



# Combined synoptic and regional weather patterns affecting atmospheric Poaceae pollen concentrations in Sydney, Australia

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**Abstract** Inhalation of grass pollen can result in acute exacerbation of asthma, prompting questions about how grass pollen reaches metropolitan areas. We establish typical atmospheric Poaceae (grass) pollen concentrations recorded at two pollen samplers within the Sydney basin in eastern Australia and analyse their correlation with each other and meteorological variables. We determine the effect of synoptic and regional airflow on Poaceae pollen transport during a period of extreme ( $\geq 100$  grains  $m^{-3}$  air) concentration and characterise the meteorology. Finally, we tested the hypothesis that most Poaceae pollen captured by the pollen samplers originated from local sources. Fifteen months of daily pollen data, three days of hourly atmospheric Poaceae pollen concentrations and fifteen months of hourly meteorology from two locations within the Sydney basin were used. Weather Research Forecasting (WRF), Hybrid

Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) modelling and conditional bivariate probability functions (CBPF) were used to assess Poaceae pollen transport. Most Poaceae pollen collected was estimated to be from local sources under low wind speeds. Extreme daily Poaceae pollen concentrations were rare, and there was no strong evidence to support long-distance Poaceae pollen transport into the Sydney basin or across the greater Sydney metropolitan area. Daily average pollen concentrations mask sudden increases in atmospheric Poaceae pollen, which may put a significant and sudden strain on the healthcare system. Mapping of Poaceae pollen sources within Sydney and accurate prediction of pollen concentrations are the first steps to an advanced warning system necessary to pre-empt the healthcare resources needed during pollen season.

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## 1 Introduction

Grass pollen is recognised as one of the leading human biological exposures worldwide (García-Mozo, 2017) and a chief cause of pollen allergy (D'Amato et al., 2007). The Poaceae (grass) pollen allergy, based on immunoglobulin E (IgE) antibody recognition, is dominated by allergen groups 1 and 5 (Andersson & Lidholm, 2003). IgE antibody reactivity will produce allergic symptoms in 90–95% (group 1) and 65–85% (group 5) of pollen-sensitised individuals (Jung et al., 2018). When inhaled, Poaceae pollen grains deposit in the upper airway and may cause allergic rhinitis (hay fever); approximately 4.6 million (19%) people experienced these symptoms in Australia (2017–18) (AIHW, 2020) and are most symptomatic during grass pollen season (AIHW, 2011). Perennial ryegrass (*Lolium perenne*) is a commonly found Poaceae species throughout Australia, heavily used in agriculture as fodder and produces large amounts of pollen during the temperate grass pollen season. Ryegrass pollen can rupture in a humid atmosphere or when immersed in water due to osmotic shock (Taylor et al., 2002), releasing hundreds of microscopic, highly allergenic sub-pollen particles per pollen grain. If inhaled, the particles can reach the small airways and induce an allergenic-asthmatic response (Suphioglu et al., 1992). Asthma has a worldwide prevalence of over 272 million (James et al., 2018) and affects 11.2% of the Australian population (Australian Bureau of Statistics, 2018). Pollen is a common cause of asthma exacerbation during pollen season, and sudden increases in concentration can have catastrophic results.

A particular motivating event for this study is that atmospheric Poaceae pollen concentrations ( $>100$  pollen grains  $m^{-3}$ ) coincided with a thunderstorm on 21 November 2016 in Melbourne. The deadly thunderstorm-pollen combination resulted in an unprecedented increase in sudden-onset asthma attacks, in the 30 h from 6 pm on 21<sup>st</sup> November asthma-related intensive care admissions increased by 3000% compared to the three-year average for this time of year (Guest, 2017) and caused ten deaths (Thien et al., 2018). This devastating event has prompted increased

interest in the dynamics of atmospheric pollen movement and the evaluation of risk in different regions of Australia. It is unknown why events similar to those in Melbourne have not occurred in Sydney, given that ryegrass is reported throughout New South Wales (state where Sydney is capital) and thunderstorms frequently occur during spring when Poaceae pollen concentrations are at their highest. This study aims to explore this question by examining how pollen is transported to Sydney.

Poaceae is predominantly wind-pollinated, and long-distance pollen transport may be detected by the collection of non-locally sourced pollen (Myszkowska et al., 2021), peaks in pollen concentrations outside of the local pollen season (Skjøth et al., 2007) or peaks outside of the local pollen-release times (Kasprzyk et al., 2011). Different pollen species have been reported travelling vast distances over complex topography: Poaceae (Smith et al., 2005), ragweed (*Ambrosia*) (Šikoparija et al., 2013), mountain cedar (*Juniperus ashei*) (Mohanty et al., 2017; Rogers & Levetin, 1998) and bentgrass (*Agrostis*) (Van de Water et al., 2007). Extending exposure of pollen-sensitive individuals outside of the local pollen season may necessitate the allocation of additional health resources (Skjøth et al., 2007). It is unclear how or if the atmospheric pollen concentrations in Sydney are routinely affected by inter- or intra-state pollen transport into the Sydney basin. However, high pollen concentrations in the Sydney basin have been positively correlated with low-pressure systems off the east and south coast of Australia, which drive dry continental westerly winds into the Sydney basin, increasing atmospheric Poaceae pollen concentrations during the warmer months (Hart et al., 2007; Stennett & Beggs, 2004). Continental westerly wind fronts may be responsible for the long-distance transport of pollen into the Sydney basin from grasslands west of the Great Dividing Range (GDR).

Additionally, meso- and synoptic-scale convergence lines, visible on radar, have been linked to long-distance transport of pollen and increased atmospheric pollen concentrations due to two wind fronts meeting and air being forced upwards (Bannister et al., 2020). Wind speed (Skjøth et al., 2013) and the atmospheric boundary layer depth (Largeron & Staquet, 2016; Smith et al., 2008) also affect horizontal dispersion. Pollen has a natural settling velocity (fall speed through the atmosphere) (Gregory, 1973),

which can be used to calculate horizontal dispersion from a known or assumed initial height under laminar airflow conditions.

The biodiversity and abundance of flowering species affect the local atmospheric pollen concentrations, which vary between seasons and states/territories, latitudes and climates (Medek et al., 2016; Beggs et al., 2015). In Sydney, the pollen season is bimodal with higher concentrations in the spring peak (September–November) than the summer peak (December–February) (Medek et al., 2016). Water availability and temperature dictate the start of the local pollen season, and unfavourable weather conditions can delay the onset and shorten its duration (Subba Reddi et al., 1988). Medek et al. (2016) reported on the Sydney pollen season lasting an average of 250 days with total seasonal grass pollen concentration ranging between 1800 and 8000 grains  $\text{m}^{-3}$  air and a maximum average daily pollen concentration between 80 and 310 grains  $\text{m}^{-3}$  air. The diurnal cycle of pollen release in Sydney has not been well documented, but in Melbourne, Poaceae pollen concentrations peak between 17:00 and 21:00 Australian Eastern Standard Time (AEST) (Ong et al., 1995), similar to other sites globally.

The complex topography surrounding Sydney, with the Great Dividing Range to the west, smaller hills to the north and south and the Tasman Sea to the east, creates a humid subtropical coastal basin (Allwine & Whiteman, 1994), with a complex drainage flow. Airflow recirculation occurs primarily during spring and summer due to afternoon sea breezes and nocturnal drainage flows (Crawford et al., 2017). Combined meso-synoptic airflow is likely to determine air quality (Jiang et al., 2017) and pollen dispersion within the Sydney basin. Thus, considering local and distant pollen sources, airflow, and meteorology are crucial to understanding and predicting the atmospheric pollen concentration within the Sydney basin.

Atmospheric pollen concentrations in eastern Australia have been significantly positively correlated with meteorological variables, in particular: temperature (Green et al., 2004), relative humidity (Rutherford et al., 1997), dew point temperature and wind speed (Stennett & Beggs, 2004). However, in laboratory experiments increasing relative humidity caused anthers to close and reduced pollen availability (Taylor et al., 2002). Precipitation is also negatively correlated with atmospheric pollen concentrations,

scrubbing pollen from the atmosphere (Green et al., 2004). However, correlations are not always consistent between years (Aboulaich et al., 2013), and sub-pollen particles may remain in the atmosphere in high concentrations after heavy rainfall (Suphioglu et al., 1992).

Pollen constitutes only a minute fraction of the atmospheric aerosols, and a manual volumetric pollen sampler is typically used to sample atmospheric pollen grains. Manual pollen samplers such as Hirst type (Hirst, 1952) are labour intensive and require pollen samples to be examined under a microscope to distinguish the taxa. Despite this, they have been used in over 500 locations worldwide to establish pollen monitoring networks with the aim of recording and predicting atmospheric pollen concentrations and reducing the burden of disease (Buters et al., 2018). However, pollen samplers are spatially sparse, and correlation between them depends on meteorology, topography and local flowering (Katelaris et al., 2004).

A standardised pollen monitoring network has been implemented by the AusPollen aerobiology collaborative partnership (Beggs et al., 2018) to track and record pollen concentrations in Australia's major population regions. AusPollen has 24 Hirst-type (Hirst, 1952) monitoring stations, 19 on mainland Australia, situated primarily in the coastal areas and five in Tasmania. Standard protocols and operating procedures have been implemented, allowing reliable comparison between pollen collection sites (Beggs et al., 2018). Typically, pollen monitors record continuously during the Poaceae pollen season, October to December in temperate climate and November to March in subtropical climates. However, several monitors record all year round. Measured pollen concentrations are used to inform a pollen forecast for the days ahead (The University of Melbourne & Western Sydney University, 2010). For example, in the state of Victoria, thunderstorm asthma warnings are issued when high pollen concentrations and thunderstorms with damaging winds are likely (Bannister et al., 2021).

This study aims, for the first time, to provide a detailed examination of the diurnal pollen cycle during a period of extreme pollen concentration in Sydney. The study starts with a description of Poaceae pollen concentrations at two sites in the Sydney Basin. Next, we characterise the relationship with meteorology, narrow our focus to a period of extreme pollen concentration,

and closely investigate the associated meteorological phenomena and provenance of Poaceae pollen sources.

## 2 Data and methods

### 2.1 Pollen data

Fifteen months of daily pollen samples from October 2017 to December 2018 were collected at Richmond and Macquarie Park within the Sydney basin 60 and 15 km from the city centre, respectively. Richmond observations started on 8 October 2017, finished on 30 December 2018 and had six days of missing data; three days were outside the pollen season and three days had low a concentration the previous day (maximum 26 grains  $m^{-3}$ ). Macquarie Park observations began on 3 October 2017 and concluded on 31 December 2018. Two Burkard Scientific continuous airflow pollen samplers (Burkard Scientific, Uxbridge, UK) collected the atmospheric pollen samples, which were subsequently processed in laboratories at Macquarie University and converted to atmospheric concentrations (grains per cubic metre).

Each Burkard pollen sampler is mounted on a horizontal flat surface 5 m above ground level. They contain a vacuum pump and sampling inlet, which intakes  $10 L \pm 1 L$  of air per minute (Hirst, 1952). The airborne particles land on an adhesive silicone (polydimethylsiloxane) base tape located on a drum, which continually rotates at a fixed speed of 2 mm/hr, allowing daily pollen concentrations to be estimated following microscopic examination (Beggs et al., 2018).

Modifying the daily pollen counting method was necessary to accurately map air trajectories and compare the timing of the arrival of synoptic air masses with hourly pollen deposition during specific study days of interest. Hourly concentrations were estimated using vertical transects on the slide 2 mm apart, each containing a full field of view. The counts are converted to atmospheric pollen concentrations per cubic metre using Eq. 1

$$c = n * \left[ \frac{L * W}{L * \left(\frac{F}{M}\right) * N} * \frac{1}{\frac{D}{1000} * t} \right] \quad (1)$$

where  $n$ =pollen count from the instrument,  $L$ =length of impact area in mm,  $W$ =width of impact area in mm,  $F$ =field number of the microscope eyepiece,  $M$ =objective magnification,  $N$ =number of

transects,  $D$ =air flow rate in l/min, and  $t$  is the duration of sampling period in minutes. The settings used to calculate the hourly concentration per cubic metre of air were:  $L=2$  mm,  $W=7$  mm,  $F=20$ ,  $M=40$ ,  $N=1$ ,  $D=10$  l/min and  $t=60$  min. A value of 7 mm is used for  $W$  instead of the usual 14 mm because the tape is cut into two halves lengthways, with one half mounted onto a glass microscope slide to be used for counting under the microscope, and the other half put into storage at  $-80$  °C for future molecular analysis.

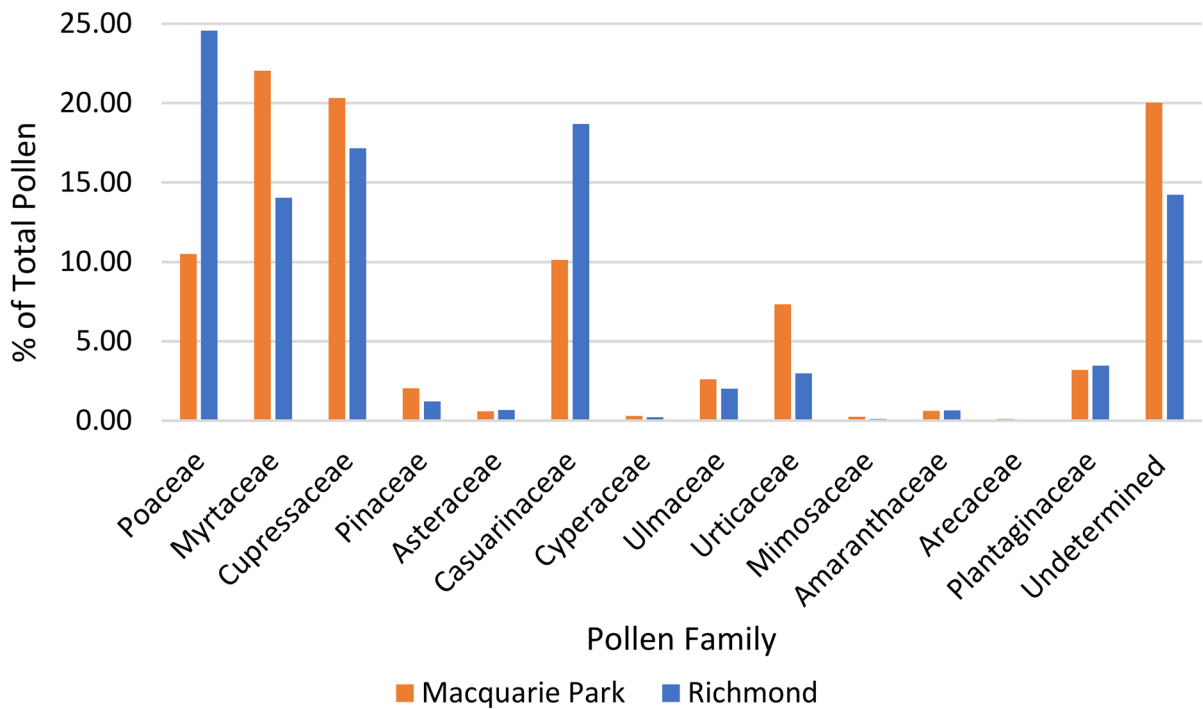
Of the thirteen taxa of pollen collected during the study (Fig. 1), Poaceae (grass), Myrtaceae, Cupressaceae and Casuarinaceae were the most common plant families to both pollen sampler locations and accounted for 74% (Richmond) and 63% (Macquarie Park) of the total pollen recorded during the study. Casuarinaceae was recorded in greater quantities during March through April, whereas Myrtaceae and Cupressaceae concentrations were higher during October through December at Richmond and Macquarie Park. However, Poaceae pollen concentration peaks differed temporally between the two locations.

From this point on, only Poaceae pollen concentrations were analysed further due to their direct link with asthma, allergic rhinitis exacerbations and thunderstorm asthma incidents. The Atlas of Living Australia Spatial Portal (Belbin, 2011) provided verified Poaceae locations used to compare the biodiversity surrounding the two pollen samplers.

The Richmond and Macquarie Park pollen monitors are collocated with (and on top of) the air quality monitoring stations. Richmond pollen sampler is located in a rural setting in the northwest of Sydney, latitude  $-33.616^\circ$  and longitude  $+150.747^\circ$  at 21 m above sea level (a.s.l.) (Fig. 2). The Macquarie Park pollen sampler is located in an urban setting closer to the east coast at latitude  $-33.765^\circ$ , longitude  $+151.118^\circ$ , 49 m a.s.l. (Fig. 2). Pollen samples were collected from the samplers late morning once a week.

#### 2.1.1 Pollen concentration peaks

We initially used Galán's "98%" (Galán et al., 1995) technique to assess the pollen season duration. However, we found the seasons were very different between Richmond and Macquarie Park, the latter extending almost the entire year. Therefore, in this study, we instead consider three "peak periods" during which pollen was evidently higher than at other times of the year. These were



**Fig. 1** Percentage of total pollen collected at Richmond and Macquarie Park per taxa during the study period October 2017 through December 2018

defined as October to December 2017 and 2018 (spring/early summer) and March to April in 2018 (autumn) and accounted for 96.3% of the total pollen collected at Richmond and 87.0% at Macquarie Park.

The atmospheric Poaceae pollen concentrations were categorised as low (0–20 grains  $m^{-3}$ ), moderate (20–50 grains  $m^{-3}$ ), high (50–100 grains  $m^{-3}$ ) and extreme (> 100 grains  $m^{-3}$ ) following a study of grass pollen in Melbourne (Ong et al., 1995). High and extreme concentrations were grouped since only a few extreme pollen concentrations were observed.

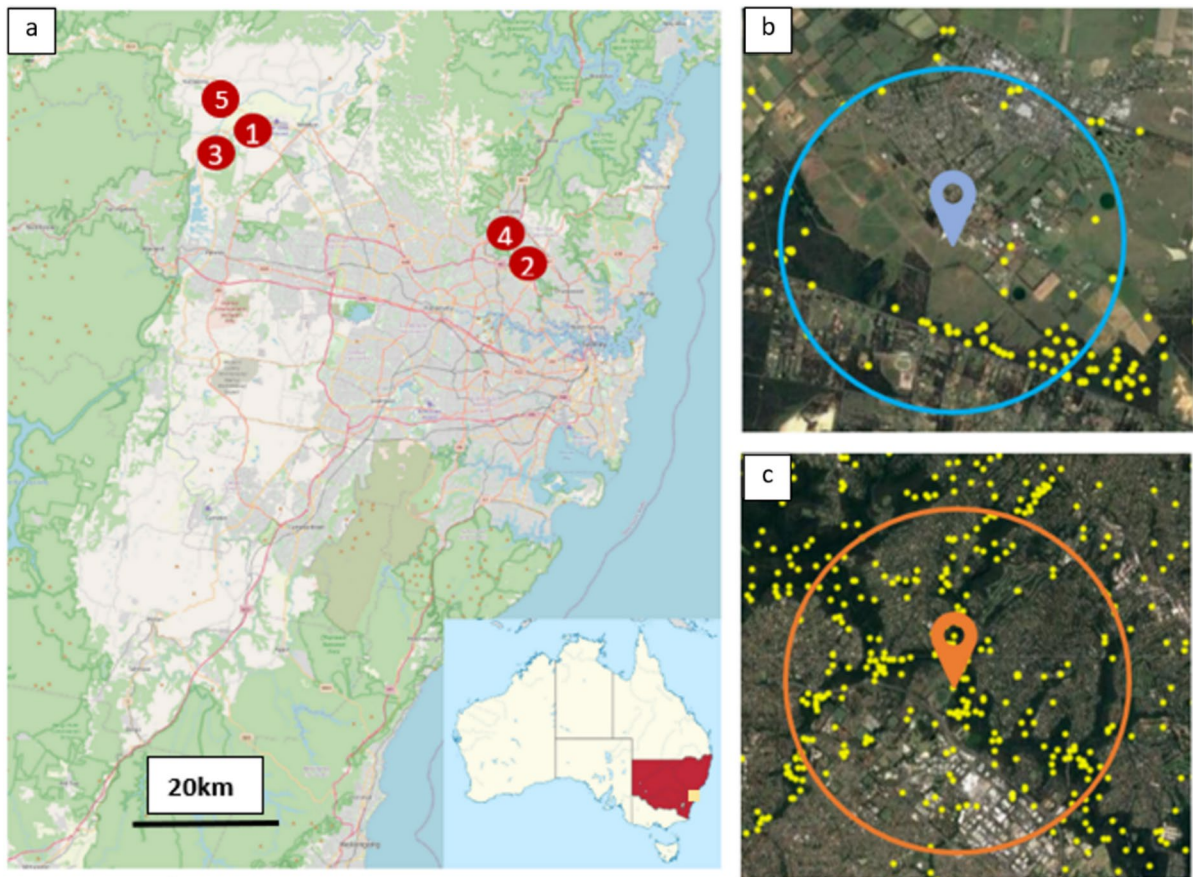
## 2.2 Meteorological and air quality data

Hourly meteorology and air quality observations obtained from the New South Wales Department of Planning, Industry and Environment (DPIE) included temperature ( $^{\circ}C$ ), relative humidity (%), wind speed ( $ms^{-1}$ ), wind direction ( $^{\circ}$ ), sigma theta (SD1) the standard deviation in wind direction ( $^{\circ}$ ) used to indicate turbulence, precipitation (mm), solar radiation ( $W/m^2$ ), and particulate matter (PM) 10 and 2.5  $\mu m$  ( $\mu g/m^3$ ).

The air quality monitoring stations (AQS) reflected meteorological conditions at pollen sampler locations.

Meteorology and air quality data were obtained from Richmond and Macquarie Park AQS.

Of the 456 study days, a maximum 0.6% of meteorological data was missing from Richmond; however, 9% of wind data was missing from Macquarie Park (October and early November 2017). Hourly wind speed and direction data from the Bureau of Meteorology (BOM) automatic weather station (AWS) at Terrey Hills was used on 12 October 2017 (an extreme pollen concentration day of interest). Terrey Hills was geographically the second closest (13 km to the north-east of the Macquarie Park pollen site) and had the least missing hourly data; therefore, it was used for the substitution. The mean difference and Spearman (rank-order) correlation coefficient ( $\rho$ ) for wind speed between Terrey Hills AWS and Macquarie Park's AQS during the 9842 h where both data were available was 1.37  $ms^{-1}$  and  $\rho=0.67$ , respectively, with mean wind speeds 2.8 m/s Terrey Hills and 1.435 m/s at Macquarie Park, with BOM Terrey Hills wind speeds consistently higher than DPIE Macquarie Park wind speeds. The wind direction circular mean difference and correlation coefficient was -30.20 degrees and  $\rho=0.53$ , which were judged to be acceptable levels of similarity.



**Fig. 2** **a** Sydney Basin, surrounded by the Great Dividing Range to the west and Tasman Sea to the east; the inset shows the state of New South Wales (red) in Australia, and Sydney (yellow square). Map markers: (1) Richmond pollen sampler, (2) Macquarie Park pollen sampler, (3) Agnes Banks Nature Reserve, (4) Lane Cove River, (5) North Richmond. **b** Rich-

mond pollen sampler (blue marker), **c** Macquarie Park pollen sampler (orange marker); large circles show a 2 km radius from pollen sampler. Yellow points are spatially verified Poaceae locations according to the Atlas of Living Australia spatial portal (<https://spatial.ala.org.au/>)

### 2.3 HYSPLIT modelling the movement of air mass

Although it is difficult to determine how far pollen has travelled in the atmosphere prior to reaching the pollen sampler, back-trajectories are commonly used to analyse airflow in combination with synoptic airflow analysis (Stępańska et al., 2020), advection (Šikoparija et al., 2013), molecular analysis (Mohanty et al., 2017) and phenology (Skjøth et al., 2007).

Our second goal in this study was to determine the provenance of air sampled at the pollen samplers during a period of extreme Poaceae pollen concentration. To do this, we used the Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT), developed by the US National

Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (Draxler & Hess, 1998). The HYSPLIT desktop model v4 was used to perform air parcel back-trajectory calculations during a period of extreme Poaceae pollen concentration on 12 October 2017. The wind fields were estimated by the WRF model (Sect. 2.3.1) and, to test the robustness of conclusions, those from a meteorological forecast model (Sect. 2.3.2).

HYSPLIT back-trajectory ensembles were calculated with starting locations at Richmond and Macquarie Park pollen samplers. Each ensemble member starts simultaneously, but the gridded 3D meteorology input used to calculate the trajectories was shifted horizontally by one grid point and vertically by 0.01

sigma unit, creating 27 ensemble members (Draxler et al., 2020). Using an ensemble enabled an assessment of trajectory sensitivity to minor imperfections in meteorology. The back-trajectory ensembles were simulated during a period of extreme Poaceae pollen concentration from 15:00 AEST back in time to 06:00 AEST and 20:00 AEST backwards to 15:00 AEST, reflecting different weather systems approaching the pollen samplers from opposite directions. The ensemble trajectories were calculated from a starting height of 500 m above ground level to minimise trajectory errors due to collision with the terrain whilst reflecting low-level and long-distance pollen transport (Smith et al., 2005).

### 2.3.1 Weather Research Forecasting simulations for use in HYSPLIT

The first model we used to simulate meteorology within the study domain was Weather Research Forecasting (WRF) (Skamarock et al., 2008), a mesoscale numerical weather prediction system that calculates meteorology using sigma pressure-hybrid terrain-following simulations. WRF was used here as a regional model and required global boundary conditions throughout the simulation. The US National Centers for Environmental Prediction (NCEP) Final (FNL) Operational Global Model boundary conditions were selected at  $1 \times 1$  degree horizontal and 6-h temporal resolution. Three-nested domains were used, having 27 km, 9 km and 3 km horizontal resolutions with respective temporal resolutions of 10, 30 and 30 min. The first six hours of the simulation were discarded to account for model instability during spin-up. The inner-most domain, covering the Sydney basin and surrounding mountains and hills, was used as meteorological input for the HYSPLIT atmospheric transport model.

In order to obtain good agreement between the WRF model and meteorological observations, several simulations were run with different combinations of physics parameterisations. All simulations were compared to local observations at Richmond and Macquarie Park and had good Spearman correlation with temperature  $\rho=0.96\text{--}0.98$  and relative humidity  $\rho=0.90\text{--}0.93$ . WRF wind speeds correlated with observations  $\rho=0.77\text{--}0.85$  but were overestimated by all simulations with a mean bias range of 1.65 to  $2.50 \text{ ms}^{-1}$ . The agreement for wind direction was

variable, with a circular correlation (used to calculate the correlation between two periodic data sets in this case wind direction)  $\rho=0.29\text{--}0.64$ . However, all simulations predicted the arrival of a westerly wind front which coincided with the extreme pollen concentration observed at Richmond.

Therefore, the WRF simulation with the lowest root-mean-square error (RMSE), highest correlation with observations, and highest Index of Agreement (Willmott, 1981) for wind speed and direction compared to observations was chosen for HYSPLIT back-trajectory simulations. The physics parameterisations of this simulation included: Microphysics WRF single momentum three-class (WSM3), cumulus scheme Kain–Fritsch, long-wave radiation rapid radiative transfer model (RRTM), short-wave radiation scheme Dudhia, boundary layer Yonsei Scheme Uni (YSU), surface layer revised (RMM5), land surface scheme NOAH, 100 vertical levels, and topographic-wind surface roughness parameterisation turned on; the latter improved wind speed agreement with observations. More information on physics parameterisations can be found in the WRF documentation (Skamarock et al., 2008).

### 2.3.2 Global Data Assimilation System (GDAS) for use in HYSPLIT

The second model used to simulate meteorology in the study domain was the Global Data Assimilation System (GDAS) forecast system, with a horizontal resolution of 0.5 degrees, 55 vertical layers and a time resolution of 3 h. The GDAS0.5 model is well established and freely available from 2011, supplied by the Air Resources Lab of NOAA.

One of the major differences between WRF and GDAS0.5 is the vertical advection. WRF predicts a non-hydrostatic vertical velocity which is included within the input to HYSPLIT, whereas GDAS0.5 calculates the vertical velocity by integrating the horizontal velocity divergence components  $u$  and  $v$  (wind moving towards the east and north, respectively). Due to this or other reasons, differences in vertical velocity can lead to discrepancies between trajectory path and height (Su et al., 2015). Therefore, the effect of the advection calculation was examined by comparing the non-hydrostatic vertical velocity trajectory and the horizontal velocity divergence trajectory for WRF. The difference between trajectory paths was

greater during periods of high wind speed. However, this did not change the overall conclusion of path trajectory.

## 2.4 Statistical Analysis

Spearman ranked correlation coefficients ( $\rho$ ), calculated in R Studio v 3.6.2., were used to compare non-circular data, including wind speed, relative humidity, temperature and pollen concentrations. Correlation between the wind directions, modelled and observed, at Richmond and Macquarie Park was computed using R Studio Circular Statistics package v0.4–93.  $P$ -values of  $<0.001$  were considered highly significant and  $p=0.001$  to  $0.05$  significant. The correlation strength: strong ( $0.7$ – $0.9$ ), moderate ( $0.4$ – $0.6$ ) and weak ( $0.1$ – $0.3$ ), was used in the interpretation of the results. Hourly meteorology was detrended using *decompose*, and the diurnal cycle removed using R Studio Stats package v 3.6.2 before correlation between the two pollen samplers.

### 2.4.1 Source-Receptor Characteristics

Source–receptor characteristics were used in this study to identify the wind conditions associated with low, moderate and high/extreme Poaceae pollen concentrations.

The conditional probability function (Ashbaugh et al., 1985; Vedantham et al., 2014) identifies and characterises air pollution sources based on wind direction. The technique has been extended to include a second variable, in this case, wind speed, on the radial axis to reveal the wind characteristics likely responsible for pollution transport (Uria-Tellaetxe & Carslaw, 2014). R Studio OpenAir package v. 2.6–6 (Carslaw & Ropkins, 2012) was used to calculate the conditional bivariate probability functions (CBPF) and general additive model (GAM) probability surfaces for low, medium and high/extreme Poaceae pollen concentrations (Eq. 2).

$$CBPF_{\Delta\theta,\Delta u}(i) = \frac{m_{\Delta\theta,\Delta u}|(i)}{n_{\Delta\theta,\Delta u}}(i) \begin{cases} 1 \leq C < 20(\text{low}) \\ 20 \leq C < 50(\text{moderate}) \\ C \geq 50(\text{high/extreme}) \end{cases} \quad (2)$$

where  $m_{\Delta\theta,\Delta u}|(i)$  is the number of samples in the wind direction sector  $\Delta\theta$  and wind speed  $\Delta u$  within a

Poaceae pollen concentration bin  $i$ , and  $n_{\Delta\theta,\Delta u}$  is the total number of samples in the wind speed–direction segment.  $C$  is the concentration of pollen in grains  $\text{m}^{-3}$ .

The wind speed and direction data were binned into ten-degree, one  $\text{ms}^{-1}$  segments, and the probability of different pollen concentrations (low, moderate, high) were estimated based on winds. Each segment had a maximum probability of one. The GAM surface had maximum probability if all the daily average pollen concentrations recorded at the sampler were within the specified pollen category. The distribution of pollen concentrations cannot be reliably determined for segments with too few data points nor associated with specific wind conditions.

The CBPF is computed here using hourly wind data, albeit we have only daily pollen data. Although not ideal, it was preferable to use the hourly wind data as daily averaging of the wind direction may result in a wind direction that did not occur (e.g. if a large wind direction change occurred during the day). Therefore, each hourly wind observation was matched with that day's pollen concentration.

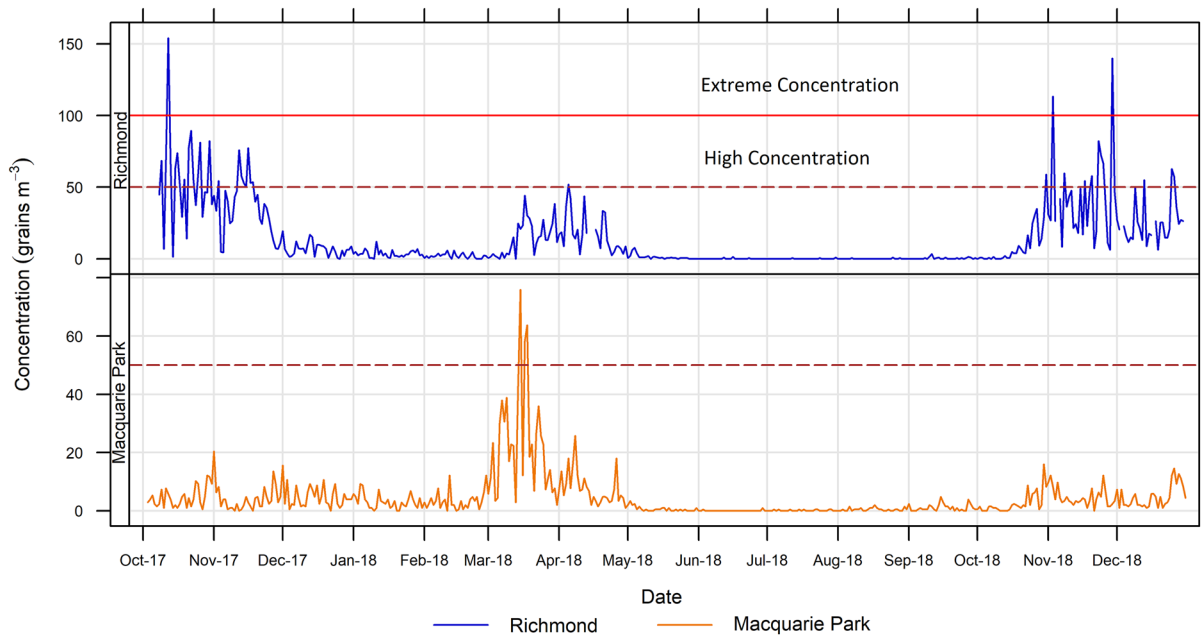
## 3 Results

### 3.1 Pollen analysis between sites

Daily time series of Poaceae pollen concentrations collected from Richmond and Macquarie Park (Fig. 3) show Richmond exhibiting two peak periods in pollen concentration, October through December (spring–summer) and March through April (autumn) compared to Macquarie Park's single peak period in autumn. In Richmond, the spring peak was smaller and started later in October 2018 compared to October 2017. The correlations between Poaceae pollen and total pollen concentrations were significant at each location (Table 1). During each peak period, Poaceae pollen represented between 27 and 38% of the total pollen collected at Richmond. At Macquarie Park, 6–9% of the total pollen was Poaceae during October through December and 36% during March and April (Table 1).

Richmond had more low and moderate and fewer high concentration days in October through December 2018 than in October through December 2017 (Table 1). Most high and all extreme Poaceae pollen





**Fig. 3** Daily Poaceae pollen concentrations recorded at Richmond (**top**) and Macquarie Park (**bottom**). Note differences in scale. The dashed and solid red horizontal lines represent high and extreme Poaceae pollen concentrations, respectively

**Table 1** Poaceae pollen peak concentration integral (grains m<sup>-3</sup> air), correlation and ratio between daily Poaceae pollen and total pollen, and the number of study days with daily Poaceae pollen concentration (grains m<sup>-3</sup> air) that measured low ( $C < 20$ ), moderate ( $20 \leq C < 50$ ), high ( $50 \leq C < 100$ ) and extreme ( $C \geq 100$ )

Location	Duration	Poaceae Integral	$\rho$	Ratio %	Number of days per concentration interval			
					L	M	H	E
Richmond	Oct—Dec 2017	2641	<b>0.71**</b>	37.9	41	23	20	1
	March – April 2018	910	<b>0.67**</b>	26.9	42	15	1	0
	Oct – Dec 2018	2203	<b>0.85**</b>	27.4	46	30	10	2
Macquarie Park	Oct—Dec 2017	404	<b>0.64**</b>	9.3	90	0	0	0
	March – April 2018	941	<b>0.84**</b>	35.6	44	14	3	0
	Oct – Dec 2018	366	<b>0.65**</b>	6.3	92	0	0	0

**\*\* $p < 0.001$**

concentration days occurred from October through December at Richmond. March to April had the lowest Poaceae integral and fewest moderate and high days compared to the other Richmond peak periods. In contrast, Macquarie Park had its highest Poaceae integral in March through April compared to October through December 2017 and 2018. All the moderate and high concentration days at Macquarie Park occurred from March through April 2018. Extreme Poaceae pollen concentrations were not observed at Macquarie Park.

Overall, Richmond Poaceae pollen was strongly correlated with total pollen concentrations during all

peaks, whereas Macquarie Park had a propensity for higher Poaceae during autumn.

### 3.2 Meteorology and pollen

The next step was to explore the local climate differences between the pollen collection sites and their relationship to Poaceae pollen concentration. From October 2017 through December 2018, all meteorological variables between Richmond and Macquarie Park were significantly positively correlated with  $p < 0.001$  (Table 2). However, wind speed and direction had weaker correlations than temperature

and relative humidity. The hourly data were decomposed and the diurnal cycle removed, the correlation between stations reduced, but associations remained significant.

The similarity of the weather at Richmond and Macquarie Park indicates that meteorological differences were not a major cause of the pollen concentration differences between Richmond and Macquarie Park.

Correlations between average daily meteorological parameters and daily Poaceae concentrations during the peak periods (Table 3) indicate a significant

**Table 2** Spearman correlation of meteorology and air quality between Richmond and Macquarie Park stations using daily data and hourly decomposed data from October 2017 to December 2018

Variable	$\rho$ – daily	$\rho$ – hourly
Temperature	<b>0.99 **</b>	<b>0.93 **</b>
Wind Speed	<b>0.80 **</b>	<b>0.63 **</b>
Wind Direction	<b>0.37 **</b>	<b>0.28 **</b>
Relative Humidity	<b>0.91 **</b>	<b>0.88 **</b>
PM <sub>10</sub>	<b>0.84 **</b>	<b>0.41 **</b>
PM <sub>2.5</sub>	<b>0.74 **</b>	<b>0.17 **</b>
SD1	<b>0.33 **</b>	<b>0.13 **</b>
Rain	<b>0.72 **</b>	<b>0.21 **</b>

\*\* $p < 0.001$ , total number of study days = 456, total number of study hours = 10,944. PM<sub>10</sub>, PM<sub>2.5</sub>: particulate matter (PM) 10  $\mu\text{m}$  and smaller and 2.5  $\mu\text{m}$  and smaller, SD1: Sigma theta (standard deviation in wind direction)

moderate, positive correlation with the temperature at both locations. Poaceae was also significantly moderately and negatively correlated with relative humidity and precipitation from October through December 2018. Sunlight (measured at Macquarie Park only) was significantly and moderately positively correlated with Poaceae pollen concentrations during 2018, reflecting the intense drought (NSW DPI, 2018) and lack of precipitation. PM<sub>10</sub> was moderately correlated to Poaceae at Richmond during October through December 2018, and both PM<sub>10</sub> and PM<sub>2.5</sub> were significantly and moderately positively correlated with low Poaceae pollen concentrations (October through December) at Macquarie Park, making it an unlikely proxy for atmospheric Poaceae pollen and linking clean air with low pollen concentrations.

### 3.2.1 Wind direction and speed during study peak periods

During the peak periods (Fig. 4), winds were weaker during March through April than October through December. However, they were generally stronger at Richmond than Macquarie Park. The most frequent winds at Richmond were 0 to 3  $\text{ms}^{-1}$  and from the west through south-west and east through north-east, compared to the 0 to 1  $\text{ms}^{-1}$  north-westerly winds at Macquarie Park. The most commonly occurring winds were similar during each peak period and thus not responsible for Poaceae pollen concentration differences. Easterly winds at both locations were

**Table 3** Spearman correlation coefficient of average daily meteorology and Poaceae pollen concentrations (grains  $\text{m}^{-3}$  air) during Poaceae pollen peak periods (N/A data not available)

	October to December 2017		October to December 2018		March to April 2018	
	Richmond $\rho$	Macquarie $\rho$	Richmond $\rho$	Macquarie $\rho$	Richmond $\rho$	Macquarie $\rho$
Temperature	–0.31	<b>0.50 **</b>	<b>0.46 **</b>	<b>0.54 **</b>	<b>0.49 *</b>	<b>0.49 *</b>
Wind Speed	–0.07	0.15	0.03	–0.02	–0.02	0.29
Relative Humidity	–0.26	–0.35	<b>–0.52 **</b>	<b>–0.54 **</b>	–0.24	–0.25
Rain	–0.20	–0.03	<b>–0.45 *</b>	<b>–0.52 **</b>	–0.24	0.02
PM <sub>10</sub>	–0.09	<b>0.39 *</b>	<b>0.38 *</b>	<b>0.48 **</b>	0.40	0.11
PM <sub>2.5</sub>	0.02	0.37	0.20	<b>0.44 **</b>	0.39	–0.08
Solar	N/A	0.08	N/A	<b>0.49 **</b>	N/A	<b>0.56 **</b>
SD1	0.12	0.30	0.05	0.05	0.04	0.17

\*\* $p \leq 0.001$ , \* $p \leq 0.05$ . The correlation strength: strong (0.7–0.9), moderate (0.4–0.6) and weak (0.1–0.3). Meteorological Day 11am through to 11am next day, Poaceae pollen collection late morning to late morning the next day. PM<sub>10</sub>, PM<sub>2.5</sub>: particulate matter (PM) 10 and 2.5  $\mu\text{m}$ , SD1: Sigma Theta – standard deviation in wind direction, Solar: solar radiation

stronger and more frequent during the warmer months (October through December), consistent with easterly sea breezes. Wind speeds above  $5 \text{ ms}^{-1}$  at Richmond and Macquarie Park were infrequent.

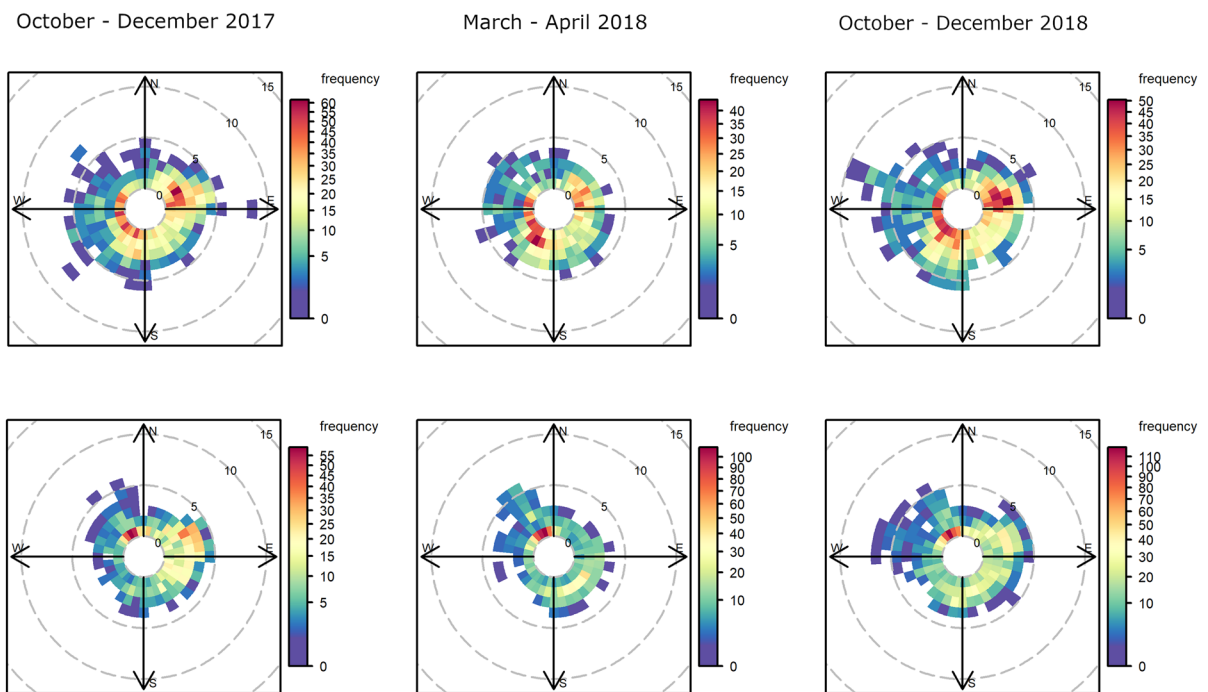
### 3.2.2 Identification and characterisation of pollen sources

At Richmond (Fig. 5), low wind speeds  $0\text{--}2 \text{ ms}^{-1}$  were associated with low Poaceae pollen concentrations. Based on the light winds, we infer that any pollen observed likely originated from the green spaces surrounding the pollen sampler (Fig. 2), whereas moderate, high and extreme Poaceae pollen concentrations were associated with higher wind speeds between  $4$  and  $10 \text{ ms}^{-1}$  primarily from two directions, northwest and south-west of the pollen sampler. Possible sources include Agnes Banks Nature Reserve, approximately  $8 \text{ km}$  south-west of Richmond pollen sampler and North Richmond, approximately  $5 \text{ km}$  northwest, consistent with spatially verified clusters of Poaceae (Fig. 2).

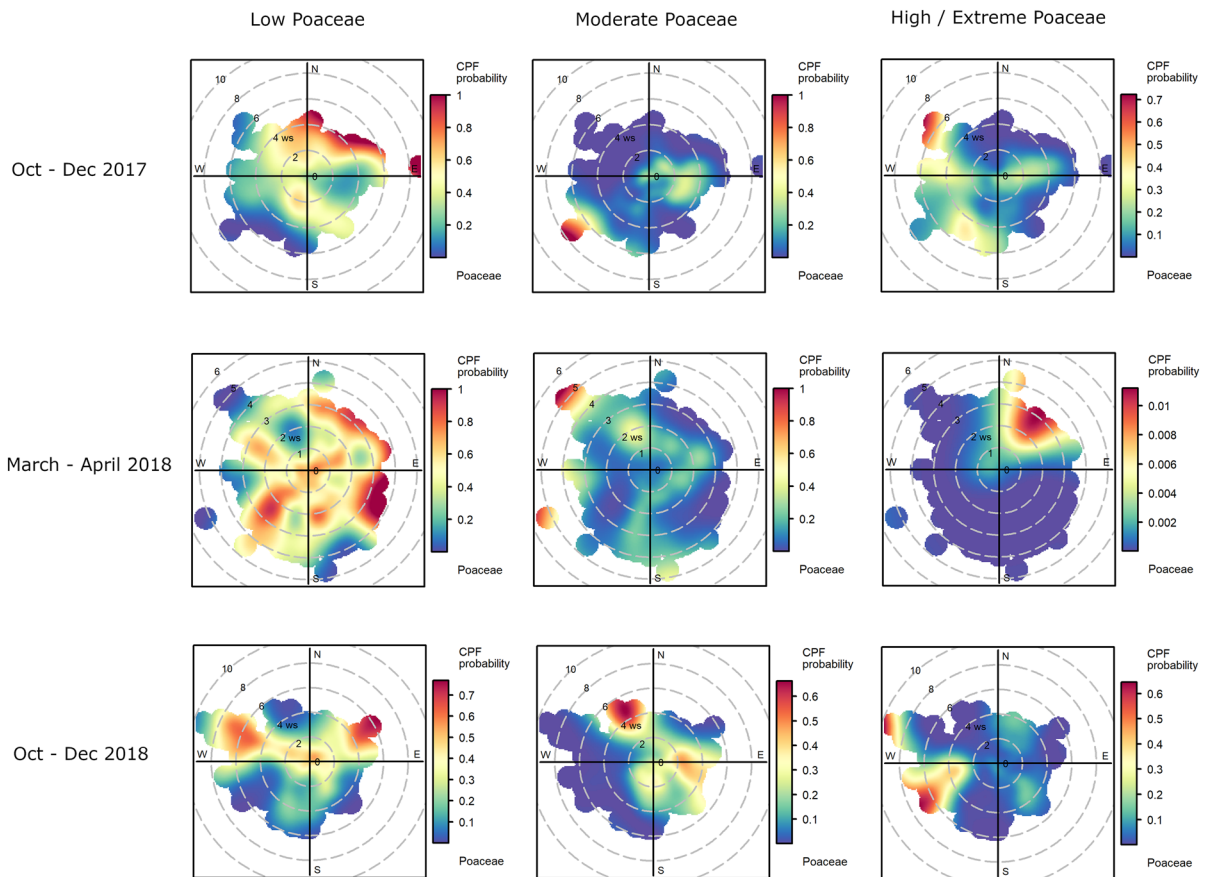
Low Poaceae pollen concentrations at Macquarie Park (Fig. 6) originated from sources in all directions under calm to moderate winds  $0$  to  $7 \text{ ms}^{-1}$ . The most frequent winds at Macquarie Park were responsible for low Poaceae pollen concentrations. During March through April 2018, moderate and high Poaceae pollen concentrations were driven by easterly through southeasterly and stronger north-westerly winds. The provenance of the Poaceae pollen is constant with Lane Cove National Park and river bank (Fig. 2).

### 3.3 Meteorology on days with extreme Poaceae pollen concentration

Three days of extreme Poaceae pollen concentration were observed at Richmond with an average daily Poaceae pollen concentration of  $154 \text{ grains m}^{-3}$  air ( $12 \text{ October 2017}$ ),  $113 \text{ grains m}^{-3}$  air ( $3 \text{ November 2018}$ ), and  $140 \text{ grains m}^{-3}$  air ( $29 \text{ November 2018}$ ). The meteorology associated with the three study days (Fig. 7) indicates the similarities between  $12 \text{ October 2017}$  and  $3 \text{ November 2018}$  related to passing



**Fig. 4** Polar frequency of hourly wind speed (radial axis), and arrival direction, Top row: Richmond, Bottom row: Macquarie Park. Each plot is subdivided into ten-degree- $1 \text{ ms}^{-1}$  wind segments, where the colour represents the total number of hours per segment



**Fig. 5** Richmond conditional bivariate probability function (CBPF), wind speed  $\text{ms}^{-1}$  on radial axis (changes between autumn and spring), wind direction reflects direction from which the wind is coming relative to the central point (Richmond pollen trap)

westerly fronts. The dry westerly winds were driven by low-pressure regions south-west of mainland Australia. The 29 November 2018 had cooler temperatures and higher relative humidity than the other two days. Cyclonic activity off the east coast caused multiple thunderstorms and widespread flooding the previous day.

### 3.4 Meteorology, synoptic and regional airflow relationship to extreme Poaceae pollen concentration

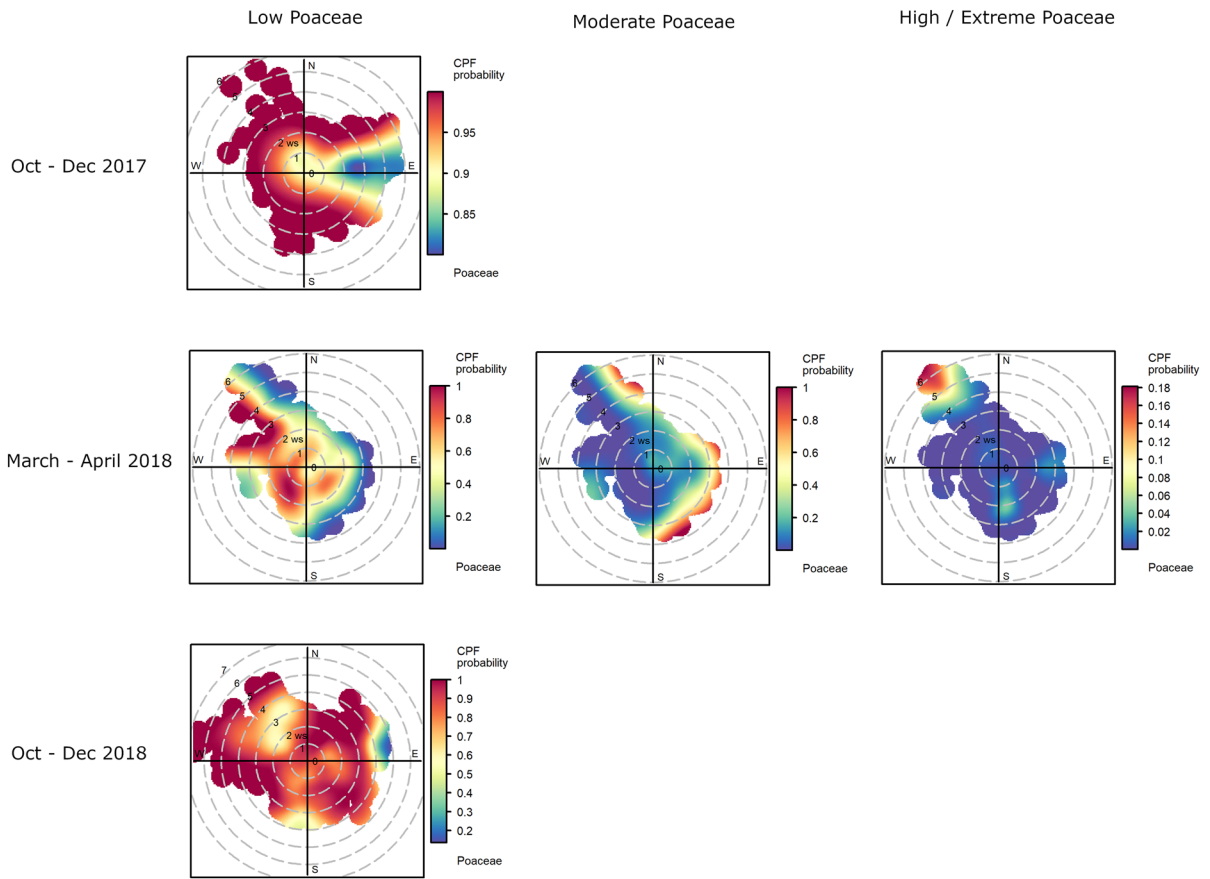
To this point, daily Poaceae pollen concentrations have been used to investigate the relationship between pollen and meteorology. However, these conditions can change within minutes, and an acute increase in atmospheric pollen can rapidly escalate asthma presentations. Therefore, we examined the largest Poaceae

peak in hourly detail to investigate airflow, weather and synoptic conditions associated with a sudden, extreme increase in Poaceae pollen concentration.

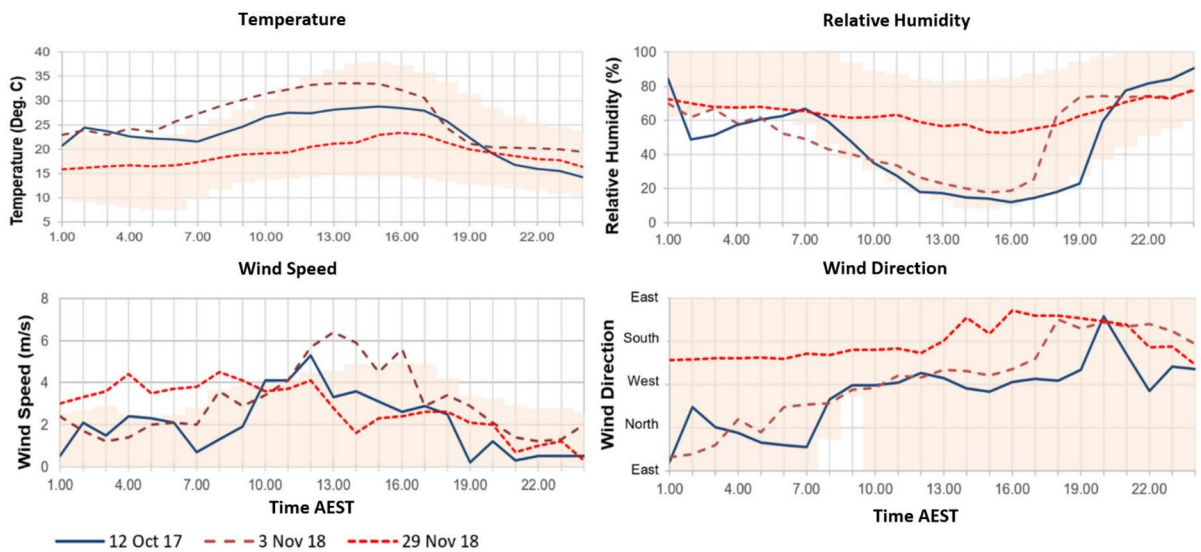
#### 3.4.1 HYSPLIT simulation of airflow on an extreme pollen concentration day—12 October 2017 at Richmond

The first step in the analysis was to examine airflow on the most extreme day and determine its provenance.

The HYSPLIT back-trajectory ensemble indicates the change in direction of the prevailing wind (discussed further in Sect. 3.4.2) and the likely path of Poaceae pollen transport. The back-trajectories from 15:00 AEST back to 06:00 AEST (Fig. 8 a and b) indicate the air parcel trajectories of the synoptic westerly winds. Both WRF and GDAS0.5 indicate similar trajectory paths originating west of the Great



**Fig. 6** As in Fig. 5 but for the Macquarie Park site



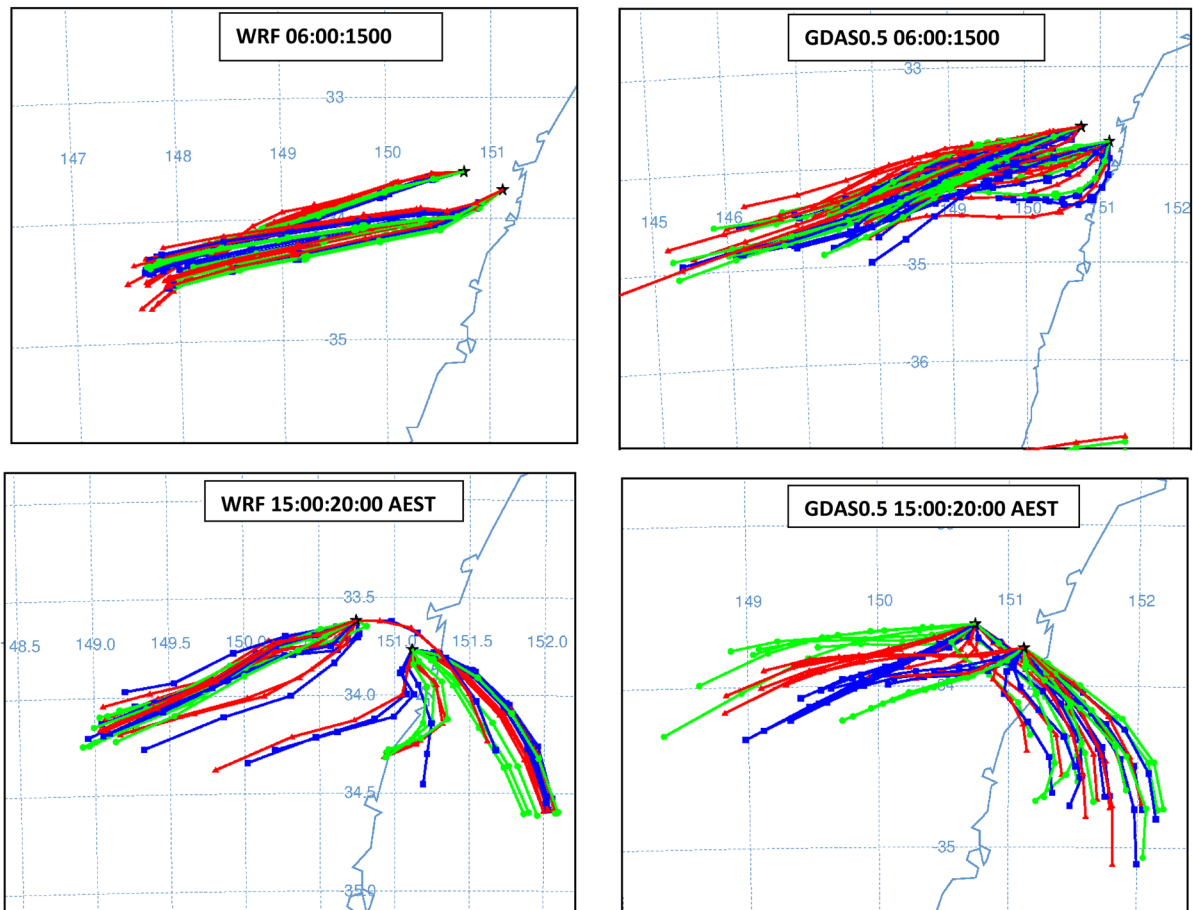
**Fig. 7** Hourly meteorology on days of extreme Poaceae pollen concentration at Richmond, shaded area October to December average hourly observation  $\pm$  2SD

Dividing Range (Fig. 1) to Richmond and Macquarie Park, although the GDAS0.5 model has longer and less well-defined trajectories. The tight cluster of back-trajectories using WRF indicates consistent westerly airflow insensitive to minor variations in input meteorology, providing confidence in the trajectory path. The second back-trajectory ensemble from 20:00 AEST back to 15:00 AEST (Fig. 8c and d) reflects the regional easterly sea breeze passing Macquarie Park and dissipating as it reaches Richmond pollen sampler. The divergence between trajectories indicated a greater level of uncertainty associated with the regional sea breeze. The differences between WRF and GDAS0.5 may be due to the horizontal resolution, as discussed in Sect. 2.3.2. Overall, between 06:00 and 15:00 AEST, the air parcel trajectory followed a path from west of the Great Dividing

Range, entering the Sydney basin and passing both pollen samplers. Thus, it is plausible that the extreme atmospheric Poaceae pollen concentration recorded at Richmond in the Sydney basin resulted from long-distance travel from the grassy plains west of the Great Dividing Range.

### 3.4.2 Hourly meteorology and Poaceae pollen concentrations on an extreme Poaceae pollen concentration day—12 October 2017 at Richmond

Hourly Poaceae pollen concentrations from 11 to 14 October 2017 (Fig. 9) show three consecutive early evening peaks. The 11 and 13 October resulted from easterly winds, and the 12 October a westerly wind front. Poaceae pollen concentrations at Macquarie



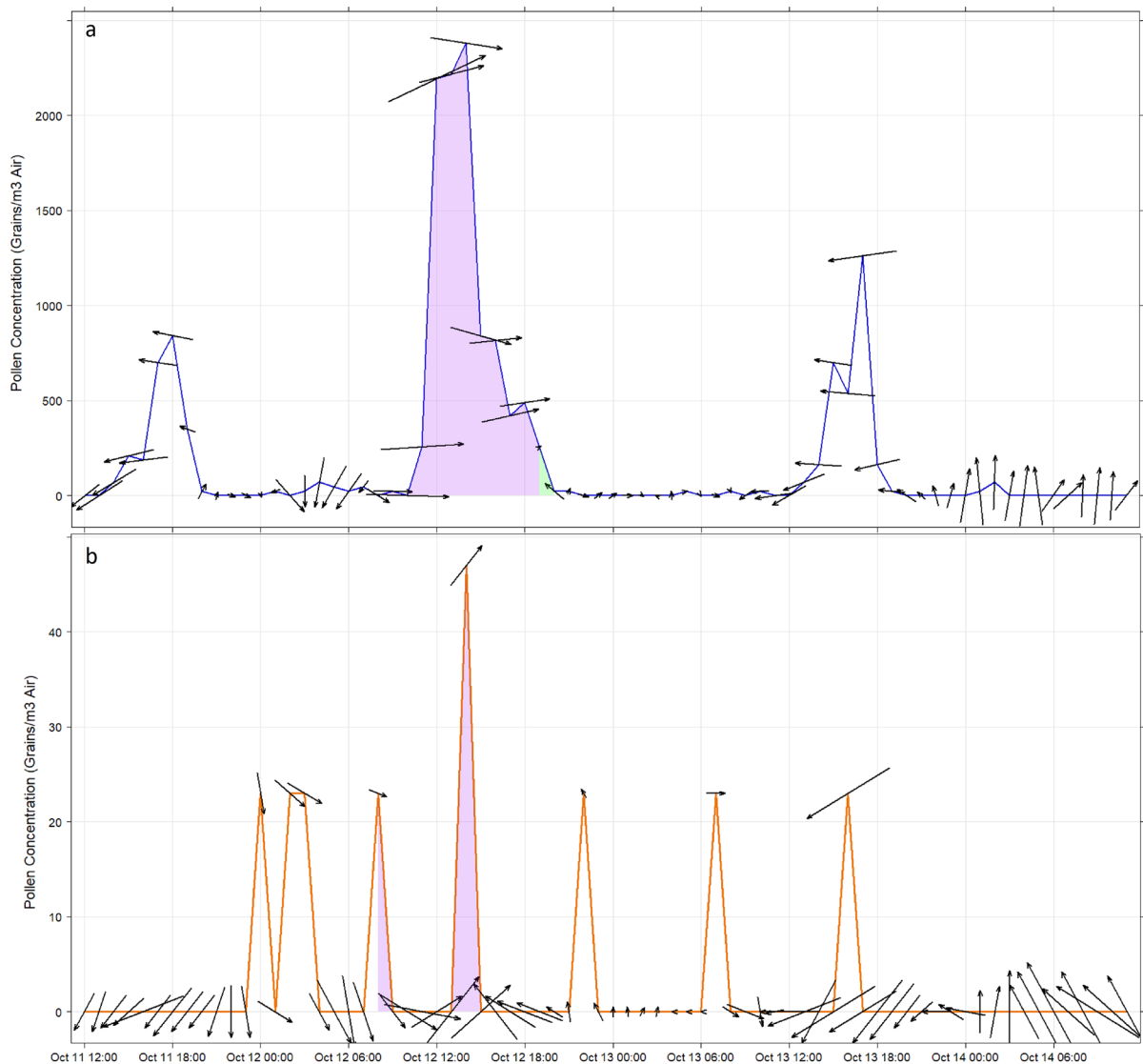
**Fig. 8** HYSPLIT back-trajectory ensemble, black stars are the locations of Richmond and Macquarie Park pollen sampler. **a** WRF 06:00–15:00, **b** GDAS0.5 06:00–15:00, **c** WRF 15:00–

20:00, **d** GDAS0.5 15:00–20:00 Trajectory colours are for illustration purposes only

Park remained low ( $<23$  grains  $m^{-3}$ ), indicating local Poaceae surrounding the rural Richmond pollen sampler dominated concentrations due to prevailing winds and not as a result of long-distance transport. The brief spikes in pollen concentration at Macquarie Park (Fig. 9) are artefacts of the counting process. A concentration of 21 grains  $m^{-3}$  air represents a single pollen grain in the hourly transect of the slide.

On 12 October 2017, a change in wind direction from north-east to west, an increase in wind speed

from  $0.7$   $ms^{-1}$  at 07:00 AEST to  $5.3$   $ms^{-1}$  at noon AEST (Fig. 9) and a decrease in the relative humidity (Fig. 7) indicated the arrival of the synoptic dry westerly wind front entering the Sydney Basin from west of the Great Dividing Range. The synoptic front produced conditions that encourage pollen release from flowering grasses (Pacini, 2000). Atmospheric Poaceae pollen concentrations at Richmond rapidly increased from 0 at 09:00 AEST to 2380 grains  $m^{-3}$  at 14:00 AEST (Fig. 9). Despite similar meteorology



**Fig. 9** Hourly Poaceae pollen concentration **a** Richmond and **b** Macquarie Park, with wind vectors shown as black arrows, from 12:00 AEST 11 October 2017 to 11:00 AEST 14 Octo-

ber 2017 (note the difference in vertical scale between panels). Purple shaded area indicates timing of westerly wind front; green shaded area is easterly sea breeze

at Macquarie Park, the Poaceae pollen concentrations remained minimal. Wind speeds dropped, indicating the passage of the westerly front from noon AEST. Poaceae pollen concentrations rapidly decreased from 14:00 AEST. At 19:00 AEST, relative humidity rose at Richmond, and the wind changed direction from westerly to easterly, indicating the arrival of an easterly sea breeze and conditions that inhibit pollen release (Taylor et al., 2002). Although the sea breeze reached as far inland as the Richmond pollen sampler, the winds were stronger at Macquarie Park. A slight increase in Poaceae pollen concentrations was observed at Richmond at 18:00 AEST prior to change in wind direction. Of the total daily pollen recorded at Richmond, 95% was associated with the synoptic westerly front. Based on wind speed and direction and the increase in Poaceae pollen concentrations at Richmond only, the likely pollen source was Agnes Banks and Agnes Banks Nature Reserve to the south-west (consistent with sources previously identified in Sect. 3.2.2.) and local green fields surrounding the Richmond pollen sampler. Westerly winds passed both pollen samplers but an increase in Poaceae concentration was observed at Richmond only, thus, not as a result of long-distance transport from west of the Great Dividing Range.

## 4 Discussion

### 4.1 Differences in Poaceae pollen concentration between Richmond and Macquarie Park

In this study, Poaceae pollen concentrations between the two pollen samplers, Richmond and Macquarie Park, located in the Sydney basin, showed spatiotemporal differences. Richmond had high/extreme ( $>50$  grains  $m^{-3}$  air) concentrations during October through December, whilst concentrations at Macquarie Park were low (Fig 3). However, Macquarie Park had higher Poaceae pollen concentrations than Richmond from March through April (Table 1). The latitude of the two Hirst-type pollen samplers was similar, their meteorology was highly correlated (Table 2), and the samples were processed in the same laboratory following AusPollen protocols (Beggs et al., 2018). The horizontal separation between the two samplers was approximately 49 km, and previous studies have shown a

good correlation up to approximately 41 km (Erbas et al., 2007; C. H. Katelaris et al., 2004; Pashley et al., 2009). Severe and prolonged drought was experienced in New South Wales in 2018, which may have reduced Poaceae pollen concentrations at both locations. Thus, the above factors do not explain the differences in Poaceae pollen concentration between the two locations. However, the microclimate surrounding each sampler differed.

Firstly, the Richmond area is 12% residential, 13% parkland, 25% agriculture, and 38% primary production. In comparison, Macquarie Park is more densely populated with 66% residential, 17% parkland, and no agriculture or primary production. The lack of green space and agriculture, and frequent mowing of domestic lawns at Macquarie Park's urban location would reduce flowering grass. It may explain the lack of Poaceae pollen during spring and summer, but not the peak during autumn.

Secondly, the temporal differences in Poaceae pollen concentration peaks (Fig. 3) between the two pollen samplers suggest biodiversity of Poaceae species in the Sydney basin, although this was not measured directly. Poaceae have two different photosynthetic and carbon fixing pathways, determining the growing and flowering characteristics and ability to retain water (Vicentini et al., 2008). C3-type grasses such as ryegrass (*Lolium* species) are cool-season grasses that produce large amounts of pollen in a single prominent pollen peak, whereas C4-type grasses such as kangaroo grass (*Themeda triandra*) prefer warmer, drier conditions and tend to produce multiple peaks in pollen concentration. Sydney has a combination of both grass types (Medek et al., 2016). These characteristics reflect the observations of this study and the long-term climate data of the two locations (Bureau of Meteorology, 2021). The results indicate that the single peak at Macquarie Park may result from flowering C3 grasses, although no solid evidence supports this conclusion. Based on monitoring at Campbelltown in the south-west of the basin, Medek et al. (2016) highlighted Sydney's multiple peaks in grass pollen concentrations, more pronounced in spring than summer, and a small peak in autumn; however, not all peaks manifest at each pollen sampler, as observed in this study (Fig. 3). Previous studies have also observed a reduction in pollen concentration with increasing distances from rural areas, changes in land-use practices and different microclimates that dictate species



biodiversity (Ianovici et al., 2015; Peternel et al., 2006; Ščevková et al., 2020).

#### 4.2 Correlation of Poaceae pollen with meteorology

In this study, Poaceae pollen concentrations were positively correlated with temperature and sunlight and negatively correlated with relative humidity and precipitation. These results are consistent with the behaviour of pollen release from the anther (Pacini, 2000) and known meteorological effects on atmospheric pollen concentrations (Taylor et al., 2002; Ianovici et al., 2015; Peternel et al., 2006; Ščevková et al., 2020; Green et al., 2004 and Stennett & Beggs, 2004). However, our results show that the correlations with relative humidity and precipitation were only significant during the last three months of the study after an intense and prolonged drought in New South Wales, which may have affected the number of extreme Poaceae pollen concentration days observed during the study. Further, historical data from a third independent pollen sampler within the Sydney basin located at Campbelltown had fourteen extreme Poaceae pollen concentration days during the past fourteen years, indicating the rarity of such events in the Sydney basin (Katelaris & Burton, 2021).

Green et al. (2004) and Stennett and Beggs (2004) observed a significant correlation of Poaceae pollen concentration with wind speed, and Hart et al. (2007) reported dry westerly winds driven by low-pressure systems off the east and south coast of Australia, increased concentrations during the warmer months. In our study, the correlation with hourly and daily wind speed was not statistically significant. Although strong winds of  $\geq 5 \text{ ms}^{-1}$  were infrequent in the region, they were more likely to occur at Richmond than Macquarie Park and during October through December (Fig 4). Two extreme Poaceae pollen concentration days experienced westerly winds  $\geq 5 \text{ ms}^{-1}$  (Fig 7); however, these wind conditions were not unique to peak periods nor high pollen concentrations. Wind direction-speed combinations responsible for transporting low, moderate and high/extreme Poaceae pollen concentrations were identified using conditional bivariate probability functions (CBPFs) (Fig 5 and 6), a technique conventionally used to identify sources of air pollution. Using this technique, in conjunction with the Atlas of Living Australia spatial portal, we established the provenance of moderate and high

concentrations at Richmond likely originated from two sources, North Richmond to the northwest and Agnes Banks Nature Reserve to the south-west. In contrast, moderate Poaceae pollen at Macquarie Park likely originated from Lane Cove river bank. Silva Palacios et al., (2000) also found wind direction to influence pollen concentrations. We agree with their study findings that the distribution and abundance of sources significantly influence atmospheric pollen concentrations. However, in the absence of local flowering, Poaceae pollen concentrations remained minimal (Fig 6) independent of wind speed and direction (Fig 4), emphasising the dominance of local species reliant upon favourable meteorology.

#### 4.3 Poaceae pollen transport and dispersion

Poaceae pollen relies predominantly on wind for liberation, transportation, and dispersion. Horizontal downwind dispersion under calm, laminar airflow conditions have been estimated using the Stokes law settling velocity; for *Lolium perenne* (ryegrass) pollen, this is approximately 22 m from the release point under the influence of  $1 \text{ ms}^{-1}$  winds (Borrell, 2012). Although individual grass species could not be identified in the study, perennial ryegrass is a commonly found species throughout the Sydney basin, thus representing Poaceae samples collected. The most frequent winds observed during the peak periods at Richmond and Macquarie Park (Fig 4) were associated with low concentrations of Poaceae pollen liberated from local sources, as indicated by the CBPFs (Fig 5 and 6). An increase in turbulence due to wind speed, topography, or convection would encourage Poaceae pollen mixing in the atmospheric boundary layer, overcoming the pollen grains' settling velocity and increasing downwind horizontal dispersion (Brunet et al., 2004). Smith et al., (2005) modelled back-trajectories for extreme Poaceae pollen concentration days in the UK. The back-trajectories inferred Poaceae pollen could travel long distances in a single day; however, the provenance was based only on the direction of the prevailing wind and trajectory path. Our study has demonstrated that despite the back-trajectories indicating the plausibility of long-distance transport, Poaceae pollen originated from within the Sydney basin. There was no evidence to support long-distance transport from the grassy plains west of the Great Dividing Range nor within the Sydney basin

from one pollen sampler to the other, 49km apart. Poaceae pollen concentration peaks at Richmond did not correspond to peaks at Macquarie Park despite winds of  $\geq 5 \text{ ms}^{-1}$ , trajectories originating from a similar location and synoptic winds passing Richmond and Macquarie Park. Airflow in the vicinity of the Richmond pollen trap is unhindered. No mountains or substantial forests between Richmond and Macquarie Park in the Sydney Basin would prevent pollen flow from one pollen sampler to the other as demonstrated by the wind flow observed at both pollen samplers on the 12th October 2017. Thus, we conclude Poaceae concentrations were dominated by local flowering and local dispersion.

The potential for daily average atmospheric Poaceae pollen concentrations to mask sudden increases in pollen which pose a health risk to pollen-sensitive individuals and asthmatics was a concern and one of the motivations for this study. It is challenging to set a threshold for the level of Poaceae pollen exposure with specific health risks, and currently, there is no universally accepted clinical threshold (Becker et al., 2021). In this study, we have categorised pollen days following Ong et al's., (1995) nine-year study of Melbourne pollen seasons; however, other classifications exist (Kiotseridis et al., 2013). Previous studies have shown the risk of hospital admission increased by 1.9% from exposure to pollen concentrations of 14 grains  $\text{m}^{-3}$  air (Dales et al., 2004) to a 17.23% risk following exposure to 104 grains  $\text{m}^{-3}$  air (Osborne et al., 2017). Even a single day recording a 10-grain per  $\text{m}^{-3}$  air increase in pollen concentrations can increase the risk of experiencing upper respiratory symptoms by 7%, ocular symptoms by 11% and increased hospital attendance by 1.88% (Kitinoja et al., 2020).

Acute increases in hourly pollen exposure have not been well documented, but health effects from a thunderstorm asthma event can be evident almost immediately (Victorian Government, 2017). In this study, a rapid increase in Poaceae pollen concentration from 0 at 09:00 AEST to 2380 grains  $\text{m}^{-3}$  air at 14:00 AEST (Fig 8) on 12 October 2017 was examined in detail. The Poaceae pollen concentration was associated with a synoptic westerly wind front. The resulting Poaceae pollen concentrations had the potential to exacerbate asthma symptoms and cause a surge in hospital presentations. The delay between the arrival of the front and the increase in atmospheric pollen concentrations

indicates pollen was not travelling on the leading edge of the synoptic front. Perhaps the delay resulted from the time taken by Poaceae to release its pollen into the atmosphere and travel towards the Richmond pollen sampler. Atmospheric Poaceae pollen concentrations remained high despite a drop in wind speed and front passage, indicating pollen settling out of the atmosphere. The extremes in Poaceae pollen concentration were observed at Richmond only (Fig. 9). Meteorology did not prevent Poaceae pollen from travelling to Macquarie Park, further evidence against long-distance Poaceae pollen transport.

Following the westerly synoptic winds, a regional easterly sea breeze arrived first at Macquarie Park at 16:00 AEST then travelled onward to reach Richmond; by 19:00 AEST, winds had dissipated, there was no evidence of increased Poaceae concentrations due to air recirculation, unlike those found in the Gassmann et al. (2002) study in Argentina.

#### 4.4 Poaceae pollen concentration links to thunderstorm asthma

Thunderstorms and convergence lines associated with high/extreme concentrations of ryegrass pollen (Lee et al., 2017) seem to trigger thunderstorm asthma incidents in Australia (Bannister et al., 2020). During this study, many thunderstorms were experienced in the Sydney basin; however, only three days of extreme Poaceae pollen concentration were recorded. Thus, thunderstorms and their associated winds are unlikely to be the primary mechanisms for producing extreme Poaceae pollen concentrations during the warm months of the pollen season. The results indicate that extreme Poaceae pollen concentrations are a prerequisite for thunderstorm asthma events. If a thunderstorm was to occur on a day with extreme Poaceae pollen concentration, the health risk could be extreme. The rarity of extreme Poaceae pollen concentrations in the Sydney basin and the absence of long-distance transport even during thunderstorms indicate local flowering may dictate the thunderstorm asthma risk in the Sydney basin.

## 5 Conclusions

The Poaceae pollen concentrations collected from Richmond and Macquarie Park within the Sydney

basin peaked at different times of the year. There was no solid evidence supporting long-distance Poaceae pollen transport over the Great Dividing Range into Sydney or within the basin from Richmond to Macquarie Park. This indicated the biodiversity of the local flowering species dominated the individual pollen samplers. On 12 October 2017, synoptic westerly winds entered the Sydney basin and liberated pollen from Richmond's flowering grasses in the path of the prevailing wind, resulting in extreme Poaceae pollen concentrations. A regional easterly sea breeze followed the synoptic westerlies, but did not increase pollen concentration. The absence of flowering grasses at Macquarie Park resulted in minimal Poaceae pollen concentrations, independent of synoptic or regional winds.

Extreme Poaceae pollen concentrations within the Sydney basin are rare, which may explain the lack of thunderstorm asthma reports in Sydney. However, daily average Poaceae pollen concentrations can mask sudden increases in pollen which could have serious health consequences in densely populated regions. If a thunderstorm occurs during extreme ryegrass pollen concentrations, the health impact could be significant and immediate. The abundance of pollinating ryegrass within the Sydney basin will directly affect the risk of thunderstorm asthma. Therefore, developing a detailed map of ryegrass phenology or measures with eDNA to ascertain genus/species within the Sydney basin could assist in determining the risk posed by thunderstorm asthma in Sydney.

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## Declarations

**Conflict of interest** The authors have no competing interests to declare that are relevant to the content of this article.

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