	5, 137	**0.545**	**0.201**	**0.266**		0.084	0.086

*Significant beta values and r^2 ($P < 0.05$) are shown in bold type

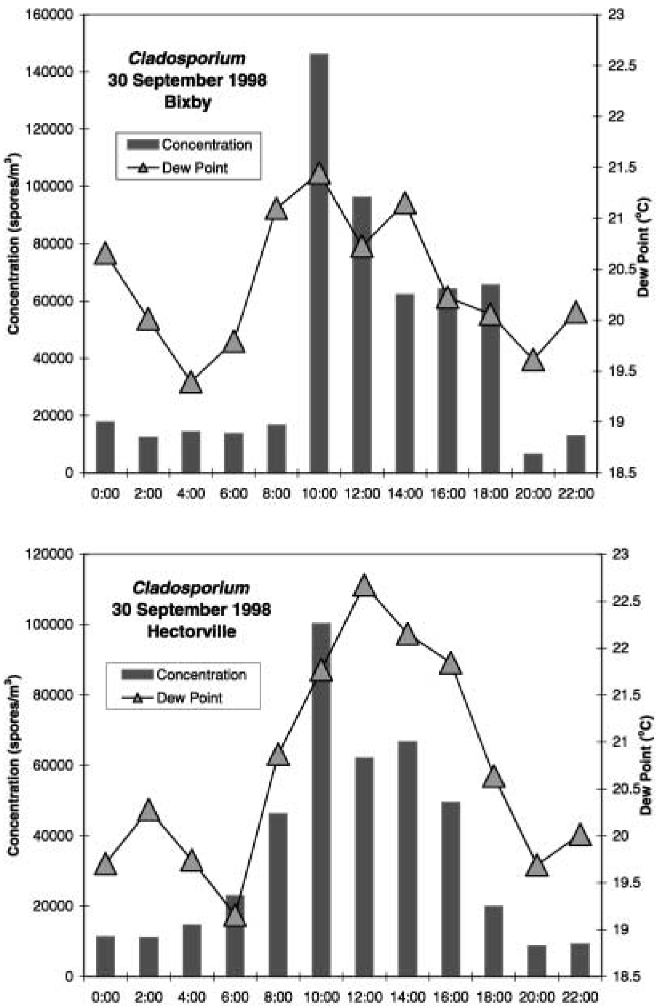

Fig. 6 Effects of dew point on *Cladosporium* concentrations on 30 September 1998 at Bixby and Hectorville

tation were significant predictors of ascospores, and ascospore concentrations were negatively correlated with wind direction, suggesting that the presence of ascospores was correlated with northeasterly winds. On 18 September 1998, 33.3% of the variation in *Cladosporium* levels was explained by the model, with temperature and air pressure being the two meteorological variables that were significant predictors. Air pressure and temperature were the two meteorological variables that were found to be significant predictors of total spore concentrations on 18 September 1998, both of them being positively correlated.

On 30 September 1998, 58.8% of the variability in the total spore concentrations was explained by the model, but no single weather variable was a significant predictor of total spore concentrations, although temperature, air pressure, dew point, wind direction, and wind speed all showed positive but non-significant correlations. Significant r^2 values were determined for every spore category for this day, and all members of the dry-air spores showed significant positive correlations with temperature. The data for 7 September 1999 show that 32.5% of the variability in total spore concentrations was explained by the model. Less of the total variance in spore concentrations was explained by the weather variables on this day than on any other. Temperature was a significant predictor for every spore type examined except for other spores and basidiospores.

Table 6 shows a statistical model in which data for each site were grouped together. The model, which examined the Tulsa site, showed that 28.0% of the variability in total spore concentrations was explained by the weather variables, and temperature and wind direction were significant predictors of total spore concentrations. Temperature was a significant predictor for all of the dry-air spores except *Epicoccum*, and wind direction was negatively correlated with almost every spore type, again suggesting a relation with northerly winds. At Hectorville, temperature and wind speed were the two weather variables that were significant predictors for most spore types; however, wind speed and air pressure were the only two significant predictors for total spore concentrations, and 31.2% of the variability in total spore concentrations was explained by the model. Temperature was once again a significant predictor for all of the dry-air

Table 5 Results from forward stepwise multiple regression analysis correlating log-transformed hourly spore concentrations with meterological parameters for 18, 21, and 30 September 1998 and 7 September 1999

Spore type	r^2	*df*	Beta values					
			T	Dew pt.	Air pressure	Wind direction	Wind speed	Precip.
18 Sep. 1998								
Cladosporium	**0.333****	4, 31	**0.520**	0.210	**0.459**	0.194		
Alternaria	**0.289**	4, 31	0.269	**0.413**		0.206	0.259	
Epicoccum	**0.431**	5, 30	**0.343**	0.232	0.299	**0.361**	**0.486**	
Curvularia	**0.534**	3, 32	**0.405**	**0.265**		**0.537**		
Pithomyces	**0.629**	5, 30	**0.511**	0.243	–0.20	**0.247**	**0.261**	
Dreschlera	**0.347**	4, 31	**0.374**	0.205		0.244	0.306	
Smut spores	**0.329**	4, 31	0.277	**0.437**	–0.32		0.198	
Ascospores	**0.302**	2, 33			**0.506**	**0.353**		
Basidiospores	**0.506**	3, 32	**–0.44**		**0.396**	0.133		
Other	**0.518**	3, 32	0.197	**0.282**		**0.625**		
Total	**0.331**	4, 31	**0.456**	0.218	**0.448**	0.270		
21 Sep. 1998								
Cladosporium	**0.576**	5, 30	**0.684**	–0.25	**0.424**	–0.20		–0.21
Alternaria	**0.669**	3, 32	**0.770**		**0.382**			–0.14
Epicoccum	**0.446**	3, 32	**0.524**		0.173	**–0.33**		
Curvularia	**0.532**	5, 30	**0.701**	**–0.63**	**0.433**		–0.23	**–0.056**
Pithomyces	**0.536**	5, 30	**0.780**	–0.30	0.249		0.268	0.029
Dreschlera	**0.350**	2, 33	**0.702**	**–0.46**				
Smut spores	**0.645**	5, 30	**0.732**	–0.30	**0.310**	**–0.27**		–0.20
Ascospores	**0.780**	4, 31	0.195			**–0.62**	0.121	**0.737**
Basidiospores	**0.583**	5, 30	**–0.60**	**0.418**		0.174	–0.22	**–0.47**
Other	**0.586**	5, 30	**0.558**	–0.25	**0.347**	–0.28	0.204	
Total	**0.680**	4, 31	**0.685**	–0.23	**0.482**	–0.33		
30 Sep. 1998								
Cladosporium	**0.574**	2, 33	**0.766**					0.123
Alternaria	**0.593**	4, 31	**0.692**	–0.16		**0.295**		**0.33**
Epicoccum	**0.530**	2, 33	**0.477**				**0.350**	
Curvularia	**0.680**	4, 31	**0.561**		**–0.39**	0.137		–0.20
Pithomyces	**0.521**	2, 33	**0.628**		**–0.25**			
Dreschlera	**0.487**	3, 32	**0.859**	**–0.36**		0.256		
Smut spores	**0.568**	2, 33	**0.671**		–0.24			
Ascospores	**0.452**	6, 29	–0.49	0.318	0.231	**–0.38**	0.241	0.214
Basidiospores	**0.234**	3, 32	–0.20		–0.28			**–0.36**
Other	**0.402**	3, 32	**0.475**	0.215	0.194			
Total	**0.588**	5, 30	0.354	0.315	0.185	–0.23	0.212	
7 Sep. 1999								
Cladosporium	**0.367**	3, 32	**0.623**	0.280			**–0.37**	
Alternaria	**0.455**	3, 32	**0.519**	**0.422**	–0.20			
Epicoccum	**0.134**	3, 32	0.307		–0.25		–0.33	
Curvularia	**0.317**	3, 32	**0.677**	–0.31	**0.489**			
Pithomyces	**0.240**	3, 32	**0.547**			–0.30		0.204
Dreschlera	**0.294**	3, 32	**0.472**		–0.33		–0.36	
Smut spores	**0.365**	5, 30	**0.784**	–0.31	**0.507**		–0.20	0.185
Ascospores	**0.703**	3, 32	**–0.85**				**0.358**	**0.295**
Basidiospores	**0.488**	2, 33			0.200		**–0.56**	
Other	**0.339**	5, 30	–0.35	–0.19	–0.29	0.268		0.318
Total	**0.325**	2, 33	**0.408**	**0.454**				

*Significant beta values and r^2 ($P < 0.05$) are shown in bold type

spore categories except *Cladosporium*. Total spore concentrations at the Bixby site showed positive relationships with temperature, dew point, air pressure, and wind speed, and 34.8% of the variability was explained by the model. *Alternaria* concentrations had positive relationships with temperature, dew point, and precipitation. The weather variables explained 60.2% of the variability in spore concentrations.

Discussion

The spore data from the 4 days and three sites examined in this study demonstrate the average hourly concentrations and their correlations to certain weather variables. The large increases in spore concentrations that occurred on each day were labeled spore plumes. Similar phenomena have been observed in Corpus Christi, Texas, and

Table 6. Results from forward stepwise multiple regression analysis correlating log-transformed hourly spore concentrations with meterological parameters for Tulsa, Bixby, and Hectorville sites

Spore type	r^2	*df*	Beta values					
			Temp	Dew pt.	Air pressure	Wind direction	Wind speed	Precip.
Tulsa								
Cladosporium	**0.266***	2, 45	**0.537**			–0.24		
Alternaria	**0.225**	2, 45	**0.373**		–0.17			
Epicoccum	**0.121**	2, 45	**0.316**			–0.27		
Curvularia	**0.262**	2, 45	**0.538**			–0.15		
Pithomyces	**0.307**	4, 43	0.252		–0.26	**–0.55**	0.239	
Drechslera	**0.343**	4, 43	**0.455**		–0.26	**–0.37**		–0.17
Smut spores	**0.256**	3, 44	**0.358**			**–0.32**	**0.290**	
Ascospores	**0.447**	4, 43	–0.19	**0.287**		**–0.37**	**0.353**	
Basidiospores	**0.375**	5, 42		**0.449**	0.281	–0.25	0.238	–0.30
Other	**0.342**	3, 44			–0.16	**–0.38**	**–0.507**	
Total	**0.280**	3, 44	**0.588**	0.214		**–0.34**		
Bixby								
Cladosporium	**0.310**	2, 45	**0.626**		0.251			
Alternaria	**0.602**	3, 44	**0.680**	**0.281**				**0.217**
Epicoccum	**0.359**	4, 43	**0.573**	0.215	0.286	–0.14		
Curvularia	**0.379**	3, 44	**0.581**	0.143				0.132
Pithomyces	**0.419**	5, 42	**0.638**	0.173	0.151	–0.21		**0.301**
Drechslera	**0.344**	2, 45	**0.596**					0.161
Smut spores	**0.427**	4, 43	0.303	**0.387**	0.193		0.299	
Ascospores	**0.363**	5, 42	–0.50	0.196		–0.20	0.318	0.260
Basidiospores	**0.481**	4, 43	**–0.47**	**0.472**			–0.19	–0.15
Other	0.100	3, 44			0.198		0.274	0.149
Total	**0.348**	4, 43	**0.459**	0.145	0.260		0.240	
Hectorville								
Cladosporium	**0.340**	4, 43	0.319		0.306		0.248	**–0.28**
Alternaria	**0.421**	4, 43	**0.507**	0.176		**0.359**	–0.15	
Epicoccum	**0.354**	4, 43	**0.371**	0.179		**–0.40**	**–0.36**	
Curvularia	**0.215**	3, 44	**0.491**			–0.17	**–0.35**	
Pithomyces	**0.278**	2, 45	**0.422**			**–0.36**		
Drechslera	**0.129**	3, 44	**0.424**		**–0.34**		–0.18	
Smut spores	**0.260**	3, 44		**0.359**	0.177	**–0.35**		
Ascospores	**0.652**	6, 41	**–0.62**	**0.228**	0.152	**–0.51**	**0.421**	**0.221**
Basidiospores	**0.498**	6, 41	**–0.30**	**0.693**	–0.26	–0.20	**–0.33**	0.143
Other	**0.304**	2, 45				**–0.48**	**0.406**	
Total	**0.312**	3, 44	0.241		**0.353**		**0.390**	

*Significant beta values and r^2 ($P < 0.05$) are shown in bold type

called spore bursts, which have been described for *Cladosporium* spores, as well as for *Alternaria* and *Curvularia* spores (Dixit et al. 2000). Although spore bursts were observed more frequently in the study by Dixit et al. (2000), none of the days examined showed spore bursts with concentrations as high as the spore plumes observed in Tulsa.

The spore plumes occurring on 21 and 30 September 1998 were similar. Both exhibited plumes at 1000 hours, with concentrations gradually declining throughout the day. The spore plume occurring on 18 September 1998 was not as pronounced as those on the other three days. Spore concentrations stayed relatively high throughout 18 September, and there was a smaller plume than on the other 3 days. The data for 7 September were unique because two spore plumes were recorded. The first plume occurring on this day was at 0800 hours, which was earlier than any of the plumes on other days. The second plume occurred at 1800 hours, which was later than any of the other plumes. The latter plume was most likely triggered by a dramatic increase in wind speed due to a severe thunderstorm accompanied by damaging winds. The large increase in total spore concentrations during the spore plumes was largely due to increases in *Cladosporium* and *Alternaria* concentrations. The diurnal rhythm for both of these spore types reaches its peak in the afternoon (Ingold 1971), but most spore plumes in this study occurred before noon. Also, the *Cladosporium* and *Alternaria* concentrations observed in many spore plumes were over two times higher than those found in a normal diurnal rhythm.

Temperature was the weather variable that was the most consistent predictor of spore concentrations for each of the 4 days, and all members of the dry-air spora showed positive correlations with temperature. Temperature was negatively correlated with ascospores and basidiospores, because they were found in the air during the cooler nighttime and evening hours. These correlations reflect the diurnal rhythm of spore release, with high ascospore and basidiospore concentrations during the cooler, wetter nighttime hours (Hirst 1953; Ingold 1971).

Air pressure, dew point, and wind speed also seemed to play a role in predicting high spore concentrations on spore plume days. Total spores, basidiospores, ascospores, and *Alternaria* spores were all significantly and positively correlated with dew point, and other spores were positively, but not significantly correlated with dew point. Basidiospores and ascospores, which require moist conditions for release, would be expected to correlate with dew point, but dry-air spores such as *Alternaria* would not be expected to show this correlation. An increase in air pressure had a significant effect on the hourly concentration of *Cladosporium* and total spores. For all three sites on 21 September 1998, air pressure was the most consistent predictor of total spore concentrations, and an air pressure increase occurred near the time of spore plumes on most days. This was not expected, as previous studies have not found air pressure to be a significant meteorological variable affecting spore levels (Hjelmroos 1993). The increase in air pressure, wind speed, and dew point during the spore plumes on 21 and 30 September 1998 is probably due to a cold front moving into the area, which caused a thunderstorm later on those evenings.

Generally, the spore plume was accompanied by an increase in wind speed. Although spores plumes were largely composed of *Cladosporium* and *Alternaria* spores, neither of these were correlated with wind speed in the regression analysis. This lack of statistical significance is thought to be due to changing weather conditions that occurred later in the evenings of 7 September 1999, 21 September 1998, and 30 September 1998. The rainfall from thunderstorms may have washed out much of the *Cladosporium* and *Alternaria* spores, resulting in low *Cladosporium* and *Alternaria* levels even though wind speeds were high.

The meteorological events occurring during a spore plume seem to be related to those events associated with an incoming cold front or thunderstorm. Cold fronts are generally accompanied by an increase in air pressure, which was observed during the spore plume for 3 of the 4 days. Thunderstorms form when warm air along the ground gets pushed upward and replaced with colder air from higher in the atmosphere. This colder air can travel downward from a developing thunderstorm and outward once it strikes the ground (Ahrens 1994). This can create a gust front, which can travel along the ground in front of a thunderstorm. The increased movement of air that occurs when thunderstorms are developing may have caused the large increase in airborne spores occurring 8–10 h before the front moved through on the days of 21 and 30 September 1998 and 7 September 1999. Also, significant vertical mixing of air occurs during stormy weather, but the vertical component of wind speed was not measured by the meteorological instruments in this study. If vertical gusts of air and downdrafts were significant factors in the dispersal of fungal spores during spore plumes, then this could also explain the low correlation of wind speed calculated in the regression analysis.

The spore plumes on 7 September 1999 and 21 and 30 September 1998 were more pronounced than the plume occurring on 18 September 1998. Only 33.1% of the variation on 18 September 1998 was explained by the weather variables in the model, a much lower percentage than on 2 of the other 3 days. These differences may be because no thunderstorm occurred on 18 September. The thunderstorms on each of the other days were probably related to the increases in dew point, air pressure, and wind speed that were necessary for spore plumes to develop.

Other studies have outlined the changes in spore concentrations before, during, and after thunderstorms (Hirst 1953; Allitt 2000). Allitt described the changes in fungal air spora that occurred during a thunderstorm over England in 1994. In this study, transient peaks of *Cladosporium* conidia were observed before and during the rainfall, but the concentrations were not as high as those observed during spore plumes. Also, Hjelmroos (1993) found that the presence of *Cladosporium* spores was significantly correlated with daily mean temperatures and daily precipitation, and *Alternaria* spores were associated with increases in daily precipitation, wind velocity, and total cloud cover. These results are similar to those seen on days when there were spore plumes.

The conditions leading up to spore plumes were varied. The spore plume on 30 September 1998 occurred after several days of dry weather followed by changing meteorological conditions. The dry weather possibly allowed for a build-up of dry-air spores, and increases in wind speed, dew point, air pressure, and changing weather conditions associated with thunderstorms allowed these spores to be dispersed. By contrast, spore plumes on 21 September 1998 occurred after a period of moist weather. The moist conditions may have allowed for a large amount of fungal growth, and spores from this growth could be released when conditions became favorable. Further studies of additional plumes from Tulsa and other areas are needed to determine if conditions on preceding days are important for the development of spore plumes.

The concentrations of *Cladosporium* and *Alternaria* observed during spore plumes might be sufficient to cause sensitization even with only a limited exposure time. This has an important clinical significance, because sensitization to spore types found in extremely high levels in this study, such as *Cladosporium* and *Alternaria*, has been linked to asthma severity. Studies have shown that sensitization to *Alternaria alternata* is associated with severe asthma apart from life-threatening exacerbations (Neukirch et al. 1999). Other studies have found significant correlations between the occurrence of respiratory symptoms and *Cladosporium* and *Alternaria* spores (Ostro et al. 2000). Also, a study examining the relationships between skin tests for fungal spores and admission to an intensive-care unit found that a positive skin test for fungal dry-weather spores such as *Cladosporium*, *Alternaria*, and *Epicoccum* was a risk factor for admission to an intensive-care unit with an acute attack of asthma (Black et al. 2000). Although the appearance of spore plumes before thunderstorms may have some effects on sensitization as well as on respiratory symptoms, further research needs to be completed.

In summary, the large increases in spore concentrations that contributed to spore plumes were mainly due to increases in *Cladosporium* and *Alternaria* concentrations. A combination of increases in temperature, air pressure, wind speed, and dew point was the most consistent and accurate predictor of the appearance of a spore plume. Of the different models examined in the regression analysis, the models grouped by date explained more of the variability. This suggests that different weather conditions on individual days were more significant factors than the ecological differences at individual sites. Although no single model could explain the data or predict the appearance of a plume, the changing weather conditions associated with thunderstorms entering the Tulsa area later in the evening could have influenced the development of a spore plume.

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