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ORIGINAL PAPER

On the causes of variability in amounts of airborne grass pollen in Melbourne, Australia

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Abstract In Melbourne, Australia, airborne grass pollen is the predominant cause of hay fever (seasonal rhinitis) during late spring and early summer, with levels of airborne grass pollen also influencing hospital admissions for asthma. In order to improve predictions of conditions that are potentially hazardous to susceptible individuals, we have sought to better understand the causes of diurnal, intra-seasonal and inter-seasonal variability of atmospheric grass pollen concentrations (APC) by analysing grass pollen count data for Melbourne for 16 grass pollen seasons from 1991 to 2008 (except 1994 and 1995). Some of notable features identified in this analysis were that on days when either extreme (>100 pollen grains m^{-3}) or high (50–100 pollen grains m^{-3}) levels of grass pollen were recorded the winds were of continental origin. In contrast, on days with a low (<20 pollen grains m^{-3}) concentration of grass pollen, winds were of maritime origin. On extreme and high grass pollen days, a peak in APC occurred on average around 1730 hours, probably due to a reduction in surface boundary layer turbulence. The sum of daily APC for each grass pollen season was highly correlated (r=0.79) with spring rainfall in Melbourne for that year, with about 60% of a declining linear trend across the study period being attributable to a reduction of meat cattle and sheep (and hence grazing land) in rural areas around Melbourne. Finally, all of the ten extreme pollen events (3 days or more with APC>100 pollen grains m^{-3}) during the study period were characterised by an average downward vertical wind anomaly in the surface boundary layer over Melbourne. Together these findings form a basis for a fine resolution atmospheric general circulation model for grass pollen in Melbourne's air that can be used to predict daily (and hourly) APC. This information will be useful to those sectors of Melbourne's population that suffer from allergic problems.

Keywords Pollen · Allergies · Asthma · Rainfall · Anticyclone · Hayfever

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Introduction

Respiratory diseases such as asthma and related allergic disorders are growing in prevalence and form an increasing disease burden on health care systems world-wide (Asher et al. 2006; Russell 2006). In Melbourne Australia, exposure to grass pollen, most notably those of the pasture grass *Lolium perenne* (perennial ryegrass), is the main cause of the seasonal appearance of hay fever during the period from late spring to early summer when grass is flowering (Hill et al. 1979; Knox 1993; Schäppi et al. 1998), while other cases of perennial symptoms of asthma may not be related to pollen grains. Levels of grass pollen in Melbourne's air are also an independent predictor of daily asthma hospital admissions (Erbas et al. 2007). Perennial ryegrass was introduced from Europe for use in sheep and cattle grazing and is now the dominant species on farms throughout southern Victoria, particularly in the grazing lands that surround Melbourne (Waller and Sale 2001). However, concentrations of grass pollen in the atmosphere vary considerably from day-to-day and from year-to-year in response to a range of climatic factors (Ong et al. 1995; Schäppi et al. 1998). Understanding the interactions between these factors and ambient pollen levels can potentially lead to the development of better forecasting methods that are able to provide timely warnings of high risk days to health services and grass pollen-sensitive individuals.

In this paper we look into sources of variability in atmospheric pollen concentrations (APC) over Melbourne on all relevant time scales using grass pollen count data from 16 seasons between 1991 and 2008.

Materials and methods

Grass pollen data

The method used to collect daily grass pollen was described in Ong et al. (1995), and used a Burkard volumetric trap fitted with a 24-h sampling head (Burkard Scientific, Middlesex, UK). Airborne grass pollen was counted on a daily basis from late September through to the end of either December or January, depending on the year. The location of the trap, on the city campus of the University of Melbourne, conformed to the Australian Standard AS 2922-1987 for the siting of ambient air sampling units for environmental monitoring (Standards Association of Australia, Sydney, NSW). Pollen grains were trapped on a glass microscope slide (76.2×25.4×1.2 mm) coated with an adhesive (Dow Corning Sylgard 527 silicone dielectric gel) by intake of air at 10 l min^{-1}. Each day during the sampling period, the slide, attached to a rotating drum on the sampling head, was removed at around 150 hours and replaced with a fresh slide. The daily concentration of grass pollen (in grains m^{-3}) was determined by staining the slide with Calberla's stain (Odgden et al. 1974) and counting grass pollen grains (identified by reference to a collection of slides prepared directly from known plants) along a random traverse of the slide's length and averaging this value across the entire slide.

The data on grass pollen counts collected at 2 h intervals over the months of October and December 1991 and 1992 are taken from Ong et al. (1995).

Meteorological data

Daily maximum and minimum temperature, precipitation for the Melbourne regional station, and wind speed and direction for the Melbourne airport station, were obtained from the Bureau of Meteorology, Australia (BoM 2009).

Reanalysis data were also available for the investigation of pollen dispersion in the horizontal and vertical, and the ERA-Interim data set (Uppala et al. 2008), which has a resolution of 1.5°×1.5° was chosen, from which the relevant fields of mean sea level pressure (MSLP), horizontal wind velocity, specific humidity and vertical velocity were extracted.

Some preliminary runs with the 3-Dimensional Spherical Trajectory Program (traj3d), developed in the School of Earth Sciences, were also made to show the trajectories of air parcels arriving over Melbourne (http://www.earthsci.unimelb.edu.au/trajectories/trajhome.htm).

Results

Meteorological conditions influencing intra-season APC

Figure 1, which shows the mean daily APC for all available seasons during the study, highlights their variability. On taking a 5-day running average, the smoothed distribution has a peak about November 30, with 75% of the grass pollen being recorded in the period 30 October–23 December (55 days), during which the average APC was between 50–60 grass grains m^{-3}. This criterion enables the severity of individual pollen seasons to be compared by defining the length as occurring between the first and last day with an APC above 30 grains m^{-3} (Table 1). According to this definition, the average length of the grass pollen season was 75 days, which is much greater than the length determined from the smoothed distribution owing to the day-to-day variability evident in Fig. 1.

Intra-seasonal variability in APC is controlled by meteorological conditions that regulate transport of grass pollen from source regions in the surrounding countryside to Melbourne. During November and December, there is a clear link (statistically significant with 95% confidence) between the anomalies in MSLP at 0600UTC (1700 hours local time) relative to climatology and APC (Fig. 2a,b). Low pollen days (<20 pollen grains m^{-3}) were typically associated with a high pressure system to the west of Melbourne and/or a low pressure system to the east, with southerly surface winds in Melbourne bringing mainly pollen-free air in from the ocean (Fig. 2a). On extreme and high pollen days (>100 pollen grains m^{-3} and 50–100 pollen grains m^{-3}, respectively) on the other hand, there was usually a high pressure system to the east of Melbourne and/or a low pressure system to the west, resulting in grass pollen from inland Victoria being transported into Melbourne (Fig. 2b). Moderate grass pollen days (20–49 pollen grains m^{-3}) do not show a relationship with MSLP as none of the results were significant to 95%. These days were, however, generally characterised by stronger winds blowing from both the ocean and inland at different times. For October and January the sample sizes were too small for analysis.

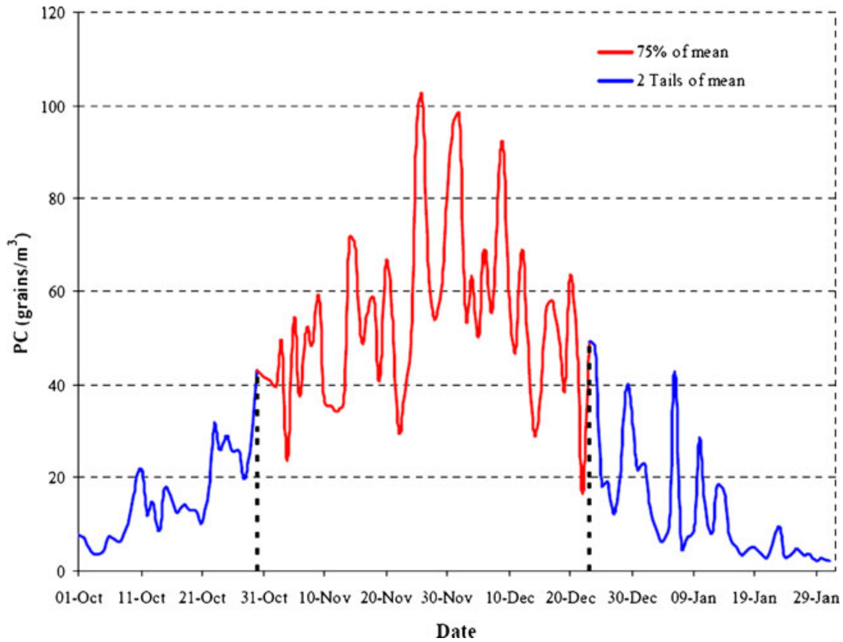


Fig. 1 Mean daily atmospheric pollen concentration (APC) for the Melbourne pollen season, October–January, during the period 1991–2008

This interpretation is consistent with wind strength and direction at the Melbourne airport station (Table 2). This station was chosen because it is less influenced by topography than the Melbourne regional station. On low grass pollen days the direction of the mean wind vector was from the south west, whereas in high and extreme grass pollen days it was generally from the north-west. Temperature and the APC are also clearly related (Table 3), with a large difference evident between the mean maximum temperature of extreme and low grass pollen days in all months. It is probable, however, that rather than temperature directly influencing variability in grass pollen counts, the correlation is due to advection, the temperature being typically higher due to winds coming from inland bringing both warm air and pollen simultaneously. Specific humidity was also significantly correlated with APC although this association is also a consequence of differences in wind direction (de Morton 2009).

Diurnal changes in APC

Ong et al. (1995) measured grass pollen levels at 2-h intervals over a 65 day period in 1991 and 1992. Figure 3 shows these data stratified into extreme to low grass pollen days. As

Table 1 Grass pollen seasons (taken from de Morton 2009)

Season no.	Year	Start	End	Length (days)
1	1991	15 October 1991	26 December 1991	73
2	1992	27 October 1992	15 January 1993	81
3	1993	23 October 1993	23 January 1994	93
4	1996	9 October 1996	9 December 1996	62
5	1997	10 October 1997	1 January 1998	84
6	1998	29 September 1998	11 January 1999	105
7	1999	18 October 1999	15 December 1999	59
8	2000	13 October 2000	1 January 2001	81
9	2001	1 October 2001	26 January 2002	118
10	2002	30 October 2002	29 December 2002	61
11	2003	15 October 2003	29 December 2003	76
12	2004	11 October 2004	24 December 2004	75
13	2005	18 October 2005	28 December 2005	72
14	2006	12 October 2006	30 November 2006	50
15	2007	21 October 2007	29 December 2007	70
16	2008	24 October 2008	9 December 2008	47

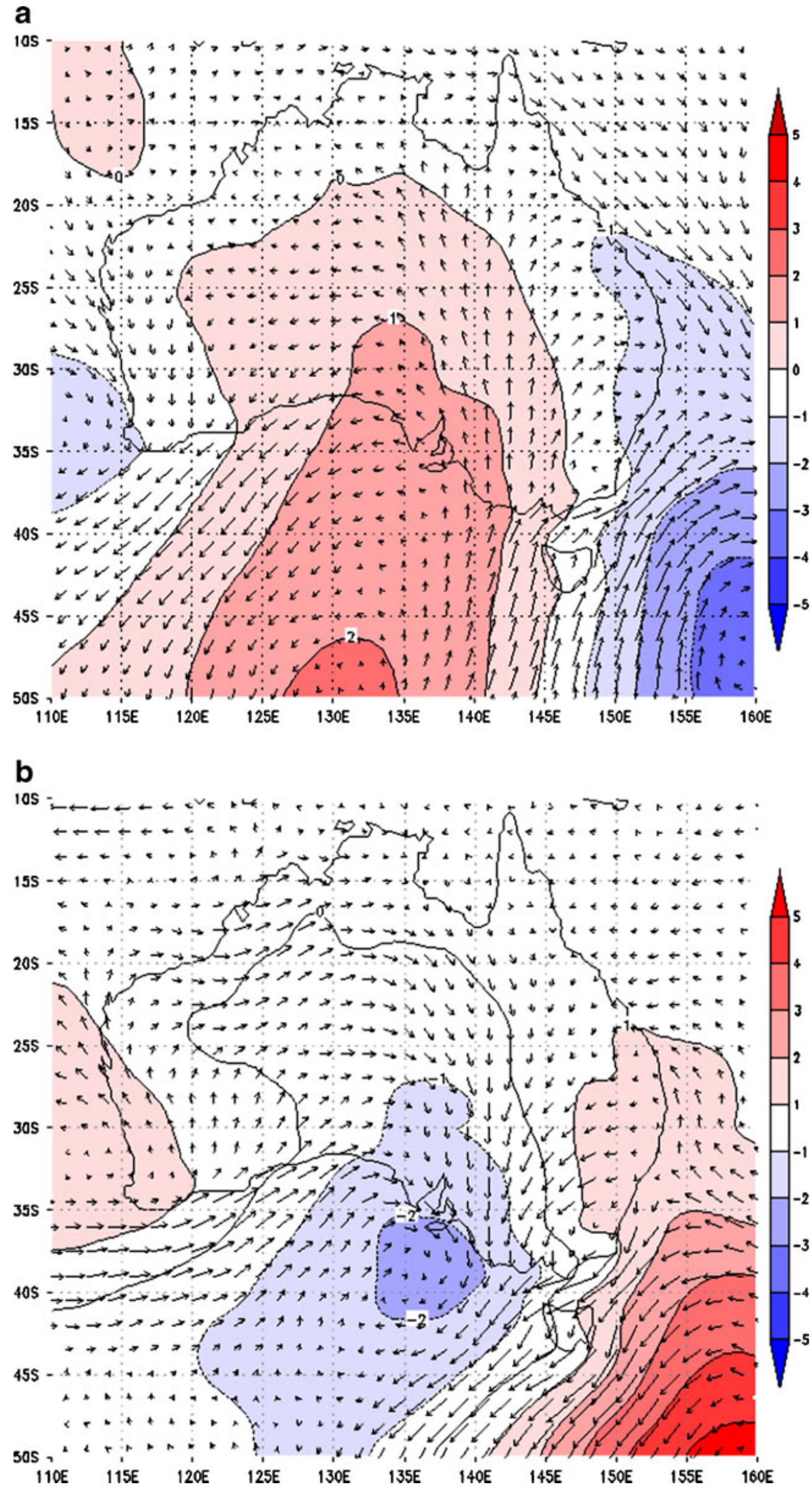


Fig. 2 Mean sea level pressure (MSLP) (hPa) and wind anomaly (ms^{-1}) for December. **a** Low pollen days, **b** extreme pollen days

noted by Ong et al. (1995) there was a peak of grass pollen on extreme and high grass pollen days between 1700 and 2200 hours. This peak occurred most frequently at 1930 hours (16 out of a sample size of 61 high or extreme days) and approximately 50% of the peaks occurred between 1730 and 2130 hours and over 70% occurred between 1130 and 2130 hours. Mean APC between 2330 and 0530 hours was low. Linear regression between the 2-hourly data and the daily mean data yields the relation $APC)_{peak}$=2.6 $APC)_{mean}$ (r=0.89).

Table 2 Mean wind vectors at Melbourne airport for extreme, high and low pollen days

	Direction of wind vector (°)	Wind speed (m/s)	Sample size
Extreme	340	2.68	1,168
High	311	2.67	1,400
Low	230	2.56	3,526

Vertical transport of pollen can be estimated using the model developed by Vogel et al. (2008) for pollen grain dispersal, which predicts a sedimentation velocity,

$$w_p = [\left(4\rho_p d_p g\right)/(3\rho\, C_D)]^{1/2} \quad (1)$$

where ρ_p and d_p are the density and diameter of the pollen grains, respectively, ρ is the density of air, C_D is a drag coefficient, and g is the acceleration of gravity. Given that for grass pollen, $d_p=3\times10^{-5}$ m, $\rho_p=10^3$ kg/m^3 and $C_D=10$ (Helbig et al. 2004), and g=10 ms^{-2} and $\rho=1$ kg/m^3, we obtain $w_p=0.2$ ms^{-1}. The sedimentation velocity is the velocity at which a pollen grain would fall out of the atmosphere if there were no other forces acting on it. Under these circumstances, a grain of pollen 1 km above the Earth's surface would thus take approximately 1.5 h to reach ground level. Enhanced sedimentation of grass pollen grains favouring extreme and high grass pollen events could be due to an increase in vertical flux. Turbulence throughout the day in the surface boundary layer would act to maintain a suspension of the pollen grains. Once the peak temperature is reached, the turbulence gradually lessens, which then reduces the forces acting to suspend the pollen grains in the atmosphere, which settle out, bringing about the observed peak in APC. This model assumes that a reservoir of pollen grains exists above the surface boundary layer due to horizontal advection from the surrounding area.

Inter-season variability in APC and land use changes

Total grass pollen count (TPC) for a season is a measure of the season's severity (Davies and Smith 1973; Emberlin et al. 1993; Green et al. 2004). Figure 4 shows TPCs across the study period and the linear decline over time,

$$TPC = -226.5y_i + 6000 \qquad r = -0.66 \quad (2)$$

where y_i is the year relative to 1991. High and extreme grass pollen days are declining at approximately the same rate and the number of high and extreme days within a season affects the TPC. The number of low and moderate days per season shows no significant trend over time. The 1992, 1993 and 2001 seasons were the most severe as they had large number of high and extreme grass pollen days contributing to a higher TPC, whereas the 2002, 2006 and 2008 seasons were very mild with lower TPCs and a low number of high and extreme grass pollen days.

Spring precipitation (Fig. 4) has a similar trend to TPC over time,

$$P_{SPRING} = -6.52y_i + 220 \quad (3)$$

where P_{SPRING} is the total precipitation (in mm) measured at Melbourne from September to November. The correlation coefficient of the detrended time series, calculated using Eqs. 2 and 3, was $r=0.79$ with 99% confidence and a slope of 15 grains/(m^{3}mm). Hence, despite the small sample size it is very likely that spring precipitation was the main factor causing inter-seasonal variability. Although there was no significant correlation between the start of the grass pollen season and TPC, the correlation coefficient between the end of the season (Table 1) and TPC was significant ($r=0.79$). Spring precipitation thus increases the

Table 3 Mean and standard deviation of temperature for October, November, December and January for extreme, high, moderate and low pollen days. *SD* Standard deviation of T_{max} (°C), *N* number of samples

		October	November	December	January
Extreme	Mean T_{max} (°C)	23.1	26.3	27.7	30.5
	SD	5.1	4.9	5.5	5.5
	N	9	84	61	9
High	Mean T_{max} (°C)	24.9	24.6	26.6	27.5
	SD	4.5	4.7	5.7	7.4
	N	30	75	82	12
Moderate	Mean T_{max} (°C)	22.4	22.1	24.4	28.5
	SD	4.6	4.7	5.2	6.5
	N	57	111	104	20
Low	Mean T_{max} (° C)	17.8	18.8	21.4	21.7
	SD	3.4	3.7	4.2	4.1
	N	160	180	133	56

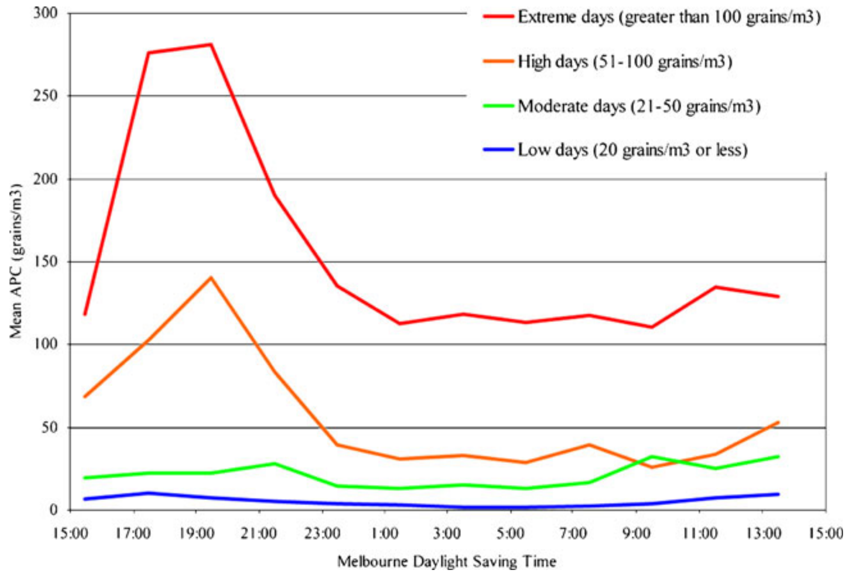


Fig. 3 Mean APC at 2-h intervals for extreme, high, moderate and low pollen days for the periods 13 October–12 December 1991 and 28 October–23 December 1992

severity of a season by both increasing the amount of grass growth and extending the period over which grasses flower.

The slope of 15 grains/(m^3mm) obtained from the detrended time series is smaller than that obtained from the ratio of the slopes in Eqs. 2 and 3, which is 35 grains/(m^3mm). Hence another factor in addition to precipitation contributes about 60% of the trend in declining TPC.

Changes in land use can also affect the grass pollen season (Emberlin et al. 1993, 1999). Figure 5 shows numbers of sheep, milk cattle and meat cattle in an approximate radius of 50 km centred on Melbourne. There has been a large reduction in the total number of S and C, with the respective trend lines being:

$$S = -5.046y_i + 192 \qquad r = -0.82 \tag{4a}$$

$$C = -3.078y_i + 168 \qquad r = -0.79 \tag{4b}$$

where S and C are the numbers (in millions) of sheep and meat cattle, respectively. Sheep and cattle are typically grazed on improved pastures composed mainly of perennial ryegrass (Waller and Sale 2001). Hence changes in sheep

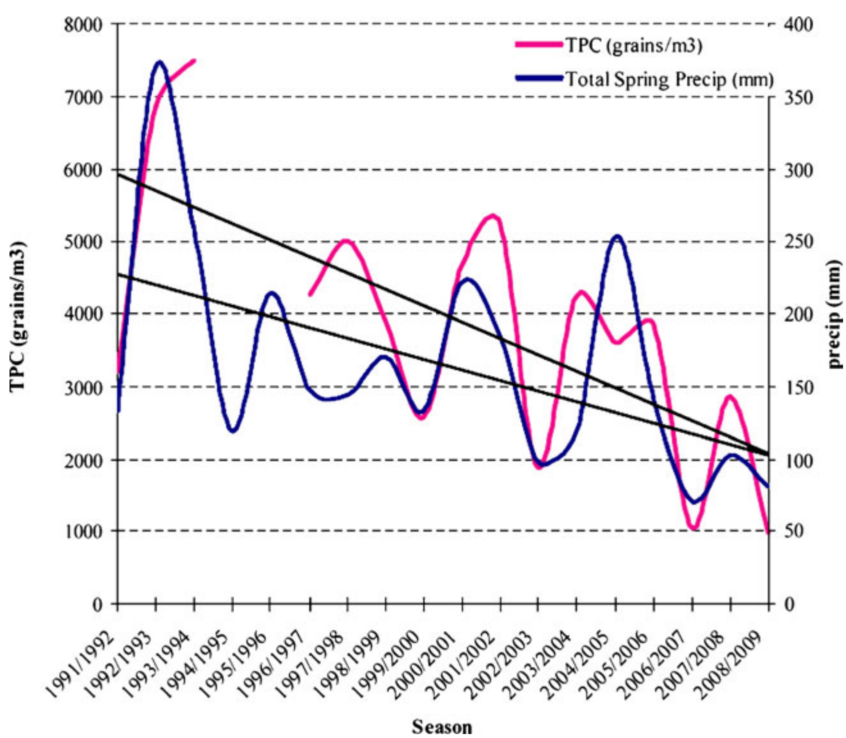


Fig. 4 Total pollen count (TPC) and spring precipitation with trend lines for the period 1991–2008

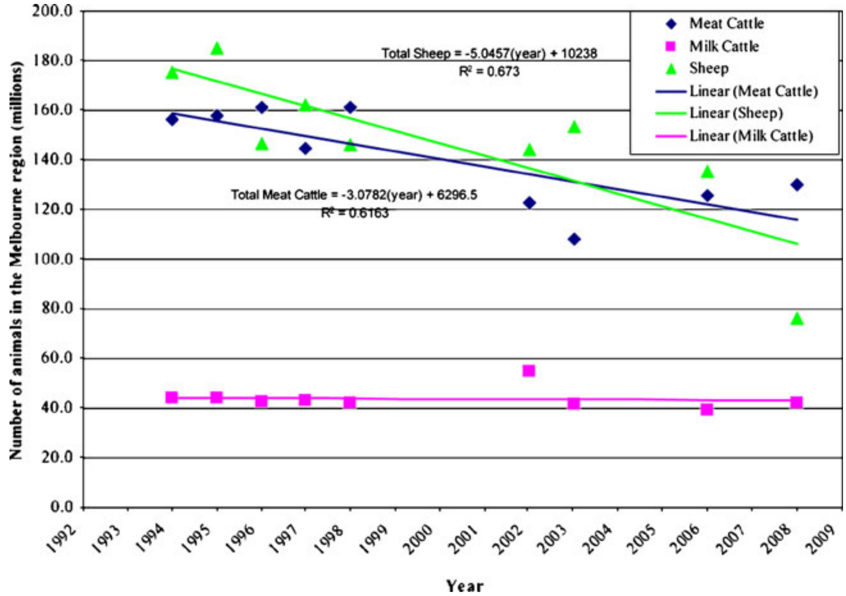


Fig. 5 Trends in the number of meat cattle, dairy cattle and sheep in the Melbourne district for the period 1990–2009

and cattle numbers relate directly to the amount of perennial ryegrass. Improved pasture is removed for land development or market gardening, and is also reduced during drought conditions. Thus, cattle and sheep numbers would be expected to reflect season-to-season changes in TPC. Table 4 shows that the number of extreme and high grass pollen days per season and mean meat cattle and sheep numbers are highly correlated.

Extreme grass pollen events

We define an extreme grass pollen event as an event of 3 or more consecutive days in which the mean APC for each day was more than 100 grass pollen grains m^{-3}. Ten events occurred during the study period, of which events 5 (5–10 December 1993) and 9 (7–9 December 2003) are analysed below. The distribution of events and their intensity appears to reflect the declining trend in TPC (Table 5). Events 1–3 occurred during the 2-h sampling period, when the highest APC recorded was 630 grass pollen grains m^{-3} at 2130 hours on December 12 1992. The 24-h average APC on this day was 281 grass pollen grains m^{-3}.

Extreme grass pollen event 5 lasted 6 days and the total APC during this period was almost 25% of the season total discussed earlier in Fig. 1. The sequence of daily values was 236, 252, 227, 231, 576 and 285 grass pollen grains m^{-3}, with the daily value of 576 grass pollen grains m^{-3} on 10 December 1993 being the highest recorded during the study period.

The MSLP anomalies at 0600UTC imply a very significant easterly transport of grass pollen to Melbourne under the influence of a strong anomalous high pressure system over the Tasman Sea (Fig. 6a). It is remarkable that the large area of MSLP anomaly of about 12 hPa persisted for more than 5 consecutive days, characterising an atmospheric blocking (Egger 1978). One can also appreciate that the pressure anomalies associated with this event were much greater and more robust than the average anomalies associated with extreme pollen days (Fig. 2b). This anomalous pattern lead to descending air over Melbourne, as is shown by the negative anomalies of vertical velocity at 850 hPa during the period of the event (de Morton 2009).

This extreme event shows the importance of synoptic variability and atmospheric blocking in contributing to pollen enhancement in Melbourne, where the descending air plays a fundamental role preventing the mixing that would have occurred were the boundary layer more vertically pronounced.

Extreme grass pollen event 9 (Table 5) was less severe than event 5, indicating a somewhat different synoptic configuration where the pressure is anomalously high to the south-east of Australia towards high latitudes (Fig. 6b), with an anomalous low to the southwest of Australia

Table 4 Correlation coefficients between numbers of meat cattle and sheep and TPC and numbers of extreme and high pollen days/season

	Meat cattle	Sheep	Meat cattle and sheep
TPC	0.64	0.72	0.84
Extreme pollen days/season	0.74	0.67	0.88
High pollen days/season	0.41	0.84	0.75

Table 5 List of extreme pollen events. *APC* Atmospheric pollen concentration

Event no.	Start–End	No. of days	Average APC grains/m^3
1	14–17 November 1992	3	295
2	30–3 December 1992	4	224
3	8–12 December 1992	5	242
4	29 November–2 December 1993	4	281
5	5–10 December 1993	6	301
6	1–3 November 1996	3	180
7	24–26 November 1996	3	233
8	27–30 November 2003	4	176
9	7 –9 December 2003	3	182
10	26–28 November 2004	3	192

indirectly intensifying the easterly winds over Melbourne. Although meteorologically different from the previous event, the circulation anomalies for event 9 reveal that, even without a blocking anticyclone over the Tasman Sea, the pollen concentration in Melbourne rose as a result of easterly wind anomalies. Most importantly, the lateral shear of this stream on approaching Bass Strait also gave rise to a region of negative anomalies in vertical velocity with descending air over Melbourne.

In preliminary experiments with the traj3d programme, the average of the vertical velocity anomaly over Melbourne for all the extreme pollen events calculated at eight pressure levels (1,000, 975, 950, 925, 900, 850, 500 and 300 hPa) for 0000, 0600, 1200 and 1800 UTC was negative at all atmospheric pressures greater than 850 hPa.

It appears therefore that descending air in the surface boundary layer (which extends upwards approximately to 850 hPa) is an important precondition for the occurrence of extreme grass pollen events.

Discussion

This paper describes the meteorological factors that influenced grass pollen counts for Melbourne, Australia on all relevant time scales for 16 of the 18 grass pollen seasons from 1991 to 2008. Grass pollen data were not available for the 1994 and 1995 seasons.

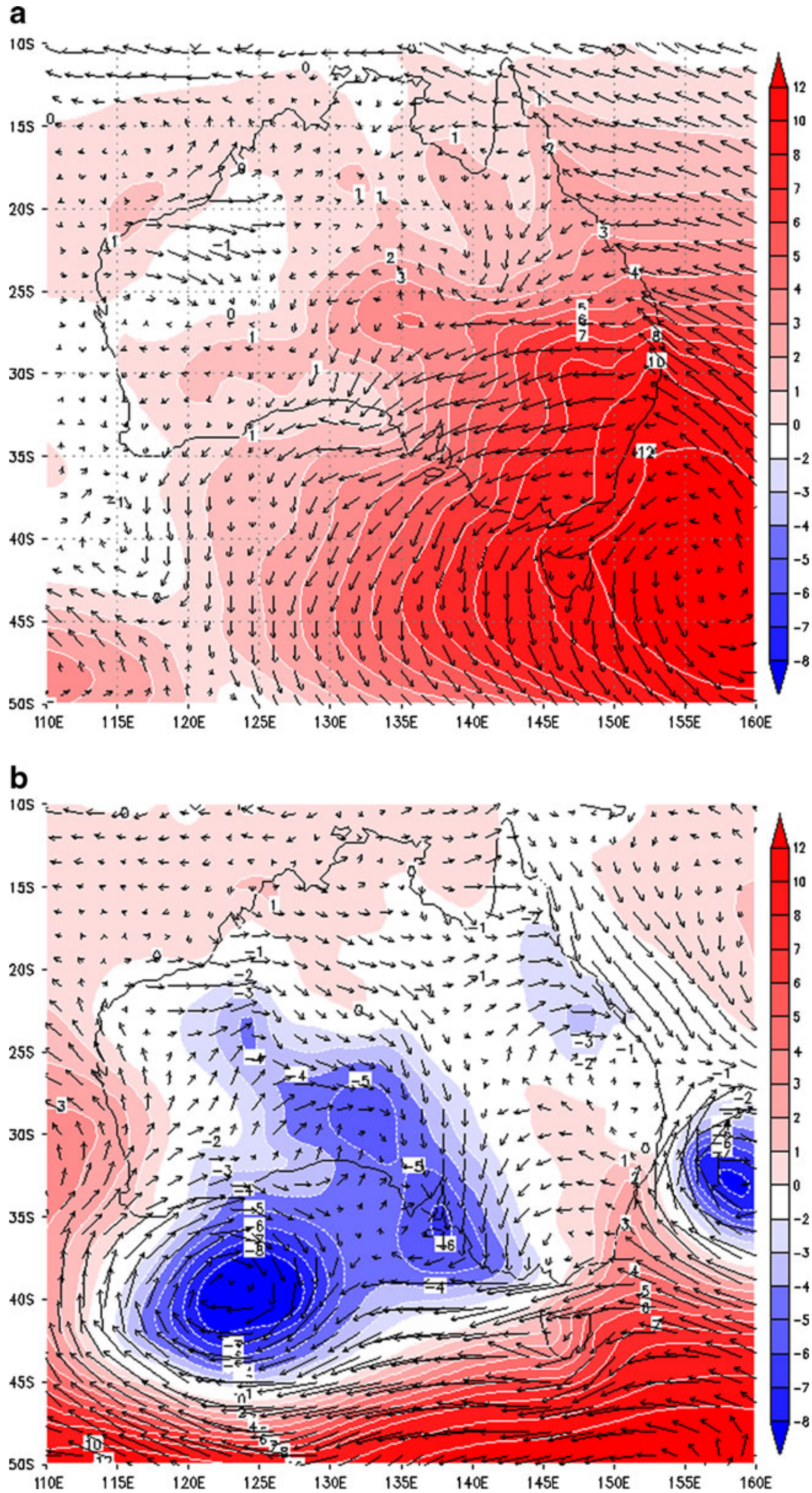
Various methods are used to define and limit the grass pollen season (Jato et al. 2006). Some authors define the season as being between the dates when pollen counts are higher or lower than a given value (e.g. Davies and Smith 1973). Others define it as the period over which a certain percentage of the total annual pollen count is recorded (Andersen 1991) or between two days that meet specific conditions (Lejoly-Gabriel and Leuschner 1983). Here, we empirically defined the season as the period that contributed 75% of the season's grass pollen because this is the period when most of the allergy-related problems can be triggered (Hill et al. 1979; Knox 1993; Schäppi et al. 1998). The average APC during this period was greater than 30 grass grains m^{-3}, and grass (family Poaceae) pollen includes pollen from many different species that flower during late spring and summer. On average, the APC has a peak around the end of November and was associated with flowering of perennial ryegrass.

As previously noted by Ong et al. (1995), over a day there is a peak in APC at about 1930 hours local time. Grass pollen is released following rupturing of the anther but its distribution is dependent on the wind (Taylor et al. 2002). Ong et al. (1995) suggested as a reason for the peak that, during the evening and night, low temperature inversions and low wind speeds over the city tended to concentrate grass pollen in the atmosphere. We found that settling of grass pollen grains from within the surface boundary layer was due primarily to a reduction in turbulence after the peak temperature had passed.

In their analysis of Melbourne grass pollen counts for the 1996 and 1997 seasons, Schäppi et al. (1998) identified a strong positive correlation between daily average air temperature and daily grass pollen count. This correlation arises due to anomalies in MSLP, with extreme and high grass pollen days associated with airflow from the interior of the continent and low grass pollen days with airflow from the ocean. Continental winds will travel over the large areas of pasture land to Melbourne's north, transporting grass pollen to the city whereas oceanic winds will be largely free of grass pollen. Schäppi et al (1998) also identified rainfall as a critical factor in the season's total production of grass pollen, in keeping with water availability being a major determinant of grass growth.

This effect is of particular interest in Australia where interannual rainfall variability is very high. A record-breaking long term drought has affected Melbourne for the 14th consecutive year, with wide economic and environmental impacts associated with low water availability and catastrophic bushfires (Cai and Cowan 2008a,b; Cai et

Fig. 6 MSLP anomaly (hPa) at 0600 UTC (1700 hours local time) relative to the December MSLP climatology, and wind vector anomaly (ms^{-1}) for **a** extreme pollen event 5 (5–10 December 1993), and (**b**) extreme pollen event 9 (7–9 December 2003)



al. 2009). But a decline in spring rainfall was not in itself sufficient to account for the total decline in TPC, which was also associated with changes in land use that reduce the amount of pasture land in the region around Melbourne. In Europe, a decrease in TPC for grass pollen has also been attributed to substantial decrease in grassland over large areas of the continent (D'Amato et al. 2007).

Possibly the most interesting finding is that extreme pollen events are associated with anomalous downward velocities over Melbourne. This has been demonstrated for two completely different atmospheric conditions leading to extreme pollen count increase in Melbourne, where the downward velocities over Melbourne are a result of the horizontal mass divergence around a large anomalous anticyclone over the Tasman Sea or surrounding areas.

One of our objectives was to develop a model that enabled the short- and long-term prediction of atmospheric grass pollen concentrations to warn allergic individuals about the likely severity of a forthcoming grass pollen season and enable them to take preventative measures on days predicted to have high or extreme grass pollen counts. Brief summary of forecasting models reported in the literature have been based on time series, linear regressions or artificial neural networks (e.g. Erbas et al. 2007; Jato et al. 2006). The meteorological processes identified in our study, however, form a platform for the forecast of APC using fine resolution atmospheric general circulation models. The accuracy of the forecast clearly depends on the skill in representing these processes. A successful outcome however is not beyond the present capabilities of the Bureau of Meteorology, and the city of Melbourne deserves a timely implementation.

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