Int J Biometeorol (2004) 48:137–141
DOI 10.1007/s00484-003-0188-9

ORIGINAL ARTICLE

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Relationships between airborne fungal spore concentration of *Cladosporium* and the summer climate at two sites in Britain

Received: 7 October 2002 / Accepted: 27 June 2003 / Published online: 19 August 2003

Abstract *Cladosporium* conidia have been shown to be important aeroallergens in many regions throughout the world, but annual spore concentrations vary considerably between years. Understanding these annual fluctuations may be of value in the clinical management of allergies. This study investigates the number of days in summer when spore concentration exceeds the allergenic threshold in relation to regional temperature and precipitation at two sites in England and Wales over 27 years. Results indicate that number of days in summer when the *Cladosporium* spores are above the allergenic concentration is positively correlated with regional temperature and negatively correlated with precipitation for both sites over the study period. Further analysis used a winter North Atlantic Oscillation index to explore the potential for long-range forecasting of the aeroallergen. For both spore measurement sites, a positive correlation exists between the winter North Atlantic Oscillation index and the number of days in summer above the allergenic threshold for *Cladosporium* spore concentration.

Keywords *Cladosporium* · Spores · Forecast · NAO · North Atlantic Oscillation

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Introduction

Cladosporium is one of the most abundant world-wide airborne fungi (Molina et al. 1998), particularly in temperate regions (Gravesen 1979). The abundance of conidia in the atmosphere is due in a large part to their ability to exist and thrive on a wide array of substrates. A number of studies have confirmed that *Cladosporium* spores are an important aeroallergen and exposure to high concentrations affects human health by increasing the incidence of asthma and bronchial ailments (Lewis et al. 2000; Barnes et al. 2001). *Cladosporium* has relatively small spores and so airborne concentrations must reach high levels in order to induce allergenic symptoms (Brown and Jackson 1978). Previous authors (Frankland and Davies 1965; Gravesen 1979) have estimated an allergenic airborne concentration threshold of 3,000 spores m^{-3} for *Cladosporium*. More recently a figure of 4,000 spores m^{-3} has been cited (Anon 2002). There is great variation both within the year and between years in the airborne concentration of *Cladosporium* conidia, which could lead to variation in the incidence of *Cladosporium*-linked allergic symptoms.

The highest concentrations of *Cladosporium* occur in the warmer summer months (Davies et al. 1963), and weather is known to have an effect on spore production and dispersal. Mean daily temperature and precipitation were shown by Hjelmroos (1993) and Kurkela (1997) to be important factors contributing to an increase in spore abundance. Both these studies investigated short-period weather variables on the basis of only a few years of data. Furthermore, these investigations only made use of weather variables taken from single stations near to spore collection sites. Such local data are unlikely to model adequately the weather influencing spore production, release and dispersal, since *Cladosporium* spores have been found to be transported hundreds of kilometers by wind (Hirst and Hurst 1967). Few studies have been carried out examining weather variables over longer seasonal periods. Such climatic data taken from a region over which spores originate are likely to be more useful in investigating climate effects on spore concentration.

Since summer weather can effect *Cladosporium* spore production and dispersal, and because there is growing evidence that British summer weather, in turn, is related to the state of a previous winter large-scale climate system, it may be possible to forecast *Cladosporium* airborne concentration. The large-scale winter climate system is referred to as the North Atlantic Oscillation (NAO)—an atmospheric pressure pattern across the Atlantic Ocean. The NAO has a profound influence on the climate in Europe (Hurrell and Van Loon 1997) and the UK (Wilby et al. 1997) and, mediated by the climate, there are numerous examples of the effect of the NAO on a wide diversity of ecosystems. These are documented by Ottersen et al. (2001), and range from the breeding behaviour of Norwegian red deer and the abundance of North Sea zooplankton through to the quality of British wheat at harvest time. No published work has been found investigating the possibility of a relationship between NAO and aeroallergens.

The behaviour of the NAO can be monitored via an index—usually monthly or seasonal. In its simplest form an index can be calculated by measuring the daily atmospheric pressure difference between a meteorological station in Iceland, and one in the mid-eastern Atlantic region—typically the Azores. The differences are standardised over the measurement period and a monthly or seasonal mean figure produced. Recognised pre-calculated indices are readily available.

The relationship between the winter (December/January/February) NAO index and winter climate is well documented. In Britain a positive winter NAO index is typically associated with a warmer winter season, whereas a negative index usually results in a colder, drier winter season (Wilby et al. 1997). More recent work has shown that the winter NAO index is correlated with summer climate. A positive winter NAO index leads to a warmer (Quian and Saunders 2003), drier summer (Kettlewell et al. 2003), with more severe drought (Wedgebrow et al. 2002). It may, therefore be possible to use the winter NAO to forecast *Cladosporium* spore concentration.

The aim of this study was to test the hypothesis that the average summer temperature and precipitation each year are correlated with the number of days in the summer when the airborne *Cladosporium* spore concentration exceeds the allergenic threshold. In addition, the winter NAO is investigated as a possible means of forecasting the airborne concentration of *Cladosporium* spores above the allergenic threshold.

Materials and methods

Fungal spores were collected in Burkard volumetric traps by the Midlands Asthma and Allergy Research Association (MAARA) in Derby in Central England (1970–1998) and by the Asthma and Allergy Research Unit at Sully Hospital in Cardiff, South Wales (1970–1997). *Cladosporium* spores collected in the trap were counted daily and the spore concentration calculated (m^{-3}).

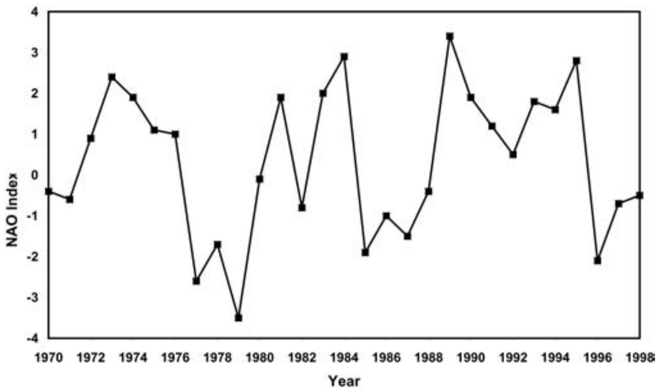

Fig. 1 Time series for mean winter (December/January/February) North Atlantic Oscillation (NAO) index (Rogers 1984)

In order to quantify the allergenic risk in each year, the number of days in the summer (June/July/August) when the spore concentration equalled or exceeded the clinical threshold of 4,000 spores m^{-3} (Anon 2002) was calculated for each year. This number is referred to subsequently as the number of days above threshold.

Correlation analysis was carried out between the number of days above threshold from both sites and total summer precipitation (June/July/August) in England and Wales (EWP) (Wigley et al. 1984), the mean summer temperature (June/July/August) for Central England (CET) (Manley 1974; Parker et al. 1992) and a mean annual winter (December/January/February) NAO index. The CET region approximates to a triangular area bounded by Lancaster at the northern corner, Stroud at the south-western corner and London at the south-eastern corner. Cardiff lies approximately 30 km outside the recognized region, but over such a small distance the difference in seasonal mean temperature is likely to be very small. Both EWP and CET datasets were obtained from the Climatic Research Unit website, University of East Anglia (http://www.cru.uea.ac.uk). The Rogers (1984) winter NAO index was used (Fig. 1), obtainable from the Ohio State University website (http://polarmet.mps.ohio-state.edu/NAO/).

Finally multiple linear regression models were analysed for each site, using the number of days above threshold as the response variable against the climatic variables CET, EWP and NAO as explanatory variables.

Correlation between variables recorded over the same time period can show significant relationships simply as a result of both variables displaying coincident long-term trends, yet having minimal relationship between short-term year-to-year variation (Stephenson et al. 2000). To eliminate the possibility that coincident trends inherent in the data were responsible for spurious correlation results, all time-series data were detrended by calculating year-to-year differences. For each year the number of days above threshold in the previous year was subtracted to give the first-order difference. This was repeated for every year (except the first year). The CET, EWP and NAO index data were also differenced before correlation coefficients were calculated. Only those correlations coefficients significant after differencing were considered to show true relationships.

Results and discussion

The number of days above threshold (Fig. 2) for the two sites followed a similar pattern. The Cardiff values are noticeably lower in magnitude than those of Derby, but data from the two sites are moderately positively correlated ($r = 0.55$; $P < 0.01$).

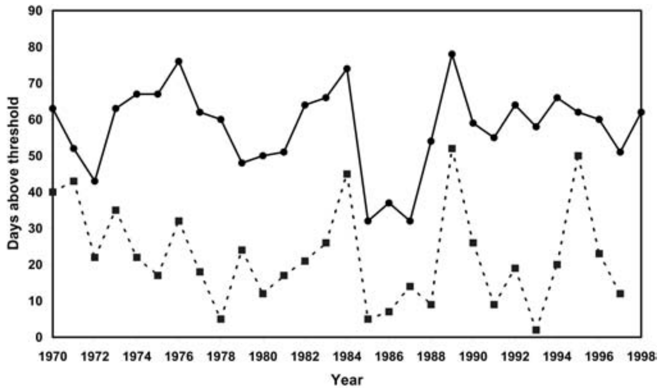

Fig. 2 Time series for the number of days in summer (June/July/August) on which *Cladosporium* summer spore concentration exceeds the allergenic clinical threshold value (4,000 spore m^{-3}) at two sites in the British Isles: Cardiff (■- - -■) and Derby (●–●)

For both sites, the number of days above threshold was significantly and positively correlated with CET (Fig. 3a, c). This relationship is consistent with the conclusions of Katial et al. (1997) and Hjelmroos (1993) using single-station daily weather data. They also indicated that there is a positive correlation with airborne spore concentration and temperature. Temperature is largely regarded as promoting spore production via mycelial growth, rather than a spore release mechanism. It can be speculated that, with the effect of climate change in Britain resulting in warmer mean summer temperatures (Barrow and Hulme 1996), the number of days with *Cladosporium* conidia at allergenic levels may become greater.

In contrast to the positive relationship with temperature, the number of days above threshold, for both sites, was significantly and negatively correlated with EWP (Fig. 3b, d). There is no clear consensus within the literature concerning *Cladosporium* and precipitation. Hjelmroos (1993) found a positive correlation between the airborne spore concentration of *Cladosporium* and precipitation over 6-h measurement periods. However, our results are in agreement with those of Katial et al. (1997) who found a negative relationship using a longer 24-h measurement period. *Cladosporium* is considered a member of the dry-air spora, but the measurement time for precipitation does appear to be crucial. Kurkela (1997) suggests that the onset of rain is important in promoting spore liberation. Other studies suggest that the intensity of rainfall is also a significant factor (Rich and Waggoner 1962) with light showers increasing atmospheric wash-out and decreasing airborne spore concentration, and heavy showers increasing the number of spores brought aloft, hence increasing the airborne concentration. The correlations with number of days above threshold are stronger with CET than with EWP (Table 1). The correlation

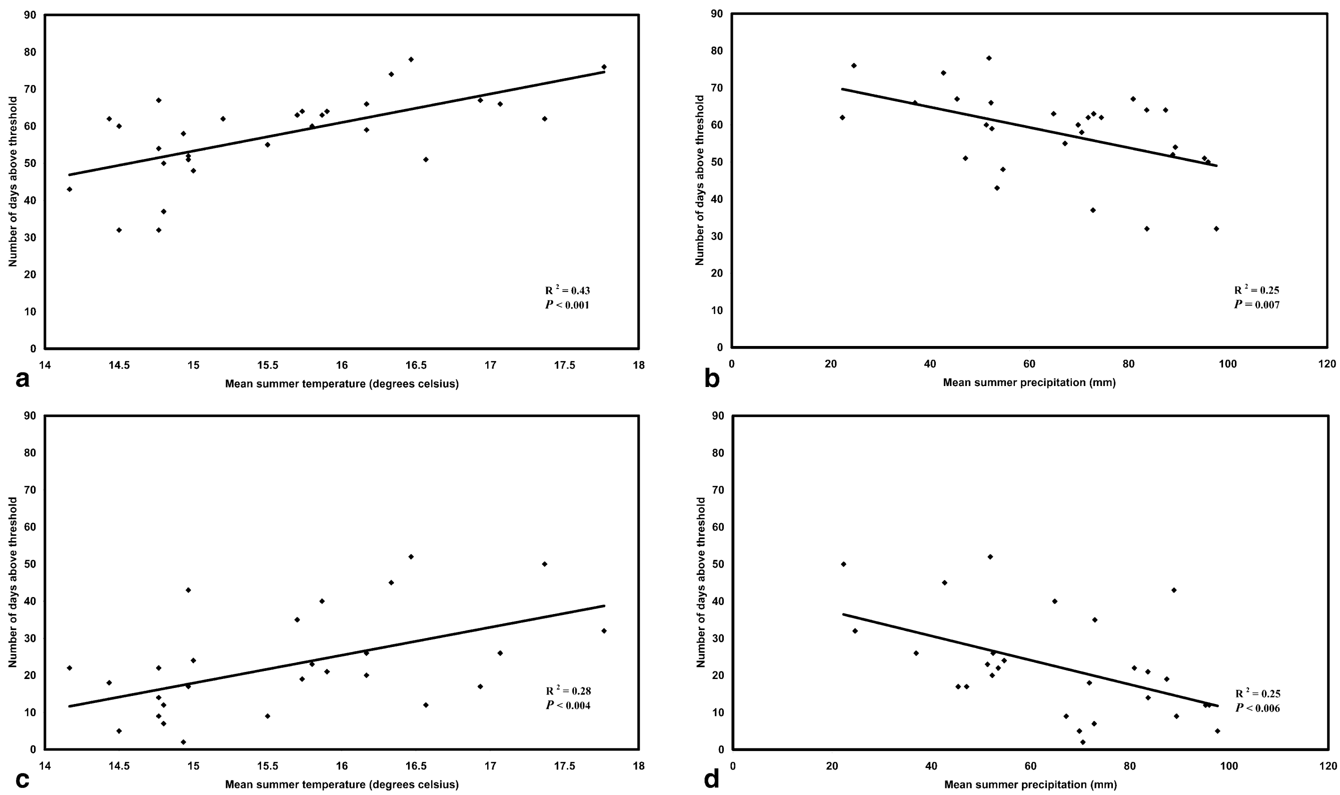

Fig. 3a–d Scatter plots correlating the number of days in summer on which *Cladosporium* spore concentration exceeds the allergenic threshold value (4,000 spores m^{-3}) with mean Central England Temperature (**a, c**) and England and Wales precipitation (**b, d**) at two sites in the UK: Derby (**a, b**) and Cardiff (**c, d**). **a** $R^2 = 0.43$, $P < 0.001$; **b** $R^2 = 0.25$, $P < 0.007$; **c** $R^2 = 0.28$, $P < 0.004$; **d** $R^2 = 0.25$, $P < 0.006$

Table 1 Coefficients for correlation between the number of days in summer when the *Cladosporium* spore concentration exceeds the clinical threshold value (4,000 spores m^{-3}) at two sites in England and Wales and summer regional climate measurements of England and Wales: precipitation (*EWP*), central England temperature (*CET*) and the Rogers winter NAO index

	Number of days above threshold		Climatic variable		
	Derby	Cardiff	CET	EWP	NAO
Number of days above threshold					
Derby	1.00				
Cardiff	0.55**	1.00			
Climatic variable					
CET	0.65**	0.53**	1.00		
EWP	–0.50**	–0.50**	–0.63**	1.00	
NAO	0.55**	0.46*	0.50**	–0.47*	1.00

* Significant at $P < 0.05$
** Significant at $P < 0.01$

Table 2 Parameters from multiple linear regression of three explanatory climatic variables: mean summer Central England Temperature (*CET*), total summer England and Wales precipitation (*EWP*), the Rogers winter NAO index, on the response variable: the number of days in summer when *Cladosporium* spore concentration exceeds the allergenic threshold (4,000 spores m^{-3}) at two sites in England and Wales

Locality	Explanatory variable	Percentage of sum of squares	*P*
Derby	CET	97.35	<0.001
	EWP	0.39	0.301
	NAO	0.25	0.083
	Overall		<0.001
Cardiff	CET	75.74	<0.001
	EWP	5.69	0.073
	NAO	1.12	0.216
	Overall		<0.001

between CET and EWP is negative ($r = -0.63$, $P < 0.01$), perhaps indicating that it is the correlation with temperature that is the direct and causal relationship with number of days above threshold. In other sites worldwide, such a negative relationship may not be so pronounced, further explaining the conflict in the literature on precipitation effects on airborne spore concentration.

Since summer mean temperature and total rainfall can be related to the number of days above threshold in summer at these two sites, it may be possible to use the winter climate NAO to forecast spore concentration. Correlations between the winter NAO index and the number of days above threshold are significant (Table 1). These relationships may be explained by the long-range effect of the winter NAO on summer weather, since correlations between the winter NAO index and summer climate are also significant (Table 1) and consistent with the findings of both Kettlewell et al. (2003) and Quian and Saunders (2003). However, these correlations are probably not strong enough to enable useful forecasts to be made.

Since a positive winter NAO is known to lead to higher winter temperatures in the UK (Wilby et al. 1997) the correlation between the winter NAO index and summer spore concentration may alternatively result from a climatic effect in winter. Milder winters may increase the development of fungal mycelium, in turn leading to a greater number of spores available for summer release. Multiple linear regression models were used to examine in more detail the spore concentration response to the winter NAO. Explanatory variables used were summer temperature, summer precipitation and the winter NAO index. Temperature rather than precipitation was fitted first because there was a stronger relationship with the number of days above threshold (Fig. 3). Precipitation was then fitted to examine whether there was any independent effect not due to the correlation between temperature and precipitation. Finally the NAO index was fitted to determine whether any additional variation in number of days above threshold could be accounted for by a climatic effect of the NAO during the winter. Summer temperature was significant at both localities, but neither precipitation nor the winter NAO index accounted for any further significant variance within the models examined (Table 2). This supports the previous hypothesis that the relationship with precipitation can be explained by the correlation between temperature and precipitation and that the relationships between number of days above threshold and temperature shown in Fig. 3a, c indicate the dominant effect of the summer climate. Lack of significance of the NAO index suggests that the winter NAO effect is indirect and mediated by the summer climate, which then impacts on *Cladosporium*.

Acknowledgements We thank the Midlands Asthma and Allergy Research Association (MAARA) for funding long term aerobiological research.

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