

A synoptic climatology of pollen concentrations during the six warmest months in Sydney, Australia

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Received: 9 June 2005 / Revised: 13 March 2006 / Accepted: 26 June 2006 / Published online: 26 September 2006
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Abstract This paper takes an air mass approach to investigating the influence of weather on pollen concentrations in the atmosphere in Sydney, Australia, by producing a synoptic classification of pollen concentrations measured in the Sydney Basin. This synoptic classification has been produced using multivariate statistical techniques including principal component analysis and cluster analysis, to assign days into meteorologically homogenous categories. Surface and upper air meteorological data for warm months (October–March) over a 10-year period were used as input into the statistical analyses. Eleven synoptic categories were found in Sydney during the warm months. Pollen concentrations for the total pollen load and five individual families measured over a 3.5-year period have been investigated for each of the synoptic categories. High pollen concentrations during the warm months in Sydney are found to be influenced by the presence of a region of low surface pressure located to the south of the continent, bringing fast dry westerly gradient winds to Sydney. It is envisaged that these results will be important from a pollen forecast and associated public health perspective.

Keywords Cluster analysis · Pollen · Principal component analysis · Synoptic climatology · Sydney

Introduction

Synoptic weather patterns and associated air mass characteristics influence atmospheric pollen concentrations with respect to factors including the timing and length of the pollination period and subsequent transport of pollen. Pollen in the atmosphere is capable of triggering symptoms of allergic respiratory diseases, and as such, is a major public health problem. The majority of previous studies analysing the effects of weather and climate on pollen concentrations have concentrated on analyses involving individual (or a small suite of) surface meteorological variables, such as temperature, relative humidity, sunshine hours, rainfall and wind speed/direction. This paper takes an air mass approach to analysing the effect of weather on pollen concentrations in the atmosphere in Sydney, Australia, by producing a synoptic classification of pollen concentrations for total pollen loads and for five important individual families measured in the Sydney Basin over a 3.5-year period. This climatology has been produced using multivariate statistical techniques including principal component analysis and cluster analysis. Meteorological inputs to these statistical procedures include both surface and upper air observations, for warm months (October to March), over a 10-year period (1992–2001), and encompass both the synoptic and meso-scale.

Sydney is located on the eastern coast of Australia at latitude 33.8°S, longitude 151°E, and experiences a temperate climate with warm to hot summers and cool to cold winters (Bureau of Meteorology 1991). The main

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urban areas are located within a basin bound by elevated terrain to the north, west and south, and the Tasman Sea to the east. The weather in the region is affected by this relatively complex topography with overnight cold-air drainage flows, particularly during cooler months, and frequent sea breezes during the warmer months. Figure 1 shows the urban extent of Sydney, the surrounding topography and the location of the pollen monitoring site used in this study.

To our knowledge, this is the first time a synoptic climatological approach has been used to demonstrate the relationship between weather and pollen. Previous studies have used statistical methods, such as regression analysis and Spearman's correlation procedures, to analyse the relationship between pollen concentrations and individual meteorological variables. In most studies, the major outcome has been a positive correlation with pollen and, temperature and sunshine hours, and a negative correlation with rainfall and relative humidity (e.g. Alba et al. 2000; Gioulekas et al. 2004; Green et al. 2004; Jato et al. 2000; Ribeiro et al. 2003; Stennett and Beggs 2004). Furthermore, Stennett and Beggs (2004) analysed the influence of mean

sea level pressure on pollen concentrations in Sydney and found a mild negative association.

A study by Laaidi (2001) undertook an analysis on the influence of meteorological conditions on pollen and pollinosis using weather types. Weather types were correlated using multiple-component analysis with both pollen concentrations in the air and pollinosis symptoms. Weather types were classified using upper air meteorological fields, including geopotential height and vertical temperature gradients. Results showed that windy conditions with little or no precipitation and temperatures greater than 6°C favoured pollen dispersal.

Other approaches for investigating the effects of meteorological parameters on pollen concentrations include analysis of hourly wind data from coastal, urban and rural meteorological stations in order to examine the effect of the sea breeze circulation on Poaceae in Mar del Plata, Argentina (Gassmann et al. 2002). The Gassmann et al. (2002) study found evidence of pollen retainment brought about by air recirculation. Laaidi et al. (2003) compared two forecast models, summing of temperatures (which consisted of a cumulative summing the daily average

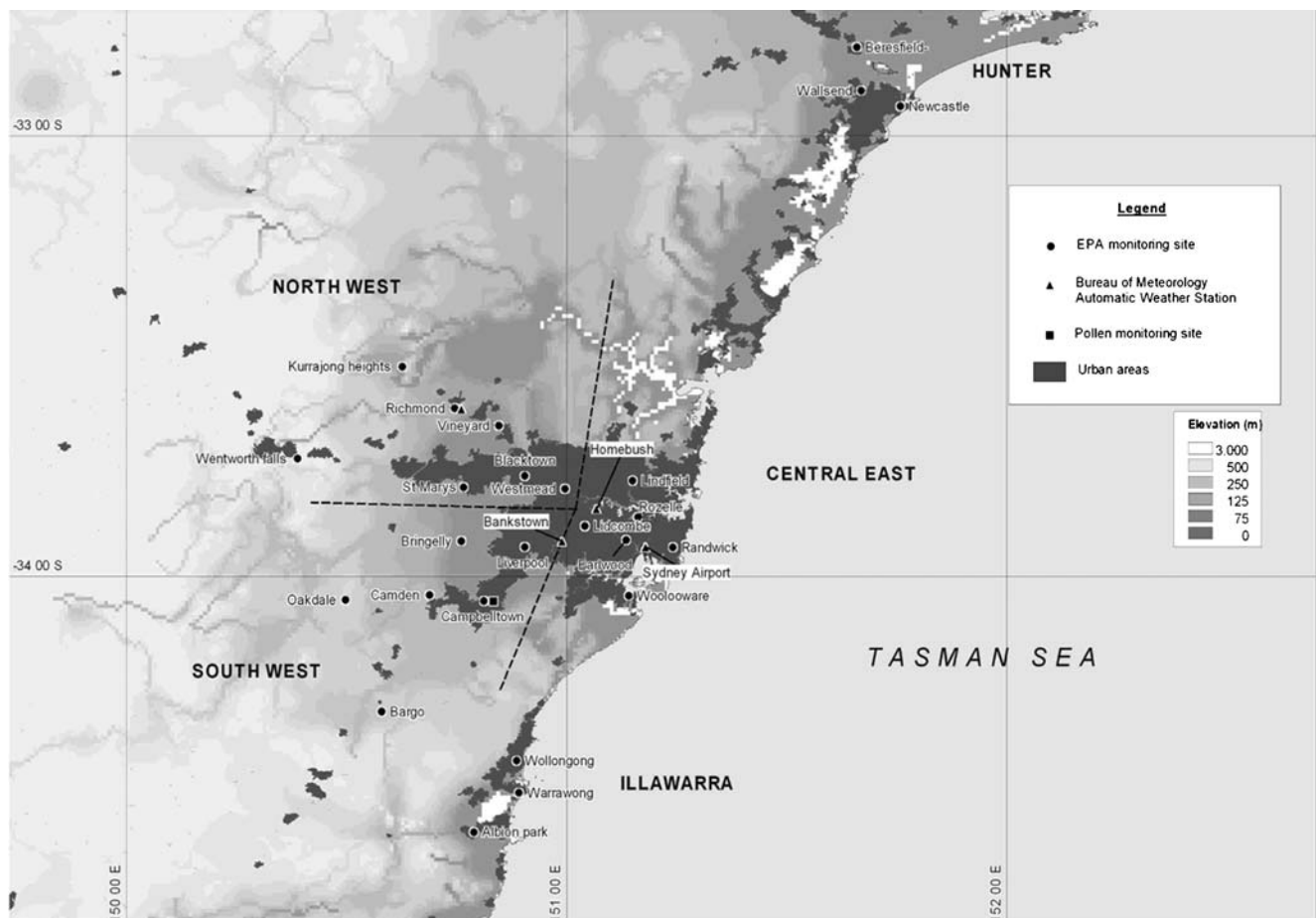


Fig. 1 Location map and topography of the Sydney Basin and surrounds. Local air quality monitoring stations and pollen monitoring site are shown

temperatures from a statistically determined date, above a thermal threshold to the start date of the pollen season), and multiple regression on 10-day or monthly meteorological parameters. They found the regression model was more accurate at predicting start and duration of the season. Recio et al. (1997) used accumulated rainfall and temperature variables (accumulated temperature and rainfall were calculated from the chilling requirement for flower bud initiation) as a predicting parameter for daily airborne olive pollen in Málaga, Spain. Daily variations in airborne olive pollen were found to depend more on accumulated temperatures than on accumulated rainfall. Growing degree hours have also been used to predict the start of the birch and grass pollen season in Nuuk, Greenland (Porsbjerg et al. 2003).

Valencia-Barrera et al. (2002) used a similar hypothesis to the one adopted in this paper in that environmental variables such as pollen are expected to respond to the air mass, as a whole, rather than individual meteorological variables. They compared correlation coefficients between daily Poaceae pollen data from León, Spain, with either simple daily meteorological variables or compound daily bioclimatic indices. For time frames larger than the main pollen period, they found bioclimatic indices produced the largest correlation coefficients, and concluded that bioclimatic indices could be more valuable for pre-season pollen forecasting.

Materials and methods

Meteorological data

Surface and upper-air meteorological data from the Australian Bureau of Meteorology's weather stations at Sydney Airport (a coastal location) and Richmond (approximately 60 km inland), for warm months, months often conducive to high pollen concentrations (October–March), over a 10-year period (1992–2001) were used as input into the statistical analysis. The general goal of any synoptic climatological method is to combine individual meteorological variables into categories that are representative of the synoptic-scale situation. Therefore a coherent combination of meteorological variables is required that is representative of distinct air mass types.

Sydney's environment is geographically complex. There are controls on weather patterns from the surrounding Sydney Basin generating a complicated drainage flow combined with sea breeze circulation. Therefore, the inclusion of upper air variables was deemed imperative to a comprehensive understanding of the air mass characteristics experienced in Sydney. The final configuration of meteorological variables presented in Table 1 was used as input to the multivariate statistical analyses.

Observations from the 850 hPa level were chosen as it is a commonly measured level and the air mass at this level is

Table 1 Surface and upper air meteorological variables used for input to statistical analyses

Meteorological variables			Units	Comments and Rationalisation
6:00 a.m.	Surface	Temperature	°C	Defining the thermal and moisture properties of the air mass
		Dew point temperature	°C	
		<i>u</i> wind	m/s	
		<i>v</i> wind	m/s	
		MSLP	hPa	
		Total cloud amount	oktas	As a surrogate for incoming solar radiation
	Upper air	850 hPa temperature	°C	Defining the thermal and moisture properties of the air mass
		850 hPa dew point temperature	°C	
12:00 p.m.		Mixing height	m	
3:00 p.m.	Surface	Temperature	°C	Defining the thermal and moisture properties of the air mass
		Dew point temperature	°C	
		<i>u</i> wind	m/s	
		<i>v</i> wind	m/s	
		MSLP	hPa	
		Total cloud amount	oktas	As a surrogate for incoming solar radiation
	Inland–coastal temperature	°C		
	Upper air	Mixing height	m	
		850 hPa temperature	°C	
		850 hPa dew point temperature	°C	
		850 hPa <i>u</i> wind	m/s	
		850 hPa <i>v</i> wind	m/s	
		975 hPa temperature	°C	Indicative of temperature conditions within the sea breeze
		925 hPa temperature	°C	Indicative of the temperature just above the sea breeze

often above the planetary boundary layer and therefore corresponds to gradient wind conditions. Mixing height was included because of its importance in the dispersion of airborne particulate matter. Mixing height is the height at which the atmosphere is uniformly mixed by convection of mechanical turbulence within an hour of a surface emission (Seibert et al. 2000). Mixing height was derived graphically from upper air temperature traces as the point at which a parcel of air rising dry adiabatically crosses the environmental lapse rate (Holzworth 1967). Midday mixing height was derived using the 6 a.m. radiosonde temperature trace and the 12 p.m. surface temperature, while the 3 p.m. mixing height was derived using the 3 p.m. temperature trace to determine the approximate height of the sea breeze. Wind components are such that a positive u component and a positive v component represent winds from the south-west quadrant.

Pollen data

There have been only isolated pollen sampling studies in the Sydney region. The pollen data set used in the current research was collected from 3.5 years of continuous observations of pollen concentrations between August 1992 and December 1995 (Bass and Morgan 1997). The pollen was collected at Campbelltown, a suburb on the south-west outskirts of the Sydney Basin, approximately 28 km from the coast. A vegetation map of Sydney and surrounding regions available online (Bureau of Rural Sciences 2005) shows that the pollen site is surrounded by native forest and woodlands to the east and south-east, native grasslands to the north-west through to south-west, with native forests and grasslands further afield. To the north and north-east of the site are the urban areas of Sydney. This dataset, although comprehensive, comes from only one sampling site and as such may not be representative of pollen concentrations experienced across the entire Sydney urban area. Pollen collected in the trap belonged to 25 families of flowering plants and 2 conifer families. Of the total airborne pollen, tree pollen comprised 65% of total pollen concentrations, weeds and herbs 11%, grasses 18%, and unidentified pollen (termed other) 6%. Daily concentrations of five of the most prolific pollen families found in Sydney by the Bass and Morgan (1997) study, along with the total concentration of all pollen (termed total pollen) have been included in this research. The five pollen analysed included: Cupressaceae, Poaceae, Myrtaceae, Oleaceae and Plantaginaceae. Figure 2 presents the mean pollen concentrations for each of the families analysed in this research for the six warmest months in Sydney. Total pollen concentrations are greatest at the beginning of the warm season (October, November, December). Concen-

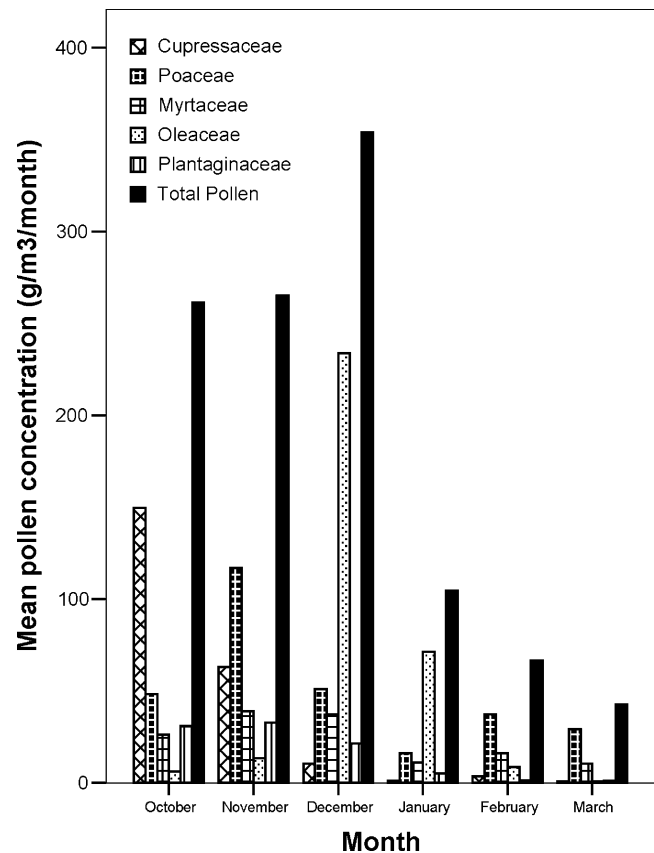


Fig. 2 Mean pollen concentrations for each taxa for each month of the warm season in Sydney

trations of Cupressaceae peak early in the warm season, in October and then progressively decrease as the summer progresses. Poaceae concentrations peak in November and Oleaceae concentrations in December. Both Myrtaceae and Plantaginaceae concentrations remain constant throughout the first half of the warm season and then decrease through the second half.

Synoptic climatology methods

An investigation of the synoptic climatology of pollen levels in Sydney was undertaken. This used multivariate statistical techniques, including principal component analysis and a two-stage cluster analysis, to classify days into meteorologically homogenous synoptic categories. These synoptic categories were then related to pollen concentrations measured within the Sydney Basin. The method of synoptic classification used in this research is the circulation-to-environment approach, in which the classification is produced first, and is then related to the environmental variable in question (Yarnal 1993). This method is commonly used to analyse the dependence of diverse variables, such as tropospheric ozone concentrations

(Cheng et al. 1992; Cheng 2001; Eder et al. 1994; Greene et al. 1999), and mortality and morbidity (McGregor et al. 1999, 2001) on air mass characteristics. To our knowledge, this is the first time it has been used to elucidate the dependence of pollen concentrations on weather.

The multivariate statistical techniques were used to group days into synoptic categories found to be representative of the air mass characteristics at that time. Principal component analysis (PCA) was used as a data reduction technique. P-mode PCA was undertaken which investigates fluctuations over time of a suite of meteorological variables at one point in space. To standardise the raw data, a correlation matrix was developed (Preisendorfer and Mobley 1988; Yarnal 1993). Data reduction is achieved in PCA by finding linear combinations (principal components) of the original variables, which account for as much of the total variance in the original variables as possible. The components are ordered such that the first one explains the greatest proportion of the variance and the second accounts for as much of the residual variance as possible, while remaining orthogonal (i.e. completely unrelated) to the first in data-space. Remaining components explain less variance than the preceding components. By retaining the leading principal components, a large amount of the original variance can be explained whilst substantially reducing the size of the data matrix for subsequent analysis to as many columns as retained components. Five principal components were retained (determined statistically) explaining 73.2% of the variance in the original data matrix (Cattell 1966; Preisendorfer and Mobley 1988; Yarnal 1993).

Each principal component comprises a series of loadings that represent the correlation coefficients between the principal component and the original meteorological parameters that constitute it. To ascertain the extent to which each day in the study period could be characterised by the principal components, component scores were calculated for each day by weighting the day's meteorological observations by their relevant loadings on each of the retained principal components. Thus, days with similar meteorological conditions will exhibit similar principal component scores (Shahgedanova et al. 1998).

The next stage in this analysis was to generate synoptic categories. Cluster analysis was applied to the principal component scores of each day in the 10-year data set. Clustering procedures grouped days with similar component scores and assigned each day into a meteorologically homogeneous subset of the data (Greene et al. 1999; Kalkstein and Corrigan 1986; Shahgedanova et al. 1998). The component scores matrix (number of days multiplied by the number of retained PCs) obtained from PCA served as the input matrix for cluster analysis. The reduced size and the absence of co-linearity in the component scores matrix make it ideal data for clustering (Davis et al. 1998).

A two-stage clustering technique was used. Firstly, average-linkage (a hierarchical, agglomerative method) was used to determine the number of clusters (synoptic categories) and the mean conditions within each cluster. The optimal number of clusters for the present climatology was found to be eleven.

Cluster seed values, the mean component scores within each cluster, were calculated for each of the 11 clusters. These seed values were then used as input to k-means clustering, which is a non-hierarchical technique using an iterative approach; days can be reclassified after they have been placed in a cluster. This approach refines the cluster solution; however the requirement of initial cluster number and cluster seed values means that it works best in collaboration with a hierarchical technique such as average-linkage. The final result of these statistical procedures is that each meteorological day is grouped with other days with similar meteorological conditions. Mean meteorological conditions within each cluster were then examined along with associated synoptic weather charts for each day within each cluster.

Results

Eleven synoptic categories were found in Sydney during the warm seasons within the 10-year study period. Figure 3 presents the number of days, over the 10-year period, that each of the synoptic categories occurred. Mean sea level pressure charts, representative of the mean meteorological conditions for each synoptic category, are presented in Fig. 4. Tables 2 and 3 present the mean meteorological conditions, plus the mean, maximum and standard deviations of pollen concentrations associated with each synoptic category, respectively. Figure 5 presents a box plot showing the within-group variance of total pollen concentrations in each of the eleven synoptic categories. Cumulative frequency plots of the Cupressaceae, Poaceae, Myrtaceae, Oleaceae and Plantaginaceae concentrations associated with each synoptic category are presented in Fig. 6a–e, respectively.

Synoptic category 1

Synoptic category 1 encompasses 9% of days. This category is characterised by an anticyclone centred over the eastern region of the Great Australian Bight bringing light west- south-westerly gradient winds over the continent to Sydney. Temperatures are mild over night and mild to warm during the day (average 24.7°C). A moderate easterly sea breeze is common during the afternoon, creating an inland - coastal temperature difference of 2.6°C on average. The mixed layer is deep at midday (average of ~1,000 m),

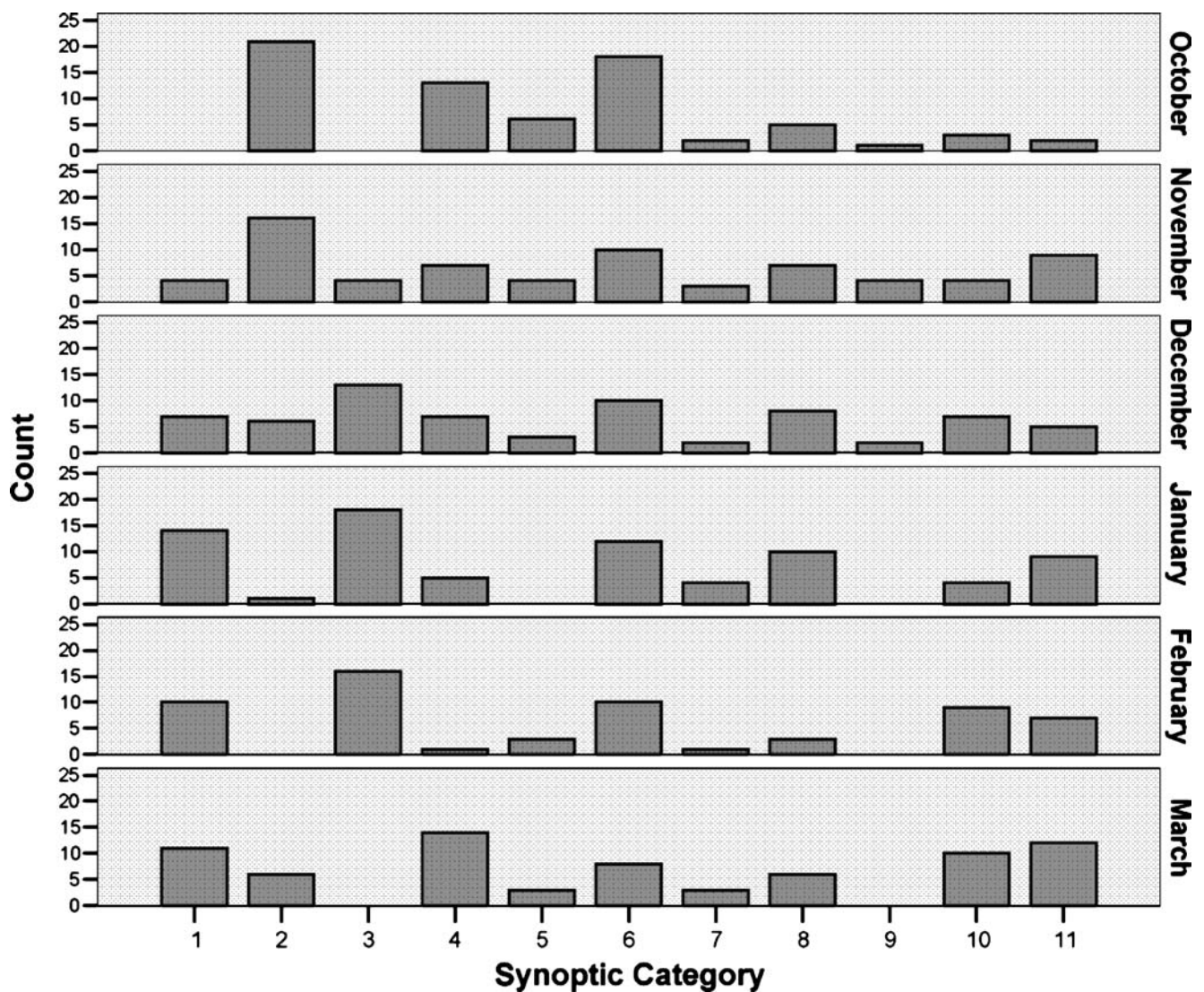


Fig. 3 Number of days per month each synoptic category occurs during the six warm months

decreasing to an average of ~700 m with the onset of the sea breeze. Meteorological conditions experienced in this category are associated with relatively low concentrations of average daily total pollen (average concentration 125 grains/m³). The pollen most prolific under these conditions is Oleaceae, with a maximum concentration of 900 grains/m³ on one of the study days.

Synoptic category 2

Days falling in synoptic category 2 experience similar synoptic conditions to category 1. However, gradient winds are stronger and temperatures are cooler, with 6 a.m. temperatures averaging 13.8°C, the coolest of all 11 categories. The anticyclone in the Great Australian Bight affecting Sydney's weather on these days was usually preceded by a cold front the day before which explains these cool temperatures. This category also included the

occasional single day with high concentrations of Cupressaceae and Poaceae. These outliers occurred early in the warm season coinciding with the period of pollination for both Cupressaceae and Poaceae.

Synoptic category 3

Synoptic category 3 is characterised by an anticyclone in the Tasman Sea ridging back across New South Wales and Queensland, bringing light northerly gradient winds shifting to westerlies in the afternoon. Temperatures are warm to hot (average 3 p.m. temperature 29.1°C), with an afternoon north-easterly sea breeze cooling conditions on the coast. This category has the greatest inland-coastal afternoon temperature difference, with an average difference of 4.5°C. The light, hot gradient winds work to inhibit mixing height growth throughout the day and the arrival of the sea breeze further reduces the depth of the mixed layer

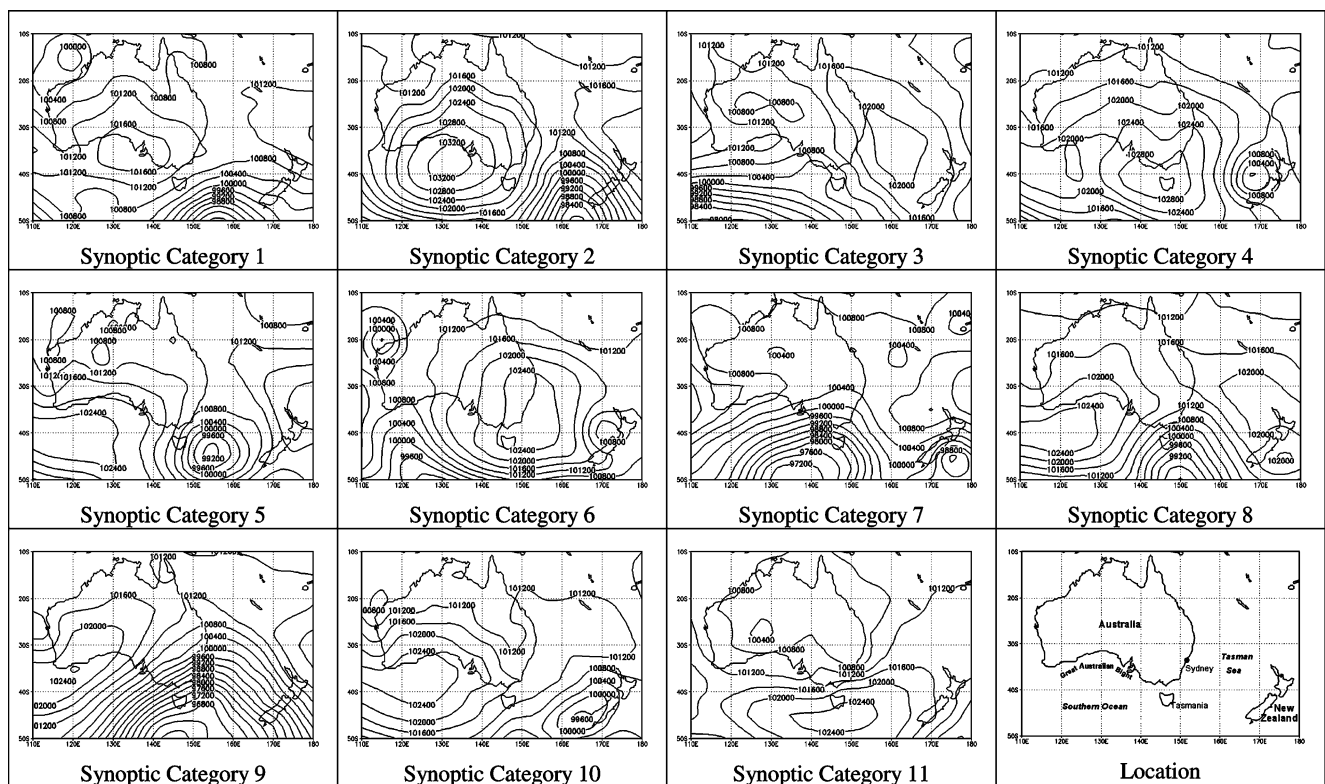


Fig. 4 Synoptic charts representative of mean meteorological conditions in each category. *Solid lines* represent mean sea level pressure in Pascals. Charts were produced using NCEP Reanalysis data

by exaggerating an inversion. Despite the occasional high concentration of Oleaceae (usually occurring during the pollination period for Oleaceae, December and January) mean pollen concentrations associated with this synoptic category are relatively low.

Synoptic category 4

Category 4 is characterised by an anticyclone located to the south of the continent, centred near Tasmania or to the south of the Great Australian Bight. The anticyclone is ridging latitudinally, bringing cool temperatures to Sydney due to southerly gradient winds and an afternoon south-easterly sea breeze. The diurnal temperature range is small and afternoon temperatures average just 19.9°C; the lowest of all categories. This southern maritime air mass produces high levels of cloud cover, instability and therefore high mixing heights. Synoptic category 4 is associated with low pollen concentrations for all five pollen families and for the total of all pollen collected.

Synoptic category 5

Synoptic category 5 is characterised by a low pressure system located to the east or south-east of Tasmania, resulting in fast (10.1 m/s on average) westerly gradient

provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at <http://www.cdc.noaa.gov/>

winds affecting Sydney. Surface temperatures are cool overnight (15.0°C) and mild (24.4°C) during the day. The ascending air associated with the low pressure system elevates mixing heights. Category 5 experiences the highest mean concentrations of Cupressaceae pollen.

Synoptic category 6

Synoptic category 6 is characterised by an anticyclone centred over Sydney bringing light north-westerly winds, with north-easterly sea breezes developing in the afternoons. Mean sea level pressure is high (1,019 hPa) and skies are clear (cloud cover on average 2.4 oktas), promoting surface convection and elevated mixing heights. There is nothing exceptional about pollen concentrations experienced in this category except for the occasional day with enhanced Cupressaceae concentrations.

Synoptic category 7

On days falling in synoptic category 7 Sydney is influenced by a low pressure system in the Southern Ocean centred to the south-west of Tasmania, bringing hot, dry, strong westerly winds to Sydney. The diurnal temperature range is large and daytime temperatures are the highest experienced of all categories (averaging 32.4°C). Mixing heights are also

Table 2 Mean meteorological conditions associated with each synoptic category

Meteorological variables		Category number (number of days in category)										
		1 (182)	2 (135)	3 (200)	4 (151)	5 (47)	6 (206)	7 (48)	8 (116)	9 (11)	10 (137)	11 (172)
6:00 a.m.	Surface	19.7	13.8	21.1	16.4	15.0	16.7	19.5	19.7	18.1	19.7	18.8
	Temperature (°C)											
	Dew point (°C)	17.1	8.1	18.4	11.9	8.3	13.3	13.8	16.7	7.9	17.2	15.8
	<i>u</i> wind (m/s)	0.3	2.7	0.1	-0.5	2.5	0.6	1.0	0.5	4.0	-0.1	-2.1
	<i>v</i> wind (m/s)	1.0	0.8	-1.0	3.9	-0.9	-1.2	-1.7	-1.3	-2.9	5.1	0.5
	MSLP (hPa)	1,015	1,016	1,012	1,021	1,008	1,019	1,007	1,010	999	1,012	1,019
	Total cloud amount (oktas)	4.5	2.5	3.4	5.7	3.2	2.4	3.9	6.1	5.5	6.6	6.6
	Upper air											
	850 hPa temperature (°C) (~ 1,500 m)	12.5	5.9	18.0	5.7	7.5	11.4	15.7	14.6	10.3	12.4	9.2
	850 hPa dew point temperature (°C)	6.5	-1.9	4.7	2.8	-1.1	-2.0	0.8	6.2	1.4	8.5	6.9
12:00 p.m. 3:00 p.m.	Surface	1,021	1,794	673	1,705	1,872	1,341	1,088	763	789	733	1,390
	Mixing height (m)	24.7	20.2	29.1	19.9	24.4	25.0	32.4	24.9	22.2	21.2	22.6
	Temperature (°C)	16.8	9.2	18.2	11.4	3.2	13.4	7.9	16.7	5.4	16.9	15.3
	Dew point (°C)	-4.3	-4.2	-4.8	-3.4	6.4	-5.4	5.8	-2.1	9.5	-1.8	-4.7
	<i>u</i> wind (m/s)	0.8	1.9	-4.2	4.1	0.5	-5.2	-2.8	-3.1	-1.7	6.5	-1.6
	<i>v</i> wind (m/s)	1,014	1,015	1,009	1,021	1,007	1,016	1,003	1,007	999	1,013	1,018
	MSLP (hPa)	3.7	2.9	2.8	5.4	3.0	2.2	3.5	6.3	6.4	6.4	6.5
	Total cloud amount (oktas)											
	Inland-coastal	2.6	3.0	4.5	1.1	-0.2	3.7	-0.6	2.0	0.1	1.4	0.5
	temperature (°C)											
Upper air	Mixing height (m)	692	757	316	1,004	2,147	581	2,049	360	1,436	388	728
	850 hPa temperature (°C)	14.0	8.2	19.9	6.5	9.1	14.2	17.2	15.3	8.8	11.7	10.5
	850 hPa dew point temperature (°C)	5.6	-2.6	5.7	1.9	-1.6	-2.2	3.2	7.1	0.7	8.1	6.7
	850 hPa <i>u</i> wind (m/s)	2.6	6.6	5.0	-0.1	10.1	3.3	10.4	9.4	18.7	1.4	-0.4
	850 hPa <i>v</i> wind (m/s)	1.1	0.9	-1.2	2.6	0.1	-0.8	-3.4	-4.2	-4.0	2.5	-1.9
	975 hPa temperature (°C) (within sea breeze)	19.9	15.5	25.9	14.8	20.3	20.3	28.7	22.0	19.2	17.6	18.0
	925 hPa temperature (°C) (above sea breeze)	16.9	12.2	24.8	10.9	15.9	18.0	24.1	19.8	15.0	14.7	14.4

Table 3 Pollen concentrations (grains/m³) associated with each synoptic category

Synoptic category	Statistics	Cupressaceae	Poaceae	Myrtaceae	Oleaceae	Plantaginaceae	Total pollen
1	Mean	5	27	12	59	6	125
	Max	68	200	138	900	50	1,168
	SD	12	45	22	176	12	242
2	Mean	72	85	33	38	23	297
	Max	1,843	825	238	738	150	2,525
	SD	270	148	42	128	34	466
3	Mean	16	42	22	53	10	169
	Max	358	643	143	1,255	108	1,463
	SD	57	99	27	179	21	283
4	Mean	13	24	12	10	14	92
	Max	225	158	108	395	175	810
	SD	39	36	21	57	31	148
5	Mean	123	51	32	7	18	293
	Max	700	413	93	23	80	1,165
	SD	234	94	26	7	27	364
6	Mean	88	55	25	22	25	263
	Max	1,308	418	183	793	188	1,830
	SD	235	73	32	99	43	371
7	Mean	60	113	51	346	31	679
	Max	580	463	113	4,700	180	5,178
	SD	149	143	41	1,207	55	1,316
8	Mean	28	65	25	122	20	298
	Max	363	518	118	1,863	100	2,240
	SD	78	101	30	416	16	506
9	Mean	15	54	49	536	38	724
	Max	68	250	143	3,618	163	4,260
	SD	24	92	61	1,360	62	1,568
10	Mean	6	35	24	16	9	124
	Max	88	208	268	233	113	648
	SD	16	47	48	49	18	170
11	Mean	5	25	11	7	8	76
	Max	155	250	70	170	100	428
	SD	23	43	15	26	19	93

very high. Days in this category do not experience a sea breeze, so the temperature gradient between the coast and inland is negligible. Synoptic category 7 is associated with the second highest mean and highest median (Fig. 5) daily concentrations of total pollen across all synoptic categories. It is also associated with the largest maximum daily total pollen concentration, as can be seen in Fig. 5. Concentrations of Poaceae and Oleaceae are particularly elevated in this synoptic category, as can be seen clearly in the cumulative frequency plots for these pollen types, Fig. 6b,d.

Synoptic category 8

This synoptic category experiences similar meteorological conditions to those in category 3. However, the anticyclone is positioned further east across the Tasman Sea, and a second anticyclone is centred to the south of Western Australia, while Sydney is affected by a trough separating the two anticyclones. Synoptic category 8 is characterised

by light north-westerly winds in the morning, an afternoon north-easterly sea breeze and a moderate west-north-westerly gradient wind. Mixing height is low and cloud amount is high (6.1–6.3 oktas), keeping temperatures moderate (an average of 24.9°C in the afternoon). Mean sea level pressure in the morning is 1,010 hPa on average, falling to 1,007 hPa in the afternoon. Category 8 is associated with the third highest mean concentrations of both Poaceae and Oleaceae pollen grains.

Synoptic category 9

Synoptic category 9 occurred the least of all the categories, with fewer than 1% of all days in the study period. This category is characterised by a large low pressure system centred either over Tasmania or to the south of Tasmania in the Southern Ocean. Gradient (averaging 19.1 m/s) and surface (averaging 9.6 m/s) winds are the strongest of all 11 synoptic categories and are north-westerly in the morning,

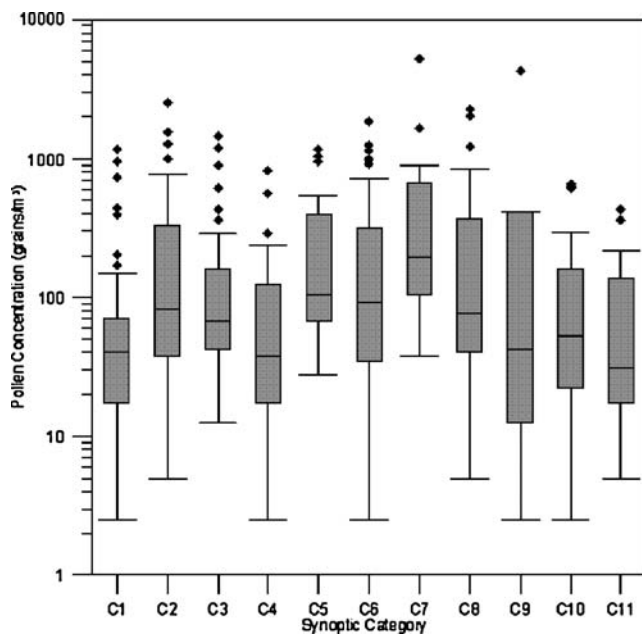


Fig. 5 Box plot showing the within group variance of daily total pollen concentrations experienced in each of the 11 synoptic categories. This graph presents the median, maximum, minimum, lower and upper quartile of total pollen concentrations, outliers are shown as *diamonds*

increasing in speed and backing to the west in the afternoon. Temperatures, both morning and afternoon, and diurnal temperature difference are relatively low. Mean sea level pressure is the lowest of all categories (999 hPa on average) producing plenty of cloud cover. Synoptic category 9 days experience the highest mean daily pollen concentrations. In particular Oleaceae pollen concentrations are high on these days.

Synoptic category 10

Category 10 is characterised by an anticyclone centred in the western region of the Great Australian Bight, bringing moderate southerly winds to Sydney in the morning which tend to back to south-south-easterly in the afternoon. This moist maritime air mass keeps temperatures moderate (afternoon temperatures average 21.2°C) and cloud cover amounts high (averaging 6.4–6.6 oktas). Days falling into category 10 experience low concentrations of all pollen types.

Synoptic category 11

Category 11's meteorology is dominated by an anticyclone centred to the south of Tasmania in the Southern Ocean that brings moderate south-easterly winds, backing to north-easterly in the afternoon in Sydney. Afternoon gradient winds are light and from the north. This maritime air mass causes temperatures to remain relatively low while cloud

cover and mixing height tend to be high. This synoptic category is associated with the lowest mean total pollen concentrations of all 11 synoptic categories.

Discussion

The highest average concentrations of total pollen were found to be due to the meteorological conditions experienced in synoptic categories 7 and 9. Both of these categories experience high concentrations of the tree species Oleaceae. Synoptic category 7 also experiences enhanced concentrations of grasses (Poaceae). Furthermore, the highest mean concentrations of the tree pollen Cupressaceae are experienced by days falling within synoptic category 5. Only 1% of days in the study period fell within category 9, so although it experienced the highest average pollen concentrations, these conditions are rare.

Both synoptic category 5 and category 7 conditions are more prevalent during the first half of the warm season (October, November, December) (Fig. 3). These pollen conducive weather conditions combined with the pollination of several tree and grass species during these months lead to a peak in pollen concentrations during the initial months of the warm season.

The main difference between the three synoptic categories associated with the highest pollen concentrations and the remaining eight categories is the low mean sea level pressure experienced, typically with a low pressure system being centred to the south of the continent, and generating strong westerly gradient winds at Sydney. Temperature appears to be not so important for the high pollen days because it differs significantly between the three high pollen synoptic categories, with very hot temperatures being associated with category 7, milder temperatures on the days within category 5, while category 9 experiences quite cool temperatures. However, the air masses associated with all three synoptic categories are consistently dry. None of the categories experiences a sea breeze, so the thermal gradient across the Sydney Basin is small.

The three synoptic categories related to the highest pollen concentrations are particularly associated with enhanced concentrations of Cupressaceae (category 5), Poaceae (category 7) and Oleaceae (categories 7 and 9). All three categories experience westerly gradient winds which would have traversed annual crop and pasture lands directly to the west of the sample site and native forests and woodlands further to the west of the Sydney Basin (Bureau of Rural Sciences 2005). High pollen concentrations at this site appear to be linked to westerly winds bringing tree and grass pollen from the adjacent crop and pasture lands and further afield native forests and woodlands.

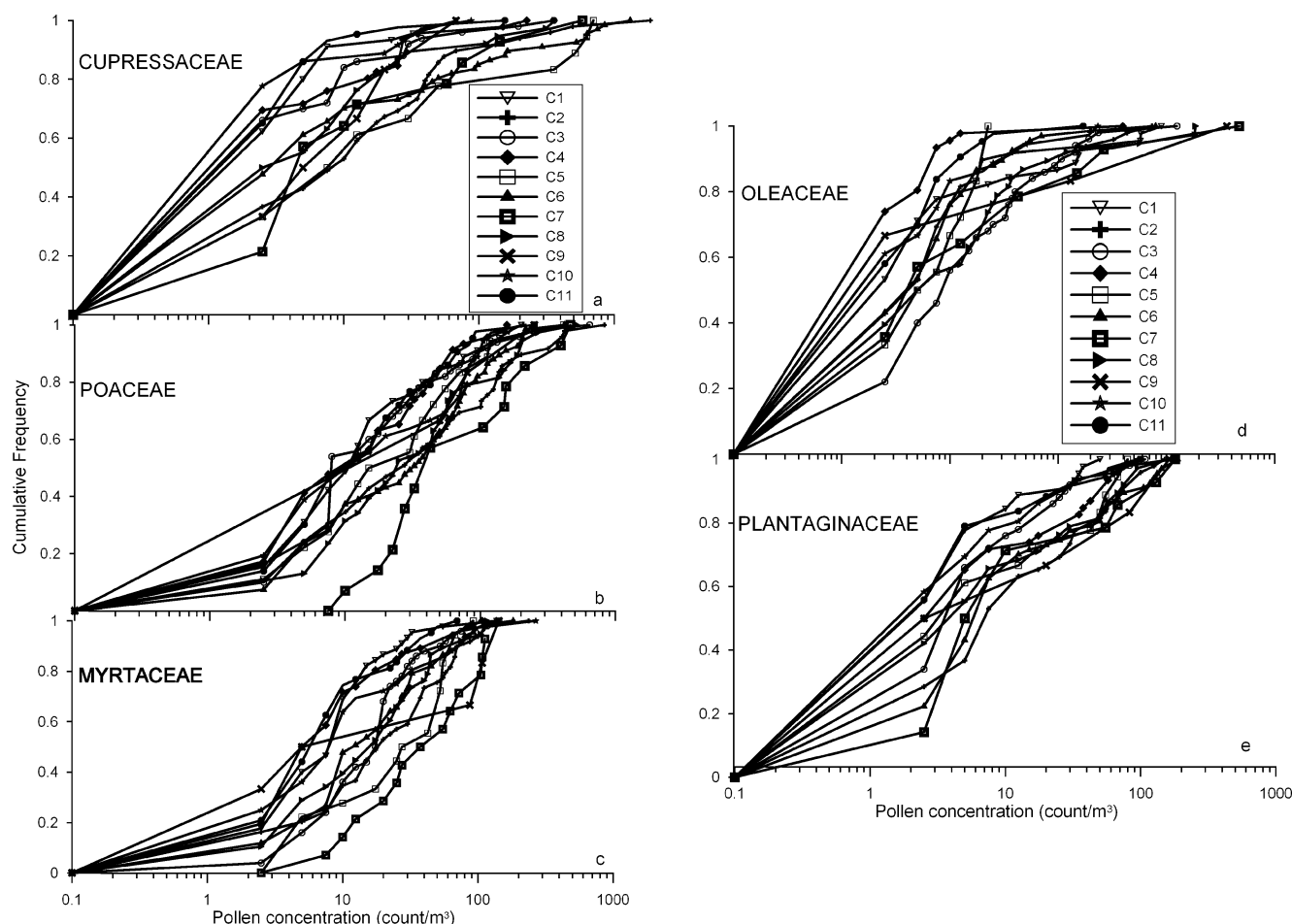


Fig. 6 Cumulative frequency plots of pollen concentrations experienced in each synoptic category for **a** Cupressaceae, **b** Poaceae, **c** Myrtaceae, **d** Oleaceae and **e** Plantaginaceae

The results of this synoptic classification of pollen concentrations in Sydney have shown that high levels of pollen are experienced when Sydney is affected by a low pressure system bringing strong, dry, continental westerlies. The dry air mass associated with high pollen concentrations in Sydney corresponds with many previous publications in which negative correlations were found between relative humidity and pollen concentrations (Alba et al. 2000; Gioulekas et al. 2004; Green et al. 2004; Jato et al. 2000; Ribeiro et al. 2003; Stennett and Beggs 2004). A previous correlation study on pollen concentrations and meteorological variables in Sydney found a negative correlation between mean sea level pressure and pollen concentrations (Stennett and Beggs 2004). This finding has been clearly corroborated by the present study's observation of cyclonic systems to the south of the continent during high pollen days.

Previous studies based on simple bi-variate statistical associations between meteorology and pollen concentrations have found positive correlations with temperature (e.g. Alba et al. 2000; Gioulekas et al. 2004; Green et al. 2004; Jato et al. 2000; Ribeiro et al. 2003; Stennett and

Beggs 2004). However, temperatures in the three high pollen synoptic categories in the current study varied from an average 3 p.m. coastal temperature of 22.2°C for days within category 9 to 32.4°C for days within category 7. The consistent meteorological variables across all three of our high pollen synoptic categories were wind, turbulence and moisture parameters, rather than temperature. However, it should be noted that the present study concentrated only on the six warmest months in Sydney. In future work it would be desirable to further investigate the temperature and pollen associations within each of these categories. Additionally a longer pollen monitoring program would allow more discussion on inter-seasonal differences.

This study has taken an air mass approach to analysing the relationship between weather and pollen concentrations in Sydney. This approach has enabled not only a discussion of the influence of individual meteorological variables on pollen concentrations, but also the influence of entire air masses and their associated circulation patterns on pollen concentrations in Sydney. High pollen concentrations during the warm months were found to be associated with

a region of low pressure located to the south of the continent which brings strong, dry, westerly gradient winds to Sydney. These conclusions could potentially be useful from a pollen forecast and associated public health perspective.

Acknowledgement The authors would like to thank Dr Diana Bass for access to her pollen dataset.

References

- Alba F, De La Guardia CD, Comtois P (2000) The effect of meteorological parameters on diurnal patterns of airborne olive pollen concentration. *Grana* 39:200–208
- Bass D, Morgan G (1997) A three year (1993–1995) calendar of pollen and *Alternaria* mould in the atmosphere of south western Sydney. *Grana* 36:293–300
- Bureau of Meteorology (1991) Climatic Survey, Sydney, NSW. Australian Government Publishing Service, Canberra
- Bureau of Rural Sciences (2005) Integrated Vegetation Online – Vegetation Maps. Australian Government. <http://www.brs.gov.au/intveg>
- Cattell RB (1966) The scree test for the number of factors. *Multivar Behav Res* 1:245–276
- Cheng S, Ye H, Kalkstein LS (1992) An evaluation of pollution concentrations in Philadelphia using an automated synoptic approach. *Middle States Geogr* 25:45–51
- Cheng W-L (2001) Synoptic weather patterns and their relationship to high ozone concentrations in the Taichung Basin. *Atmos Environ* 35:4971–4994
- Davis JM, Eder BK, Nychka D, Yang Q (1998) Modeling the effects of meteorology on ozone in Houston using cluster analysis and generalized additive models. *Atmos Environ* 32:2505–2520
- Eder BK, Davis JM, Bloomfield P (1994) An automated classification scheme designed to better elucidate the dependence of ozone on meteorology. *J Appl Meteorol* 33:1182–1199
- Gassmann MI, Pérez CF, Gardiol JM (2002) Sea-land breeze in a coastal city and its effect on pollen transport. *Int J Biometeorol* 46:118–125
- Gioulekas D, Balafoutis C, Damialis A, Papakosta D, Gioulekas G, Patakas D (2004) Fifteen years' record of airborne allergenic pollen and meteorological parameters in Thessaloniki, Greece. *Int J Biometeorol* 48:128–136
- Green BJ, Dettmann M, Yli-Panula E, Rutherford S, Simpson R (2004) Atmospheric Poaceae pollen frequencies and associations with meteorological parameters in Brisbane, Australia: a 5-year record, 1994–1999. *Int J Biometeorol* 48:172–178
- Greene JS, Kalkstein LS, Ye H, Smoyer K (1999) Relationships between synoptic climatology and atmospheric pollution at 4 US cities. *Theor Appl Climatol* 62:163–174
- Holzworth GC (1967) Mixing depths, wind speeds and air pollution potential for selected locations in the United States. *J Appl Meteorol* 6:1039–1044
- Jato MV, Rodríguez FJ, Seijo MC (2000) *Pinus* pollen in the atmosphere of Vigo and its relationship to meteorological factors. *Int J Biometeorol* 43:147–153
- Kalkstein LS, Corrigan P (1986) A synoptic climatological approach for geographical analysis: assessment of sulfur dioxide concentrations. *Ann Assoc Am Geogr* 76:381–395
- Laaidi K (2001) Predicting days of high allergenic risk during *Betula* pollination using weather types. *Int J Biometeorol* 45:124–132
- Laaidi M, Thibaudon M, Besancenot J-P (2003) Two statistical approaches to forecasting the start and duration of the pollen season of Ambrosia in the area of Lyon (France). *Int J Biometeorol* 48:65–73
- McGregor GR, Walters S, Wordley J (1999) Daily hospital respiratory admissions and winter air mass types, Birmingham, UK. *Int J Biometeorol* 43:21–30
- McGregor GR (2001) The meteorological sensitivity of ischaemic heart disease mortality events in Birmingham, UK. *Int J Biometeorol* 45:133–142
- Porsbjerg C, Rasmussen A, Backer V (2003) Airborne pollen in Nuuk, Greenland, and the importance of meteorological parameters. *Aerobiologia* 19:29–37
- Preisendorfer RW, Mobley CD (1988) Principal component analysis in meteorology and oceanography. Elsevier, New York
- Recio M, Cabezero B, Trigo MDM, Toro FJ (1997) Accumulative air temperature as a predicting parameter for daily airborne olive pollen (*Olea europaea* L.) during the pre-peak period in Málaga (Western Mediterranean area). *Grana* 36:44–48
- Ribeiro H, Cunha M, Abreu I (2003) Airborne pollen concentration in the region of Braga, Portugal, and its relationship with meteorological parameters. *Aerobiologia* 19:21–27
- Seibert P, Beyrich F, Gryning S-E, Joffre S, Rasmussen A, Tercier P (2000) Review and intercomparison of operational methods for the determination of the mixing height. *Atmos Environ* 34:1001–1027
- Shahgedanova M, Burt TP, Davies TD (1998) Synoptic climatology of air pollution in Moscow. *Theor Appl Climatol* 61:85–102
- Stennett PJ, Beggs PJ (2004) Pollen in the atmosphere of Sydney, Australia, and relationships with meteorological parameters. *Grana* 43:209–216
- Valencia-Barrera RM, Comtois P, Fernández-González D (2002) Bioclimatic indices as a tool in pollen forecasting. *Int J Biometeorol* 46:171–175
- Yarnal B (1993) Synoptic climatology in environmental analysis. Belhaven Press, London