Aerobiologia (2016) 32:289–302
DOI 10.1007/s10453-015-9399-x

ORIGINAL PAPER

# Regional and seasonal variation in airborne grass pollen levels between cities of Australia and New Zealand

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Received: 5 December 2014 / Accepted: 18 July 2015 / Published online: 29 July 2015

**Abstract** Although grass pollen is widely regarded as the major outdoor aeroallergen source in Australia and New Zealand (NZ), no assemblage of airborne pollen data for the region has been previously compiled. Grass pollen count data collected at 14 urban sites in Australia and NZ over periods ranging from 1 to 17 years were acquired, assembled and compared, revealing considerable spatiotemporal variability. Although direct comparison between these data is problematic due to methodological differences between monitoring sites, the following patterns are apparent. Grass pollen seasons tended to have more than one peak from tropics to latitudes of 37°S and single peaks at sites south of this latitude. A longer grass pollen season was therefore found at sites below 37°S, driven by later seasonal end dates for grass growth and flowering. Daily pollen counts increased with latitude; subtropical regions had seasons of both high intensity and long duration. At higher latitude sites, the single springtime grass pollen peak is

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potentially due to a cooler growing season and a predominance of pollen from $C_3$ grasses. The multiple peaks at lower latitude sites may be due to a warmer season and the predominance of pollen from $C_4$ grasses. Prevalence and duration of seasonal allergies may reflect the differing pollen seasons across Australia and NZ. It must be emphasized that these findings are tentative due to limitations in the available data, reinforcing the need to implement standardized pollen-monitoring methods across Australasia. Furthermore, spatiotemporal differences in grass pollen counts indicate that local, current, standardized pollen monitoring would assist with the management of pollen allergen exposure for patients at risk of allergic rhinitis and asthma.

**Keywords** Aerobiology · Latitude · Grass pollen · Plant distribution · Australia · New Zealand

## 1 Introduction

Grass pollen exposure represents a major public health burden in Australia and New Zealand (NZ) for patients with seasonal allergic rhinitis and asthma (Hill et al. 1979; Erbas et al. 2007a, 2012). Although grass pollen is generally regarded as the major outdoor aeroallergen source in Australasia (Bousquet et al. 2007), there are limited data on geographic and temporal patterns of grass species phenology and their allergenic effects. Allergic sensitization to $C_3$ grasses has been well characterized. Introduced ryegrass (*Lolium perenne)* has been identified as one of the most significant aeroallergens of southern temperate Australia (Ford and Baldo 1986; Schäppi et al. 1999). Tropical and subtropical regions have received less attention in the study of respiratory allergy although $C_4$ grasses are recognized as significant contributors to allergic disease in northern Australia (Johnston et al. 2009; Davies et al. 2012). The $C_4$ grasses of the Chloridoideae and Panicoideae subfamilies contain allergenic pollen (as reviewed in Davies 2014). Currently, there has been no systematic study to evaluate differences in incidence of allergic disease triggered by $C_3$ and $C_4$ grass pollen; however, patients in subtropical regions show higher levels of allergic sensitization and species-specific IgE reactivity to subtropical ($C_4$) species than temperate $C_3$ species (Davies et al. 2011, 2012; Nony et al. 2015). Therefore, grass species distribution has clinical significance due to both differences in season timing, and differences in allergen composition and consequently immune recognition between subtropical and temperate grass pollen (Andersson and Lidholm 2003; Johansen et al. 2009; Davies 2014).

Growth and flowering of grass species are closely coupled to seasonal variation in climate, and continental scale climate gradients. For example, in Australia, seasonal water availability is a predictor of $C_4$ relative abundance, while daily minimum temperature in January may predict $C_4$ grass species richness (Murphy and Bowman 2007). Climate change projections of increasing mean temperatures with variable effects on rainfall (IPCC 2013) will have direct effects on plant phenology and on the distribution of allergenic species. These changes will additionally influence pollen season and therefore the prevalence and severity of allergic rhinitis and asthma, although our understanding of these changes is currently limited and based on research that is largely derived from northern hemisphere locales. Projecting these impacts in Australia and New Zealand requires an understanding of variation in pollen seasonal dynamics over latitudinal and climatic gradients.

Australia presents a latitudinal gradient of both temperature and rainfall. The northern tropics and subtropics are warm throughout the year, with summer rainfall, while southeastern Australia has cool winters and either less seasonal or winter-dominant rainfall patterns. Inland, winter and spring frosts are common. New Zealand's climate is less diverse, and is similar to southeastern Australia, though generally characterized by cooler temperatures and higher rainfall (Sturman and Tapper 2006). Across these climate gradients, there is distinctive variation in the composition and distribution of vegetation communities and the airborne pollen assemblages they produce (Haberle et al. 2014).

Grass pollen from indigenous and introduced species form a major component of airborne pollen

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in Australian and NZ and in broad terms reflects the distributions of a wide diversity of $C_3$ and $C_4$ grasses. While all plants fix and assimilate carbon into a three-carbon sugar, $C_4$ photosynthesis involves a four-carbon intermediate, coupled with altered leaf anatomy, allowing effective concentration of $CO_2$ around carboxylation machinery. This reduces water loss, and increases carboxylation efficiency, allowing $C_4$ grasses to grow in drier, hotter environments (Ehleringer et al. 1997). The relative distributions of $C_3$ and $C_4$ grasses are strongly latitudinally dependent (Fig. 1). While $C_3$ grasses, such as ryegrass (*Lolium perenne*), dominate in temperate regions of Australia and New Zealand (Hill et al. 1979), $C_4$ species dominate grasslands of northern and central Australia, where the growing seasonal average temperatures exceed 22 °C (Collatz et al. 1998) or season minimum temperatures exceed 12–15 °C (Fig. 1; Hattersley 1983). These species include *Sorghum halapense* (Johnson grass), *Paspalum notatum* (Bahia grass) and *Cynodon dactylon* (Bermuda grass) plus invasive species *Andropogon gayanus* (Gamba grass) and in the arid zone, *Cenchrus ciliaris* (Buffel grass). In temperate NZ, grass flowering follows a latitudinal trend, being later in the growing season at the southernmost latitudes (Newnham 1999). Similar patterns are likely to occur over broader climatic zones in Australia, but to date this question has not been addressed.

Although available for most capital cities, seasonal grass pollen monitoring in Australia has been poorly coordinated at a national level, with campaigns of variable duration and using a variety of methodologies (Haberle et al. 2014). Aerobiological research in NZ has also been limited in geographic coverage and temporal duration. The only study at a national scale was conducted for a single season in 1988/89 (Newnham et al. 1995). Despite limitations with data availability, an analytical synthesis of the data derived

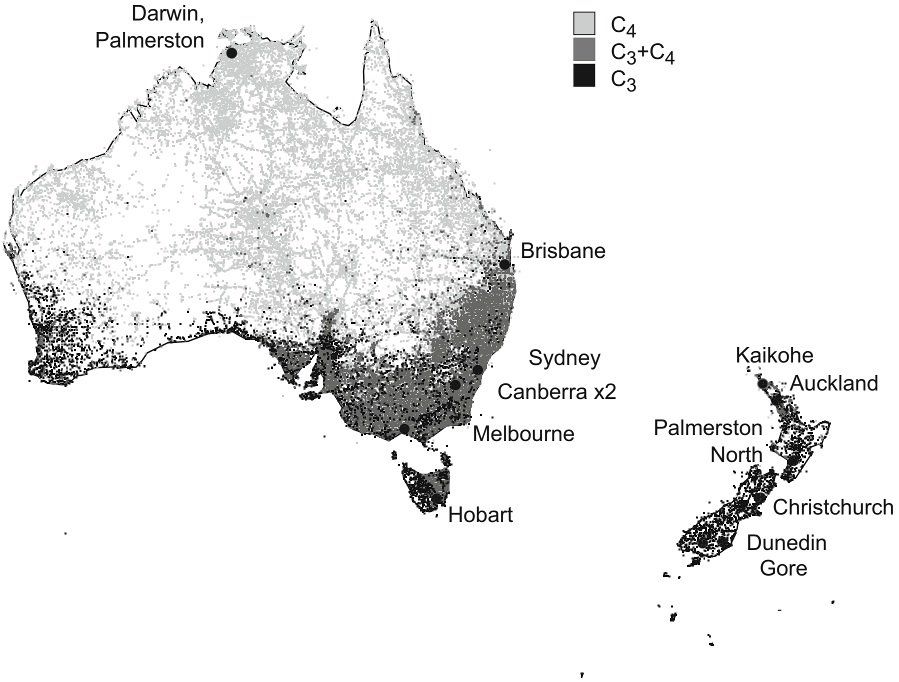

**Fig. 1** Location of pollen-monitoring sites, with distribution of $C_3$ (*black*) and $C_4$ (*light gray*) grass genera, and sites of co-occurring $C_3$ and $C_4$ grasses (*dark gray*) in Australia and New Zealand based on observation of $C_3$ (*Agrostis, Avena, Bromus, Dactylis, Danthonia, Festuca, Holcus, Hordeum, Lolium, Phalaris, Phleum, Poa, Rytidosperma, Triticum,* and *Zoysia*) and $C_4$ (*Andropogon, Aristida, Astrebla, Cenchrus, Cynodon, Echinochloa, Enteropogon, Eragrostis, Panicum, Paspalum, Sorghum, Sporobolus, Themeda,* and *Triodia*) in Australia, and $C_3$ (*Agrostis, Anthoxanthum, Austrostipa, Avena, Bromus, Chionochloa, Critesion, Dactylis, Deschampsia, Deyeuxia, Festuca, Holcus, Koeleria, Lachnagrostis, Lolium, Nassella, Pennisetum, Phalaris, Phleum, Poa, Rytidosperma,* and *Trisetum*) and $C_4$ (*Andropogon, Cynodon, Panicum, Paspalum, Setaria,* and *Sorghum*) in NZ. *Sources* Atlas of Living Australia (http://www.ala.org.au/), and New Zealand Virtual Herbarium (http://www.virtualherbarium.org.nz/)

from these previous datasets provides an opportunity to explore trends that can be further investigated using standardized pollen counting methodology, such as the rigorous standards used across Europe and the USA (Galán et al. 2014; American Academy of Allergy, Asthma & Immunology 2015). Here, we specifically assess latitudinal variation and climate influences on the grass pollen season timing and intensity, by analyzing existing pollen records along latitudinal gradients in eastern Australia and NZ.

We have previously shown that the diversity of pollen recorded from Australian and New Zealand monitoring sites reflects climate, land use and plant introduction (Haberle et al. 2014). We have also observed that the timing of the grass pollen season differs between geographic locations and over time (Beggs et al. 2015). Here, we investigate the drivers of variation in the characteristics of the grass pollen season across latitudinal and climatic gradients.

## 2 Methods

We assembled daily (24 h) airborne grass pollen concentration data from eight Australian and six NZ urban sites for sampling periods spanning from 1 to 17 years (Table 1; Haberle et al. 2014). Pollen counts were performed and converted to grains per cubic meter of air for sites in (from lowest to highest latitude) Darwin (two sites), Brisbane, Sydney, Canberra (two sites) and Hobart over 2, 5, 8, 4 and 3 fiscal years, respectively (Dass 2010; Erbas et al. 2007b; Green et al. 2004; Katelaris and Burke 2003; Newnham et al. 1995; Newnham 1999; Stevenson et al. 2007, Tng et al. 2010). Airborne pollen were counted within the expected grass pollen season of 92 days for Melbourne (October–December) over 13 of the 17 seasons, the others being full years, and between 88 and 134 days for the NZ sites (October–April) over one season. Both Burkard (Australia) and Rotorod (NZ) volumetric samplers were used, which for grass pollen, have been shown to be equivalent (Peel et al. 2014). For a summary of sampling and counting techniques at each site see Table 1, references therein, and Haberle et al. (2014).

Despite variability in timing, duration, sampling and counting techniques between sites, data allowed for an exploration of both temporal and spatial variability in grass pollen seasons. Pollen season timing was described by season start, end, duration and peak, calculated as days since 1st July (Southern Hemisphere winter). For sites with year-long records, i.e., Darwin, Brisbane, Sydney, Canberra, and Hobart, and for 4 years in Melbourne, the pollen season was defined as the period including 1–99 % (i.e., 98 %) of the total grass pollen counts over the counting period or year (Galán et al. 1995). Start and end dates and total season counts were excluded from analyses when the total count over the first or last 5 days of measurement exceeded 1 % of the season total count. In these instances, it was assumed that the grass pollen season extended beyond the sampling dates. This exclusion applied to Sydney 2007, Palmerston, Northern Territory (NT) 2004, Canberra 2008, South Canberra 2010, Hobart 2007 and 2010, and Melbourne 1996–2012. Seasons were classified as having multiple peaks if a 20-day running mean grass pollen count dropped below 5 grains $m^{-3}$, and then exceeded 5 grains $m^{-3}$ for >2 days. This technique identified most sites with visually identifiable later-season peaks, with the exception of 1 year in Brisbane when counts did not drop sufficiently. Where multiple season peaks were identified, the day of the second peak maximum count was recorded. To describe variation in pollen counts over the season, we calculated the total annual count, maximum daily concentration and number of days exceeding 20 and 50 grains $m^{-3}$.

Daily maximum and minimum temperature (°C) and daily rainfall (mm), were obtained from the Australian Bureau of Meteorology (www.bom.gov.au) and for NZ, the national climate database (http://cliflo.niwa.co.nz/). Average spring temperature was defined as the daily average of maximum and minimum temperature, averaged over the months of spring (September–November).

The distribution of data was assessed by the Kolmolgorov–Smirnov test for normality. For variables used to define pollen season intensity, differences between sites were assessed by Kruskal–Wallis Test with Dunn's pairwise comparisons.

For season timing, least squares linear regression was performed on the medians for each site, examining correlation of pollen start, end and peak dates, and total season count with latitude, temperature, and July rainfall. We chose median as it is robust in comparison with the mean due to the underlying variation between years. Data were

**Table 1** Site characteristics, including latitude (°S), years of pollen records used, average annual maximum (MaxT) and minimum (MinT) temperatures, mean annual precipitation (MAP), and elevation

| Site | Latitude (°S) | Years | MaxT (°C) | MinT (°C) | MAP (mm) | Elevation (m) | Environment | Climate | Monitor height (m) | Monitor type | Magnification, transects |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Australia | | | | | | | | | | | |
| Darwin (two sites)[a] | 12 | 2003–2004 | 33.3 | 19.3 | 1730 | 13 | Urban, open woodland | Tropical, winter dry | 14 | Burkard | 40×, 4 transects |
| Brisbane[b] | 27 | 1994–1998 | 30.3 | 10 | 997 | 13 | Urban | Humid subtropical | 2 | Burkard | 25×, entire slide |
| Sydney[c] | 34 | 1993–1995<br>2008–2012 | 25.9 | 8 | 1213 | 74 | Urban, evergreen forest, woodland | Maritime temperate | 10 | Burkard | 40×, 3 transects |
| Canberra (two sites)[d] | 35 | 2007–2010 | 28 | −0.1 | 612 | 569 | Urban, cropland, grassland | Maritime temperate | 8, 14 | Burkard | 40×, 4/1 transects |
| Melbourne[e] | 38 | 1996-2012 | 25.9 | 6 | 650 | 43 | Urban | Maritime temperate | 14 | Burkard | 20×, 1 transect |
| Hobart[f] | 43 | 2008–2010 | 21.6 | 4.5 | 616 | 58 | Evergreen forest, urban | Maritime temperate | 12 | Burkard | 40×, 4 transects |
| New Zealand | | | | | | | | | | | |
| Kaikohe[g] | 35 | 1988 | 24.3 | 7.8 | 1304 | 198 | Evergreen forest | Maritime temperate | 2 | Rotorod | 40× |
| Auckland[g] | 37 | 1989 | 23.7 | 7.1 | 1239 | 15 | Urban | Maritime temperate | 3 | Rotorod | 40× |
| Palmerston North[g] | 40 | 1988 | 22.9 | 4.7 | 968 | 36 | Grassland, cropland | Maritime temperate | 5 | Rotorod | 40× |
| Christchurch[g] | 44 | 1988 | 23 | 2 | 651 | 14 | Urban, grassland | Maritime temperate | 20 | Rotorod | 40× |
| Dunedin[h] | 46 | 1992 | 18.9 | 3.2 | 814 | 4 | Grassland, mixed forest | Maritime temperate | 5 | Rotorod | 40× |
| Gore[g] | 46 | 1988 | 18.7 | 1 | 1149 | 57 | Grassland | Maritime temperate | 2 | Rotorod | 40× |

“Environment” lists the most common land use types based on International Geosphere–Biosphere Programme classifications, within a 10-km radius of the site. “Climate” lists each site’s Köppen climate classification. Elevation refers to height above sea level. Monitor height refers to height above ground level at the site. “Magnification, transects” refers to the objective used when counting, and the number of transects performed across each slide. For further information on monitoring protocols and site descriptions, see Haberle et al. (2014)

[a] Stevenson et al. (2007), [b] Green et al. (2004), [c] Katelaris and Burke (2003), [d] Dass (2010), [e] Erbas et al. (2007b), [f] Tng et al. (2010), [g] Newnham et al. (1995), [h] Newnham (1999)

analyzed using the statistical package *R* (2.15.3). Results are expressed as medians with 95 % confidence intervals (CI). All of the analyses were done at a significance level of 0.05 unless otherwise stated.

Growing degree days (GDD) for the timing of season peaks were calculated. This parameter is widely used in the modeling of phenology (McMaster and Wilhelm 1997). The GDD is the cumulative temperature, in degrees, over the season, calculated based on the average temperature for each day, summed over days from 1st July to the season peak. Average temperature for each day is the average of daily temperature maximum and minimum. While many GDD calculations exclude days below a baseline temperature, no baseline temperature was defined.

## 3 Results

### 3.1 Total grass pollen count

To examine variation in the intensity of the grass pollen season, the total pollen counts were compared between sites. In Australia, the total grass pollen per season (or year for Darwin, Brisbane, Sydney, Canberra and Hobart) ranged from 793 (median, IQR 712–1066) grains $m^{-3}$ in Darwin to 4028 (median, IQR 3425–6093) grains $m^{-3}$ in Brisbane (Fig. 2a).

The interannual variation in total pollen within Australian sites was reflected in the wide variation within sites, and by the large difference between the highest and lowest season total grass pollen counts (median 2.6, IQR 2.1–3.2). Darwin showed significantly lower total grass pollen counts than Brisbane and Melbourne. Hobart showed statistically significant lower total grass pollen counts than Brisbane. In NZ, total grass pollen per season ranged from 783 grains $m^{-3}$ in Christchurch to 11,910 grains $m^{-3}$ in Gore. In interpreting this data, it should be noted that total pollen counts may have been influenced by differing trap heights.

### 3.2 Grass pollen season peaks

The maximum daily grass pollen count displayed both broad geographic and interannual variability. In Australia, maximum daily pollen counts ranged from a median of 44 (IQR 22–76) in Darwin to 231 (IQR 151–328) grains $m^{-3}$ in Melbourne (Fig. 2b). Melbourne showed significantly higher maximum daily grass pollen than Darwin, but the apparent differences between Melbourne and other Australian cities (particularly Brisbane and Hobart) were not statistically significant. At sites with data from multiple seasons, there was considerable year-to-year variability in maximum daily grass pollen count; the difference between the highest and lowest value varied 3.8-fold (IQR; 2.9–3.9). In NZ, maximum daily grass pollen counts ranged from 45 in Christchurch to 2005 grains $m^{-3}$ in Gore (Fig. 2d).

### 3.3 Seasonal distribution of pollen counts

Brisbane had the highest number of days per season with counts >20 grains $m^{-3}$ (Fig. 3a), whereas Melbourne showed the highest median number of days >50 grains $m^{-3}$. For NZ sites, Kaikohe, Palmerston North and Gore all showed >25 days per season with pollen counts >50 grains $m^{-3}$ (Fig. 3d).

### 3.4 Distribution of grass pollen concentrations

The character of the pollen season differed substantially between latitudes (Fig. 4). In northern Australia, for example Brisbane, pollen seasons had multiple peaks, with summer/early autumn peaks that were often larger than spring peaks. In mid-latitudes, for example Sydney, grass pollen seasons again had multiple peaks, but spring peaks were larger than summer peaks. In contrast, in southernmost sites, for example Hobart, seasons were characterized by a single peak, occurring in spring/summer (Fig. 4a). In NZ, no sites aside from Auckland showed multiple seasonal peaks. Indeed, when comparing sites with one and two or more peaks, sites with multiple peaks tended to be at lower latitudes (Fig. 4b, $p < 0.01$).

### 3.5 Pollen season timing

Grass pollen season timing was strongly linked to latitude, and likewise to average spring temperature, partly from the presence or absence and timing of the second seasonal peak. While overall the season start date showed no relationship with latitude or average spring temperature, among southern temperate sites, start date occurred later at cooler, higher latitude sites.

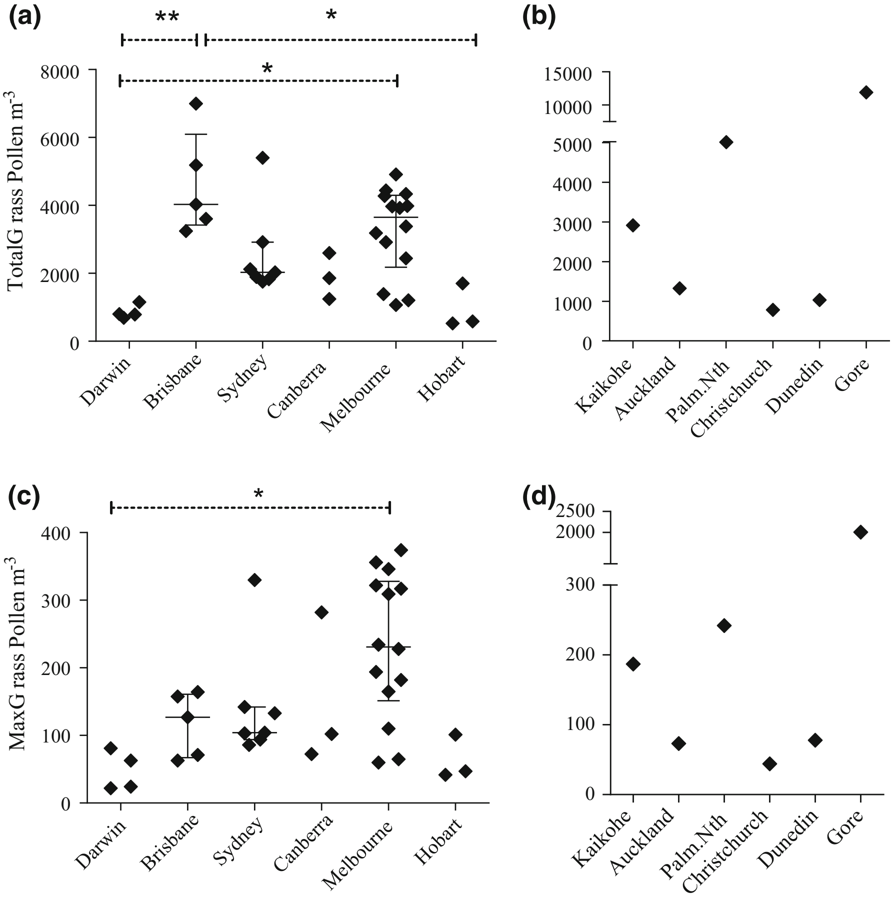

**Fig. 2** Variation in airborne grass pollen season intensity as described by total (**a**, **b**) and maximum (**c**, **d**) grass pollen count for Australia (**a**, **c**) and New Zealand (**b**, **d**). *Data points* represent values for separate seasons. For Melbourne, pollen count data were only available for 3 months from October 1 (Kruskal–Wallis with Dunn's pairwise comparisons; $*p < 0.05$; $**p < 0.01$). Median and Interquartile ranges are shown for sites with data for >4 seasons

Likewise, across all sites, season end date occurred earlier with increasing latitude and decreasing average spring temperature. Thus, season length decreased with distance from the equator, or decreasing spring temperatures (Fig. 5c, d). The timing of season peak, the highest pollen count from 1st July, occurred later in lower latitudes, but of the higher latitude sites, peaks occurred later with increasing latitudes or colder spring temperature (Fig. 5e, f). Latitudinal trends in season start and peak dates were similar when comparison was made within countries (and thus within the groups of sites that used only Rotorod or Hirst-type spore traps), but only trends in peak and end date were significant in Australia, and no trends achieved statistical significance in New Zealand data.

Seasonal maximum pollen peaks occurred at high latitudes on a median growing degree day of 1977 °C (interquartile range 1693–2151). The GDD of low latitude pollen season peaks was greater and more variable, with a minimum of 2483 °C in Brisbane (1996) to a maximum of 8374 °C in Darwin (2003).

The correlation between pollen season timing and rainfall was examined. A trend was found for increasing total grass pollen count with increasing July rainfall (not shown, $p = 0.05$), yet half the variance in season count remained unaccounted for ($R^2 = 0.5$). This trend was not improved by removing Darwin and Brisbane from the analysis. There were also no clear trends in total grass pollen counts with latitude or spring temperature (total season count vs. latitude, $p = 0.24$, $R^2 = 0.21$).

## 4 Discussion

Grass pollen season duration and intensity are among the most important parameters for determining allergy symptom duration and severity. In Australia and NZ,

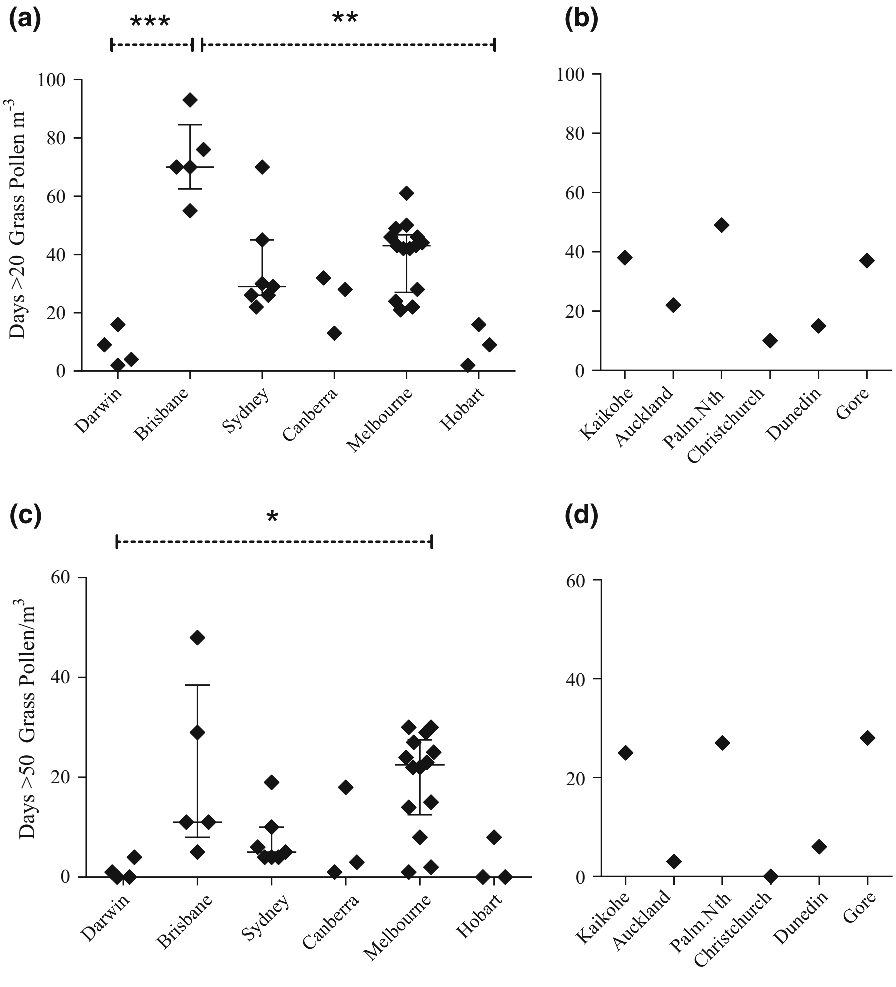

**Fig. 3** Sum of days with grass pollen levels exceeding 20 (**a**, **b**) or 50 (**c**, **d**) grains m$^{-3}$ in Australia (**a**, **c**) and New Zealand (**b**, **d**). *Data points* represent values for separate seasons. For Melbourne, pollen count data were only available for 3 months from October 1 (Kruskal–Wallis with Dunn's pairwise comparisons; $*p < 0.05$; $**$, $p < 0.01$; $***p < 0.005$). Median and Interquartile ranges are shown for sites with data for >4 seasons

the currently available datasets suggest that considerable geographical variability exists in both total grass pollen counts and peak season duration. Within the temperate sites, the grass season start date occurred later in more southern latitudes with cooler climates; however, the data indicate an even greater latitudinal response in season end date, occurring earlier with increased latitude. These changes led to the consistent trend of shorter seasons at higher latitudes. The grass pollen trends are likely to reflect climate influences on both species distribution and grass phenology. Delayed season end date in lower latitudes is likely to reflect the presence or absence of summer and autumn pollen peaks. Multiple peaks within a season may represent different species flowering at various temporal intervals and/or multiple flowering events for the same species in a year. For example, the flowering season of Gamba grass is noted to occur after that of native grasses in NT (Stevenson et al. 2007). These variables have not been able to be evaluated on a broader scale as the pollen-monitoring methods used do not differentiate grass pollen to species level nor between $C_3$ and $C_4$ types.

While $C_3$ grasses tend to flower in spring, $C_4$ species are summer-flowering (Ehleringer et al. 1997; Bass et al. 2000; Australasian Society of Clinical Immunology and Allergy 2014). The multiple peaks in summer through autumn in northern Australia are likely to represent the flowering of $C_4$ species. Additionally, at higher latitudes, summer peaks may reflect a second generation of spring-flowering grasses germinating and flowering, which may only be possible where development to flowering occurs before autumn frosts.

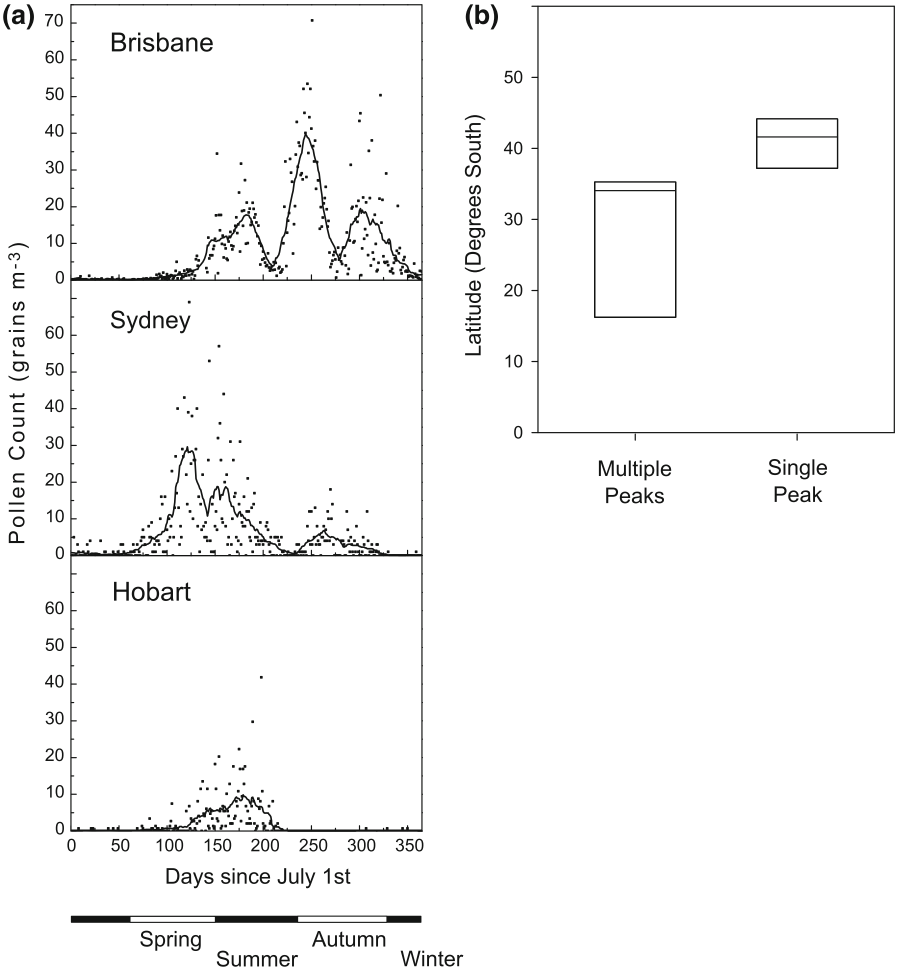

**Fig. 4** Latitudinal gradients in seasonal distribution of pollen. **a** Examples of pollen season distributions for sites in warmer climates (Brisbane and Sydney) that show two or more grass pollen peaks, and a cooler-climate site (Hobart) that shows one season peak. *Lines* represent 20-day moving average pollen counts, and *points* represent daily counts. Counts are plotted over a fiscal year from July 1st. **b** Latitudinal distribution of sites with single (Melbourne, Hobart, Kaikohe, Palmerston North, Christchurch, Gore) versus multiple (Darwin, Brisbane, Sydney, Canberra and Auckland) peaks in pollen seasons (median and IQR)

Some of the observed variation in pollen season timing with latitude is likely to be related to consistent latitudinal trends in temperature. However, both day length and rainfall patterns are also strongly dependent on latitude in Australia (Sturman and Tapper 2006). These additional factors are likely to influence grass distribution and development. Again, while the temperate season peak could be roughly estimated by growing degree day calculations, there was considerable variability between sites, suggesting the importance of variables other than temperature. Indeed, within sites, rainfall influences phenology. Spring rainfall is a predictor of total season pollen count in Melbourne (de Morton et al. 2011), whereas the pollen season of Darwin is closely related to the onset of the wet season and bears little relation to seasonal temperature change (Stevenson et al. 2007). While pollen levels in Brisbane were associated with rainfall, this relationship was not associated with cumulative winter rainfall as observed in Melbourne, but with summer rainfall events (Green et al. 2002). In our study, winter rainfall was a poorer predictor of median seasonal counts across all sites, and even across southern temperate sites alone.

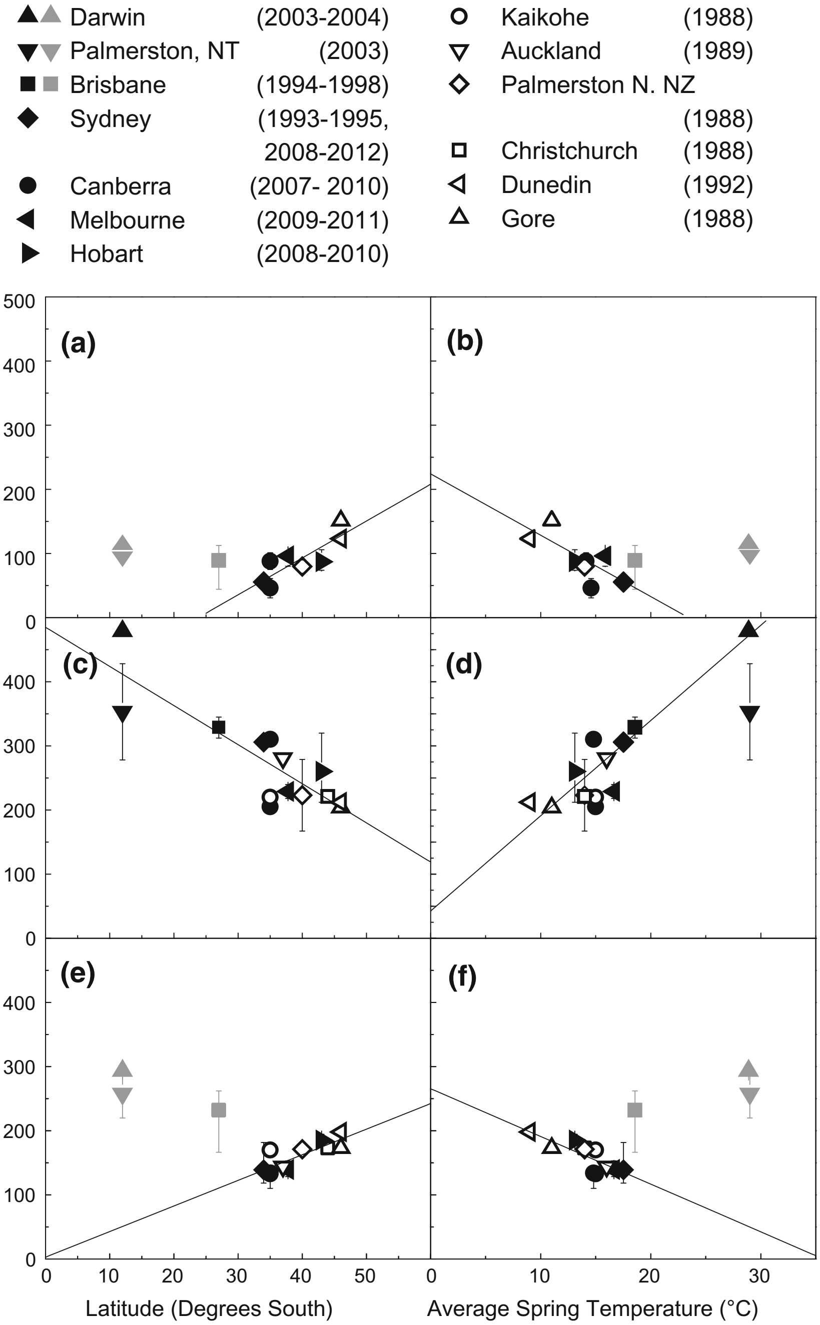

**Fig. 5** Variation in timing of pollen season with latitude (**a**, **c**, **e**) and average spring temperature (**b**, **d**, **f**). Three measures of pollen season timing are shown: season start (**a**, **b**) and end date (**c**, **d**), and season peak (**e**, **f**). *Points* represent medians, with *bars* representing the interquartile range when more than two values were available. *Filled symbols* represent Australian sites and *hollow symbols* represent NZ sites. Significant regression lines are presented. *Gray symbols* in panels **a**, **b**, **e**, **f** indicate Northern Territory and Brisbane sites, which are excluded in these cases from the regression. For statistical details, see Table 2

The underlying cause of the trends in grass pollen season across latitudinal gradients is linked to climate effects on grass species abundance and species diversity, especially seasonal patterns in temperature and water availability (Murphy and Bowman 2007). Agricultural practices and thus pasture composition is likely to be influenced by climate change; moreover, the response of introduced species to climate change in Australia is uncertain, and will likely involve altered ranges and patterns of dominance (Haberle et al. 2014). It will therefore be important to monitor the distribution of $C_4$ and $C_3$ grasses for changes that may have a clinical impact upon the exposure to pollen and immune responses of patients to different allergen

**Table 2** Results of simple linear regression for pollen season parameters against latitude and average spring temperature (Spring *T*)

| Pollen season parameter | Comparison | Slope | CI | $R^2$ | $p$ |
|---|---|---|---|---|---|
| Start date | Latitude | 5.8 | 2.0, 9.5 | 0.69 | 0.010 |
| (Excl. NT and Brisbane) | Spring *T* | −9.6 | −17.9, −1.2 | 0.57 | 0.030 |
| End date | Latitude | −6.1 | −8.4, −3.8 | 0.74 | <0.001 |
|  | Spring T | 14.9 | 9.1, 20.7 | 0.87 | 0.001 |
| Season length | Latitude | −7.7 | −11.8, −3.7 | 0.78 | 0.003 |
|  | Spring T | 14.3 | 5.0, 23.5 | 0.70 | 0.009 |
| Season peak | Latitude | 4.0 | 1.9, 9.7 | 0.67 | 0.002 |
| (Excl. NT and Brisbane) | Spring T | −7.4 | −11.6, −3.3 | 0.65 | 0.003 |

Sites in the Northern Territory (Darwin and Palmerston) and Brisbane were excluded from linear regression of season start and peak

repertoires present within pollen of subtropical and temperate grasses (reviewed in Davies 2014).

In this study, trends in the number of days above 20 and 50 grains $m^{-3}$ were found to reflect both season intensity and season duration. While the variation in years of measurement, collection and counting methods suggests that care should be exercised when analyzing absolute pollen counts across sites, and the extreme high counts of the southern states contrast with the low daily counts yet long seasons in northern sites. How allergic disease manifests in the population may vary accordingly. While Darwin had very long seasons, daily pollen counts were relatively low. In contrast, Melbourne showed the highest number of days over 50 grains $m^{-3}$. Brisbane was characterized by long seasons with the most days above 20 grains $m^{-3}$ of any location (with the caveat that Brisbane's spore trap was situated lower to the ground than that of any other Australian site). Patients sensitized to $C_3$ and $C_4$ grass species may be symptomatic for longer periods in Brisbane than in southern urban centers. Allergic disease would be expected to be of higher prevalence in the south, where seasons are typically short and intense, yet sufferers would remain symptomatic for a shorter period of time.

Relationships between pollen counts and symptoms are, however, likely to be complex, and influenced not only by severity of sensitization and cumulative exposure over the season, but also priming by exposure to tree pollens earlier in the season (Katelaris 2000). Whereas extended exposure to pollen could lead to chronic symptoms with sustained nasal congestion, short duration exposure at high concentration could lead to more acute symptoms of rhinorrhea and sneezing, presenting as same-day and lagged effects.

Late-season pollen peaks are apparent in our data. Their presence is not confined to the Southern Hemisphere (Frenguelli et al. 2010; Kosisky et al. 2010; de Weger et al. 2011), but aerobiological studies have hitherto paid less attention to these peaks. Late-season peaks may be particularly important for allergic disease, as earlier exposures can prime sufferers for symptoms (Katelaris 2000), while later-season pollen may be more allergenic (Buters et al. 2010; Galán et al. 2013), and species composition and thus allergenic composition may differ (Frenguelli et al. 2010). Identifying the species composition of these peaks, for example by molecular characterization and phenologic studies, is imperative for predicting and understanding seasonal pollen allergic disease.

Local, current pollen counting and reporting, based on standardized methodology would assist with management of allergen exposure for patients at risk of symptom exacerbation due to pollen allergy. Our comparisons between sites are confounded by differing years of measurement, and differing methodologies. Although season timing is unlikely to be affected, different spore trap heights, type of spore trap (Burkard or Rotorod), sampling (weekly tapes or daily slides) and counting methodologies (including magnification and number of transects) may impact on seasonal counts. Inter-seasonal variability was considerable and likely to be related to variability in climatic conditions across different regions in Australia and NZ. Thus, projecting response of grass pollen and allergic disease to climate change requires repeated local pollen counts over many seasons with continual monitoring and validation of start and end dates. We have presented a simple correlation analysis of the association between latitude and season timing.

The availability of a larger dataset would allow for more rigorous analysis to fully unravel seasonal and region-specific associations in the future.

## 5 Conclusion

To date, monitoring of airborne grass pollen across Australia and New Zealand has been uncoordinated and collected for different purposes. As a result, any analytical comparison of this data presents some challenges and any conclusions drawn must be considered indicative. Despite these issues, some important broad patterns and trends are discernible. The pollen season displays spatiotemporal variability across Australia and New Zealand. Much of the variation over latitude lies in the less-studied late-season pollen peaks. These peaks may relate to the presence of warmer-climate $C_4$ grasses in northern latitudes. Patterns of allergic disease may reflect the differing seasonal characters, with longer, lower intensity seasons in northern latitudes, and shorter yet more intense seasons in southern latitudes. These trends in grass pollen aerobiology need to be confirmed with well-designed, prospective studies employing standardized collection and counting methodologies across multiple sites in the Australasian region.

**Acknowledgments** The Australian Aerobiology Working Group was supported by the Australian Centre for Ecological Analysis and Synthesis (ACEAS), Terrestrial Ecosystem Research Network (TERN). Merck Sharp and Dohme provided additional independent untied co-sponsorship for the Working Group. The authors wish to thank Associate Professor Alison Specht, Program Manager, and the staff of ACEAS, TERN for assistance in organizing the Workshops of the Working Group "Understanding Australian aerobiology to monitor environmental change and human allergenic exposure", North Stradbroke Island, Australia (March and November, 2013). We thank Doctors Diana Bass and Geoffrey Morgan for provision of their published pollen count data from Sydney. Alison Jaggard has been assisted by the New South Wales Government through its Environmental Trust (project reference number 2011/RD/0049). The findings and the conclusions in this report are those of the authors and do not necessarily represent the views of the US National Institute for Occupational Safety and Health. The authors also acknowledge the contributions a diverse group of people made to this study through counting pollen and maintaining the pollen records that we consolidated and analyzed. Finally, the authors wish to thank Associate Professor Jeroen Buters (Germany), Associate Professor Frank Murray (Australia), and Dr Michel Thibaudon (France) for their contributions to the working group.

**Author declarations** JMD's institute has received collaborative research funds from Stallergenes, consultancy fees, Honoraria payments from Stallergenes and Glaxo Smith Kline for presentations at Australian Society for Clinical Immunology and Allergy Education Meetings. JMD is an inventor on a patent granted in Australia and further applications for improving diagnosis and treatment of subtropical grass pollen allergy.

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