



Review article

A systematic review of the role of grass pollen and fungi in thunderstorm asthma

Nur S. Idrose^a, Shyamali C. Dharmage^a, Adrian J. Lowe^a, Katrina A. Lambert^b, Caroline J. Lodge^a, Michael J. Abramson^c, Jo A. Douglass^{d,e}, Ed J. Newbigin^f, Bircan Erbas^{b,*}

^a Allergy and Lung Health Unit, Melbourne School of Population and Global Health, The University of Melbourne, 207 Bouverie St, Carlton, Victoria, 3053, Australia

^b School of Psychology and Public Health, La Trobe University, Bundoora, 3086, Victoria, Australia

^c School of Public Health and Preventive Medicine, Monash University, 553 St Kilda Rd, Melbourne, Victoria, 3004, Australia

^d Department of Clinical Immunology and Allergy, Royal Melbourne Hospital, Parkville, 3050, Victoria, Australia

^e Department of Medicine, University of Melbourne, Parkville, Victoria, 3052, Australia

^f School of BioSciences, The University of Melbourne, Victoria, 3052, Australia

ARTICLE INFO

Keywords:

Asthma

Fungi

Grass

Pollen

Thunderstorm

ABSTRACT

Background: Thunderstorm asthma is defined as epidemics of asthma occurring shortly after a thunderstorm. While grass pollen has been implicated in thunderstorm asthma events, little is known about the role of fungi and studies have not been synthesised.

Objective: This systematic review aims to evaluate whether grass pollen is necessary in thunderstorm asthma events and whether fungi also play a part in these associations.

Methods: We conducted a systematic search using six electronic databases (i.e. CINAHL, Medline (Ovid), Web of Science, ProQuest Central, EMBASE and Google Scholar) and checked reference lists. The search terms used were pollen AND thunderstorm* AND asthma. The inclusion criteria were studies published in English with original human data relating to outdoor pollen and thunderstorm asthma.

Results: Twenty of 2198 studies were eligible. Reported findings differed due to variation in methodological approaches and a meta-analysis was not possible. Nonetheless, of the 20 studies included, 15 demonstrated some relationship with nine demonstrating lagged effects up to four days for increasing grass pollen counts associated with increased risk of thunderstorm asthma. Of the 10 studies that examined fungi, nine demonstrated a positive relationship with thunderstorm asthma. The fungal taxa involved varied, depending on whether measurements were recorded before, during or after the thunderstorm. Nevertheless, none of the studies considered fungi as a potential effect modifier for the pollen-thunderstorm asthma association.

Conclusion: We found evidence to suggest that grass pollen was a necessary factor for thunderstorm asthma but there are other as yet unrecognised environmental factors that may also be important. Further research is required to examine the role of fungi and other environmental factors such as air quality as potential effect modifiers of the association.

1. Introduction

Thunderstorm asthma is defined as asthma outbreaks that occur during or shortly after a thunderstorm, where affected individuals experience asthma symptoms such as breathlessness, wheezing and cough. Epidemic thunderstorm asthma events have been reported since the early 1980s and to date, 22 outbreaks have occurred worldwide (Davies et al., 2017; Lindstrom et al., 2017). The thunderstorm asthma

event that occurred in the UK during early summer of 1994 resulted in 640 asthma presentations within just 30 h, about 10 times the expected number of patients (D'Amato et al., 2013).

However, this could not be compared to the scale of the event which struck Melbourne, Australia, on November 21, 2016. This event was directly responsible for the deaths of ten people and for over 3000 excess (i.e. a 6-fold increase compared to the three-year average of 501) respiratory-related cases presenting at emergency departments across

Abbreviations: CI, confidence interval; ED, emergency department; GP, general practitioner; ICU, intensive care unit; RHA, regional health authority; RR, relative risk; SHA, strategic health authority; SPT, skin prick test

* Corresponding author. School of Psychology and Public Health, La Trobe University, Bundoora, Victoria, 3086, Australia.

E-mail address: b.eras@latrobe.edu.au (B. Erbas).

<https://doi.org/10.1016/j.envres.2019.108911>

Received 23 July 2019; Received in revised form 6 November 2019; Accepted 7 November 2019

0013-9351/ Crown Copyright © 2019 Published by Elsevier Inc. All rights reserved.

Melbourne over a 48-h period, placing a substantial burden on health services (Davies et al., 2017; Pearce, 2017; Thien et al., 2018). All Melbourne thunderstorm asthma events have occurred during peak grass pollen seasons and it has been suggested that the increased frequency and severity of these events may be due to changing climatic conditions (D'Amato et al., 2016).

It is well-established that intact pollen grains ($> 20\mu\text{m}$) are trapped in the upper airways, triggering allergic rhinitis and asthma during peak pollen seasons (Erbas et al., 2018). Thunderstorm asthma events have been reported to affect the population on a larger scale because it is hypothesised that pollen grains rupture during thunderstorms (Marks and Bush, 2007). Each ruptured pollen grain releases hundreds of allergenic starch granules that are small enough ($< 3\mu\text{m}$) to penetrate into the lower airways (Suphioglu et al., 1992). The abundance of these small-sized pollen granules in the air results in asthma symptoms during thunderstorm asthma events, and respiratory distress in individuals even with no history of diagnosed asthma. The documented thunderstorm asthma events in Australia have mostly involved high levels of grass pollen, but events in the UK have shown that other pollen such as tree and weed are important triggers too (Davies et al., 2017).

To date, the findings reported on the association between pollen exposure and thunderstorm asthma have been inconsistent. There are a number of reviews related to thunderstorm asthma, but almost all were narrative reviews which discussed either high risk groups (e.g. patients with pollen allergy/sensitisation), the aerobiology of pollen and fungi, the types of asthma outbreaks, the independent effects of climate change on pollen and asthma and many more. Davies et al. (2017) did conduct a comprehensive narrative on thunderstorm asthma with focus on environmental, lifestyle and individual characteristics. However, it was a scoping review that did not have a primary focus on pollen exposure and its association with thunderstorm asthma. Hence, no reviews to date have focused on pollen as the primary exposure and outcomes during a thunderstorm asthma event.

It is also possible that pollen is not the only cause of thunderstorm asthma and other aeroallergens such as fungi may be important. For example, Anderson et al. (2001) reported an increase in the number of asthma admissions as a result of a thunderstorm, but this could not be explained by an increase in pollen counts, as there was no correlation between pollen and asthma admissions nor was there evidence of interaction between pollen and rainfall. The risk assessment conducted by Campbell et al. (2019) also showed that there is low probability of a thunderstorm asthma event occurring as a result of thunderstorms during peak grass pollen seasons. Nevertheless, there is possible interaction between pollen and fungi during thunderstorms, because in the early study by Packer and Ayres (1985), the concentrations of both pollen and fungi were high up to two days before the thunderstorm asthma event. Few more recent studies have considered fungi and the evidence surrounding an interplay with pollen is limited. Past reviews also did not consider the role of fungi in the pollen-thunderstorm asthma association. Therefore, we aimed to not only assess the growing evidence on the relationship between ambient pollen and thunderstorm asthma, but also how and if other aeroallergens, including fungi, were considered when assessing this pollen-thunderstorm asthma association. This would assist the development of interventions to inform the public of “high-risk” days.

2. Methods

This review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for reporting systematic reviews (Moher et al., 2009). The review protocol was prospectively registered with the International Prospective Register of Systematic Reviews (PROSPERO Registration no. CRD42018099939).

2.1. Eligibility criteria

Inclusion criteria were original human studies that were published in English up until April 15, 2019. The included studies had to investigate the relationship between outdoor pollen and thunderstorm asthma. No restrictions were applied on study population or design.

2.2. Search strategy

We conducted a literature search using six bibliographic databases: CINAHL, Medline (Ovid), Web of Science, ProQuest Central, EMBASE and the first 100 records of Google Scholar. The search strategy included terms relating to the exposure (pollen); outcome (thunderstorm* AND asthma); and were combined (thunderstorm* AND asthma AND pollen). Fungi was not included as a search term because we assumed that all studies that investigated the role of fungi in the pollen-thunderstorm asthma associations would have been picked up from the ‘pollen’ search term. Additional searches were conducted by checking reference lists of included studies. After removing the duplicates, we screened abstracts of all identified papers for initial inclusion and then assessed the full-text articles for eligibility. This process was conducted by two reviewers (NSI and KAL), independently. Any discrepancies were resolved by a third reviewer (BE).

2.3. Extraction of data

The data extracted from the included studies were: name of author (s), year of publication, study design, study population, number and age of participants, exposure definition (pollen family) and measurement (type of trap), outcome definition, patients’ characteristics, study findings, estimated effect sizes if statistical models were used and other variables that were included in the model such as confounders and effect modifiers.

2.4. Quality assessment

A quality assessment of included studies was conducted independently using the validated Zaza et al. (2000) framework by two reviewers (NSI and BE). It consisted of a checklist that assessed the methodology in terms of population description and selection; the validity and reliability of exposure and outcome measurements; the appropriateness of statistical methods and controlling for potential biases; and other problems associated with data analysis that could limit the interpretation of the results. The maximum score that could be attained was 17.

2.5. Assessment to conduct a meta-analysis

Unfortunately, there were no two studies that had comparable outcome or exposure estimates, so a meta-analysis could not be performed.

3. Results

3.1. Flow diagram

After removing the duplicates, we identified 2198 articles through electronic searches and reviewing reference lists; 1877 were excluded (Fig. 1). Studies were excluded if they were non-English, non-human, unable to be found, not related to either the exposure or outcome, a review article or from a source other than a journal such as government reports, dissertations, newspaper articles etc. In total, 20 studies were included in the qualitative synthesis. These studies are summarised in Tables 1–4.

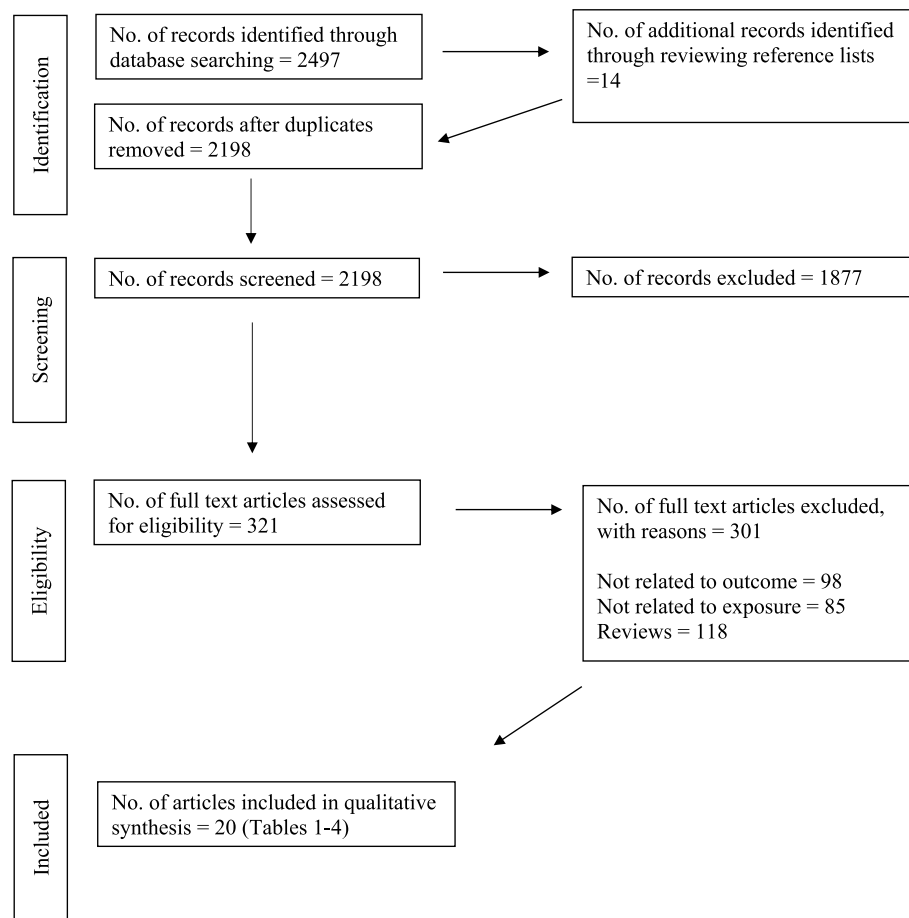


Fig. 1. The PRISMA flow diagram.

4. Characteristics and findings

4.1. Observational case-report studies

These observational case report studies performed no statistical analyses. They only described the pollen counts on days prior to or on the day of the thunderstorm asthma event. The results are summarised in Tables 1 and 2. Out of nine observational case-report studies (Thien et al., 2018; Packe and Ayres, 1985; Marks et al., 2001; Davidson et al., 1996; Lee et al., 2017; Venables et al., 1997; Andrew et al., 2017; Darvall et al., 2018; Howden et al., 2011), three were conducted in the United Kingdom (Packe and Ayres, 1985; Davidson et al., 1996; Venables et al., 1997) and the other six in Australia (Thien et al., 2018; Marks et al., 2001; Lee et al., 2017; Andrew et al., 2017; Darvall et al., 2018; Howden et al., 2011). Of these, five different thunderstorm asthma events were investigated: the 1983 (Packe and Ayres, 1985) and the 1994 (Davidson et al., 1996; Venables et al., 1997) events in the United Kingdom; the 1997 (Marks et al., 2001) event in New South Wales, Australia; and the 2010 (Howden et al., 2011) and 2016 (Thien et al., 2018; Lee et al., 2017; Andrew et al., 2017; Darvall et al., 2018) events in Melbourne, Australia.

The types of pollen investigated varied between settings. Two studies (Packe and Ayres, 1985; Howden et al., 2011) were unclear on the type of pollen family they investigated. The others (Thien et al., 2018; Marks et al., 2001; Davidson et al., 1996; Lee et al., 2017; Venables et al., 1997; Andrew et al., 2017; Darvall et al., 2018) focused on grass pollen as their primary exposure with some (Thien et al., 2018; Venables et al., 1997; Darvall et al., 2018) investigating tree and weed pollen too. Most studies (Packe and Ayres, 1985; Marks et al., 2001; Davidson et al., 1996; Venables et al., 1997; Andrew et al., 2017) used a

Burkard volumetric spore trap to collect the pollen particles.

Pollen counts were described differently, depending on the region. Most of the Australian studies (Erbas et al., 2018; Marks et al., 2001; Lee et al., 2017; Andrew et al., 2017; Darvall et al., 2018) reported pollen counts on the day of the thunderstorm asthma event, rather than lagged effects. According to the Wagga Wagga study (Marks et al., 2001), the concentration of intact grass pollen grains and ruptured pollen grains (of any taxa) increased by 4-fold and 7-fold, respectively at the hour beginning 9.30pm on October 30, 1997, compared to the hour before. Thunderstorm outflow was detected at 9.42pm while the first emergency call for assistance was made at 10pm. Lee et al. (2017) reported that 94% of the patients had outdoor exposure, where grass pollen levels were extreme (> 100 grains/ m^3) on November 21, 2016 in Melbourne, Australia. Similar findings were observed in three other studies (Thien et al., 2018; Andrew et al., 2017; Darvall et al., 2018) that investigated the same thunderstorm asthma event as Lee et al. (2017). Nonetheless, both grass and non-grass pollen concentrations seemed to have dropped by 30%–50% during the onset of the thunderstorm, and the levels remained low afterwards (Lindstrom et al., 2017). Although other thresholds have been used (Zink et al., 2013), most of the thunderstorm asthma events occurred in Melbourne or close to this region. Therefore, the thresholds were considered as “low” if the counts per day were < 20 grains/ m^3 , “moderate” if 20–49 grains/ m^3 , “high” if 50–99 grains/ m^3 and “extreme” if > 100 grains/ m^3 . Thien et al. (2018) and Darvall et al. (2018) who investigated the same 2016 thunderstorm asthma event in Melbourne, Australia, provided graphical analysis (i.e. a visual presentation of data using a two-dimensional graph) to demonstrate a rise in tree, weed and broken pollen on the day of the thunderstorm asthma event.

Only one (Howden et al., 2011) of the Australian studies described

Table 1
The characteristics of observational case report studies.

Author(s) (Year)	Study population	Sample size	Exposure definition (family) ^a	Exposure measurement	Patients characteristics	Age range of participants
Observational case report studies						
Packe and Ayres, 1985	Patients attending eight hospitals in Birmingham, UK between 6 and July 7, 1983 due to acute asthma or other acute respiratory disease	106	● Not stated	● Volumetric slit sampler at Dudley (13 km to the west) and Leamington Spa (20 km to the south-east) ● Burkard 7-day recording volumetric spore trap	History of allergic rhinitis, history of summer asthma and whether there were complaints of symptoms on thunderstorm day None	14 months to 63 years old
Marks et al., 2001	Patients attending ED in six towns (Wagga Wagga, Tamworth, Orange, Bathurst, Dubbo and Albury), NSW, Australia between January 1995 to December 1998 due to asthma	Unknown	● Grass	● Location: Charles Sturt University (6.7 km north/north-west of the central of Wagga Wagga) ● Volumetric spore trap ● Location: the roof of the University of North London (distance not specified)	History of allergic rhinitis, history of chronic obstructive airways disease, history of asthma and whether these people had inhalers	Unknown
Davidson et al., 1996	Patients presenting with asthma or other respiratory disease at 12 ED departments in London, UK between 27 May and July 23, 1994	640	● Grass	● Trap not stated ● Collected pollen data from 'Melbourne Pollen Count'	Asthma history, history of allergic rhinitis during spring (September to November), allergic sensitisation to twenty aeroallergens (SPT, IgE-specific serology test), outdoor exposure during thunderstorm, smoking status	At least 16 years old
Lee et al., 2017	Patients with asthma-suggestive symptoms attending ED departments of Alfred Health in Melbourne, Australia from 1700 h 21 November to 1700 h November 23, 2016	85	● Grass: Ryegrass	● Pollen count data from the Pollen Research Unit ● Burkard volumetric trap was used at Holloway and North London. Did not state which trap was used at other places	None	Unknown
Venables et al., 1997	Patients attending ED and general practices across southern and eastern England, UK on June 24, 1994 due to asthma	Unknown	● Grass ● Tree: <i>Tilia</i> (lime), <i>Castanea</i> (sweet chestnut), <i>Sambucus</i> (elder) ● Weed: <i>Rumex</i> (dock), <i>Plantago</i> (plantain), Nettle ● Grass	● Burkard volumetric trap ● Location: University of Melbourne (distance not specified) ● Trap not stated ● Location: Parkville and Burwood (distance not specified) ● Data collected by University of Melbourne and Deakin University	History of asthma	Age groups (0–14, 15–30, 31–50, 51–70, ≥ 71) ED: All ages (< 20, 20–59, 60+) ICU: 9–69 years old
Andrew et al., 2017	Those who were attended by emergency medical services between January 1, 2015 and December 31, 2016 in Victoria, Australia	1726	● Grass	● Trap not stated	Gender, country of birth, prior respiratory disease (i.e. asthma, COPD, current smoker, allergic rhinitis, grass/pollen allergy), respiratory medication use	9–69 years old
Thien et al., 2018	Patients attending ED in eight of Melbourne, Australia's, health services with respiratory symptoms from 6pm on November 21, 2016 for up to 48 h or patients who were admitted to an ICU in any one of the 15 Victorian hospitals with a diagnosis of asthma from 6pm on November 21, 2016 for up to 48 h	ED: 2242 ICU: 35	● Grass ● Tree ● Weed	● Location: University of Melbourne (distance not specified) ● Location: Parkville and Burwood (distance not specified) ● Data collected by University of Melbourne and Deakin University	Ethnicity, country of birth, history of respiratory diagnoses, history of respiratory medication use	Age groups (0–14, 15–30, 31–50, 51–70, ≥ 71) ED: All ages (< 20, 20–59, 60+) ICU: 9–69 years old
Darvall et al., 2018	Patients admitted to both public and private Victorian intensive care units (ICUs) due to TA event on 21–22 November 2016 as well as patients who were in the Australian and New Zealand Intensive Care Society (ANZICS) Adult Patient Database (APD) in 2016 due to asthma.	Case: 35 Controls: 1062	● Grass ● Tree ● Weed	● Trap not stated ● Location not specified ● Data collected by University of Melbourne	Gender, country of birth, prior respiratory disease (i.e. asthma, COPD, current smoker, allergic rhinitis, grass/pollen allergy), respiratory medication use	9–69 years old
Howden et al., 2011	Patients presenting with acute asthma to the Austin Health emergency department, Melbourne, Australia in Spring (2010)	Unknown	● Unknown	● Trap not stated ● Location not specified ● Data collected by university of Melbourne	None	Children and adults but age range not specified

^a = Refer to Table S3 for the classification of pollen species.

Table 2
The findings of observational case report studies.

Author(s) (Year)	Outcome definition	Findings	Confounders	Interactions
Observational case report studies Packer and Ayres, 1985	Presentation of acute asthma or other acute respiratory diseases	Pollen: Total pollen counts were high (mean = 100–300m ³ of air) on 2–5 July and remained high until 6 July (TA event) before the onset of rain. The total pollen counts decreased when it rained. Pollen count increased again by 7 July, in the afternoon.	None tested	None tested
		Fungi: Level of allergenic fungi i.e. <i>Cladosporium</i> were high two days before the TA event, and continued to peak until a few hours before the thunderstorm; then the levels decreased. When this happened, the levels of <i>Didymella extitidis</i> ascospores suddenly rose. Soon after the rain i.e. during the period of high humidity, the concentrations of <i>Sporobolomyces</i> basidiospores increased.		
Marks et al., 2001	Number of asthma exacerbations epidemic days	Results below are based on one epidemic day (October 30, 1997) for pollen : Thunderstorm outflow detected at 9.42pm. At the hour beginning 9.30pm: • 4-fold increase in intact ryegrass pollen grains during TA event compared to the hour before or 8-fold increase compared to the average, 9 h before • Ruptured grains increase by 7-fold compared to the hour before event or 12-fold compared to the average, 9 h before The first call of emergency assistance occurred at 10.08pm. Fungi: No reports on fungi.	None tested	None tested
Davidson et al., 1996	Number of patients presenting with asthma or other airway disease (wheeze, hay fever, allergy with wheeze, breathing difficulty, shortness of breath, cough, chest infection, requiring inhaler/asthma treatment)	Pollen: Daily average pollen count data was 258 grains/m ³ (exceptionally high) two days before the epidemic. Concentration remained high until the thunderstorm on June 24, 1994. Fungi: The level of allergenic fungi was not exceptionally high before, during or soon after the epidemic. However, levels of damp air spores i.e. <i>Phaeosphaerianigrans</i> and <i>Diatriypaceae</i> increased during and after the thunderstorm.	None tested	None tested
Lee et al., 2017	Presentation to the ED with asthma-suggestive symptoms (cough, wheeze, respiratory disease and dyspnoea)	94% of the 85 people affected had outdoor exposure between 5pm and 8pm on Nov 21, 2016 (TA event). Pollen: Outdoor pollen count was 102 grains/m ³ (extreme) on Nov 21, 2016 (TA event). Fungi: No reports on fungi.	None tested	None tested
Venables et al., 1997	Presentation of asthma at general practices and ED departments	Pollen: Concentrations of grass pollen rose on 20 June, 4 days before TA event (24 June). The grass pollen count was 258 grains/m ³ (exceptionally high) 2 days before epidemic (22 June) and it remained high until the onset of rain on 24 June. The count then decreased to moderate or low (provided graphical analysis). Other pollen types exhibited same general pattern as grass pollen but the counts were low (no numerical data provided). Fungi: The fungal spore content in the air varied from site to site (graphical analysis). • London & Runnymede: There was a rise in dry powdery wind-released spores immediately before the storm. • Cambridge & Leicester: There was a transient increase in <i>Cladosporium</i> just before the storm. • Cambridge & Norwich: The levels of ascospores of <i>Phaeosphaeria nigrans</i> and <i>Diatriypaceae</i> were unusually high after the storm. • Cambridge: The concentrations of <i>Sporobolomyces</i> spores were extremely high hours after the TA event.	None tested	None tested
Andrew et al., 2017	Number of cases attended by emergency services	Pollen: On thunderstorm asthma day (6pm–11.59pm on November 21, 2016), grass pollen readings were 102 grains/m ³ (extreme) compared to < 20 grains/m ³ (low) the next few days. Fungi: No reports on fungi.	None tested	None tested
Thien et al., 2018	Presentation of respiratory symptoms at ED or diagnosis of asthma at ICU	Pollen: Airborne grass pollen concentrations were extremely high (i.e. > 100 grains/m ³) on 4,7 and November 12, 2016. On thunderstorm asthma day (November 21, 2016), airborne grass pollen concentrations were extreme (101 grains/m ³ and 171 grains/m ³ at Parkville and Burwood, respectively). Recorded rise in tree, weed and ruptured pollens on November 21, 2016 (provided graphical analysis). Fungi: There was a rise in fungal spores on November 21, 2016 (provided graphical analysis).	None tested	None tested

(continued on next page)

Table 2 (continued)

Author(s) (Year)	Outcome definition	Findings	Confounders	Interactions
Darvall et al., 2018	Admission due to asthma (APACHE [Acute Physiology and Chronic Health Evaluation] III-J code 209, Australian and New Zealand Paediatric Intensive Care code 431) or acute bronchospasm with alternative coding	Pollen: The levels of airborne grass pollen were extreme (≥ 100 grains/m ³) on the day of TA event (November 21, 2016). Graphical analysis showed that other pollen types (i.e. tree, weed and broken pollen) were present. Fungi: Graphical analysis showed that fungal spores were present. Pollen: Levels were extreme (> 100 grains/m ³) on some of the days before the thunderstorm, but only moderate on the day of the storm (graphical analysis). Fungi: No reports on fungi.	None tested	None tested
Howden et al., 2011	Presentation to the emergency department with acute asthma		None tested	None tested

lagged effects of pollen and the counts on the day of the thunderstorm asthma event of November 25, 2010. Pollen counts were extreme on the days prior to the thunderstorm but only moderate counts on the day itself.

All the British studies (Packe and Ayres, 1985; Davidson et al., 1996; Venables et al., 1997) reported the lagged effects of pollen. Both Davidson et al. (1996) and Venables et al. (1997) observed that the grass pollen count reached 258 grains/m³ two days before the thunderstorm asthma epidemic that occurred on June 24, 1994 and that the concentration remained high up until the thunderstorm. The other pollen families that were investigated by Venables et al. (1997) exhibited the same general pattern as grass pollen but the counts were lower. Similar patterns were observed in the original study by Packe and Ayres (1985): total pollen counts were high up to four days before the onset of thunderstorm and the counts decreased when it rained.

The studies (Thien et al., 2018; Packe and Ayres, 1985; Davidson et al., 1996; Venables et al., 1997; Darvall et al., 2018) that described the levels of fungi in relation to thunderstorm asthma events, reported increased concentrations of different fungal taxa, depending on whether measurement was recorded before, during or after the thunderstorm. The concentrations of allergenic fungi, particularly *Cladosporium* species, were reported to be high up to two days before the thunderstorm, after which the levels decreased (Packe and Ayres, 1985; Venables et al., 1997). During the thunderstorm, the levels of damp air spores (i.e. a group of spores that are released in damp air and are used as an indicator for night-liberated spores (Hirst et al., 1967)), particularly *Phaeosphaeria nigrans*, *Diatrypaeaceae* and *Didymella exilis* species, were documented to be unusually high (Packe and Ayres, 1985; Davidson et al., 1996; Venables et al., 1997). After the storm, *Sporobolomyces* levels were found to be extremely high (Packe and Ayres, 1985; Venables et al., 1997). Thien et al. (2018) and Darvall et al. (2018) reported that fungal spores were present on the day of the thunderstorm asthma event but did not report the levels or the taxa involved. Nonetheless, both studies investigated the 2016 thunderstorm asthma event in Melbourne, Australia, when the average grass pollen level on the day varied between 102 and 210 grains/m³ depending on the location, and average fungal spore levels, which were composed mainly of *Cladosporium*, *Alternaria* and smuts were reported to be 366 spores/m³ at one site (Lindstrom et al., 2017).

4.2. Time-series studies

Time-series studies were the most common design used to explore the association between outdoor pollen and thunderstorm asthma events (see Tables 3 and 4). They involved time-series data, which were typically measured at successive time points. Most studies were conducted in the United Kingdom (Anderson et al., 2001; Pulimood et al., 2007; Celenza et al., 1996; Lewis et al., 2000; Newson et al., 1997, 1998; Hajat et al., 1997) while others in Australia (Campbell et al., 2019; Erbas et al., 2012; Silver et al., 2018) and Canada (Dales et al., 2003). Of these, three different thunderstorm asthma events were investigated: the 1994 (Celenza et al., 1996; Hajat et al., 1997) and 2002 (Pulimood et al., 2007) events in the United Kingdom; and the 2003 (Erbas et al., 2012) event in Australia. The other studies (Anderson et al., 2001; Campbell et al., 2019; Lewis et al., 2000; Newson et al., 1997; Silver et al., 2018; Dales et al., 2003) explored the effects of thunderstorms on daily asthma admissions, while taking into account the levels of pollen. All the studies examined grass pollen as the primary pollen family with some also assessing tree (Lewis et al., 2000; Newson et al., 1998; Dales et al., 2003) and weed pollen (Newson et al., 1998; Hajat et al., 1997; Dales et al., 2003). Only five studies (Pulimood et al., 2007; Lewis et al., 2000; Newson et al., 1997; Silver et al., 2018; Dales et al., 2003) stated the type of trap used to collect pollen data. Of which, four (Pulimood et al., 2007; Lewis et al., 2000; Newson et al., 1997; Silver et al., 2018) used Burkard volumetric traps and one (Dales et al., 2003) used a Rotorod. Generally, Burkard volumetric spore traps

Table 3
The characteristics of time-series studies.

Author(s) (Year)	Study population	Sample size	Exposure definition (family) ^a	Exposure measurement	Patients' characteristics	Age range of participants
Time-series studies						
Anderson et al., 2001	Those admitted to hospitals in Cardiff and Newport, UK due to asthma between January 1990 to December 1996	Unknown	• Grass	• Trap not stated Pollen data collected by Sully Hospital Asthma and Allergy Research Unit	None	Unknown
Pulimood et al., 2007	Patients attending Cambridge University Hospital and hospitals in the Suffolk, Norfolk, Cambridgeshire and Trent Strategic Health Authority (SHA) from June 1996 to August 2005 due to asthma	Unknown	• Grass	• Burkard volumetric trap • Location: Derby, UK, 60 miles of east Cambridge	Allergic sensitisation (SPT, IgE serology test), history of asthma, previous thunderstorm-related asthma symptoms, history of asthma admissions, oral corticosteroids and contemporaneous asthma treatment	Unknown
Celenza et al., 1996	Those presenting with asthma who attended the ED department of St Mary's Hospital, London, UK between 1 June and July 31, 1994	148	• Grass	• Trap not stated • Sourced from the Pollen Research Unit, University of North London • Location: University of North London, roughly 6 km from St Mary's Hospital	None	At least 16 years old
Lewis et al., 2000	Patients attending the ED departments of Derby Royal Infirmary and Derby City Hospital, UK between January 1993 to December 1996 due to asthma	Unknown	• Grass • Tree: Birch	• Burkard volumetric trap • Location: approximately 4 km south-west of the city centre	None	At least 14 years old
Newson et al., 1998	Patients who were admitted due to asthma between 1987 and 1994 in England, UK and who are in the Hospital Episodes System (HES)	Unknown	• Tree: Birch, Oak • Grass • Weed: Nettle	• Trap not stated • Data was collected by Pollen Research Unit, Worcester, UK.	None	Two age groups: 0–14 and ≥ 15 years old
Newson et al., 1997	Patients who were admitted due to asthma between January 1990 (beginning) to March 1994 (end) in England, UK and who are in the Hospital Episodes System (HES)	Unknown	• Grass	• Volumetric trap • Data collected from multiple areas of the European Aeroallergen Network, UK by Pollen Research Unit	None	Two age groups: 0–14 and ≥ 15 years old
Hajat et al., 1997	Patients attending 45 to 47 GP practices in London, UK from 1992 to 1994 due to asthma	Unknown	• Grass • Weed: Nettle	• Trap not stated • Data obtained from the National Pollen Monitoring Network.	None	Age groups: 0–14 (children), 15–64 (adults), 65+ (elderly)
Erbas et al., 2012	Children presenting with asthma at ED in Victoria, Australia in 2003	2559	• Grass	• Trap not stated • Data collected by University of Melbourne	None	Children less than 15 years old
Silver et al., 2018	Patients admitted to public hospitals within the Greater Melbourne region, Australia, between January 1990 to June 2015 due to asthma	170,344	• Grass • Non-grass	• Burkard volumetric trap • Location: University of Melbourne in Parkville, Victoria (1.7 km north of central Melbourne)	None	All ages (0–9, 10–19, 20–64, 65+)
Campbell et al., 2019	Patients presenting with asthma at emergency departments in Tasmania, Australia, public hospitals between December 20, 2002 to June 30, 2017	Unknown	• Grass	• Unknown	None	Unknown
Dales et al., 2003	Patients attending the ED of The Children's Hospital of Eastern Ontario (CHEO) in Ottawa, Ontario, Canada between 1993 and 1997 due to asthma	Unknown	• Grass • Tree • Weed: Ragweed	• Rotorod • Location: Ottawa Airport (approximately 4 miles from CHEO)	None	Unknown

^a = Refer to Table S3 for the classification of pollen species.

Table 4
The findings of time-series studies.

Author(s) (Year)	Outcome definition	Findings	Confounders	Interactions
Time-series studies Anderson et al., 2001	Number of daily asthma admissions by using ICD9 codes 493.0, 493.1 and 493.9	Pollen: During thunderstorms, asthma admissions increased (graphical analysis) but it could not be explained by an increase in pollen counts ($r = -0.07$), nor by any interaction between pollen counts and rainfall (no data provided). Total pollen counts were lower on thunderstorm days (provided graphical analysis). Fungi: Graphical analysis showed that counts were not significantly higher on thunderstorm days. There were no significant correlation ($r = -0.09$) between fungi and asthma admissions. There was also no evidence of interaction between rainfall and fungal spores in relation to asthma admissions. Pollen: Levels of grass pollen in Derby, UK was intermittently above the threshold (i.e. 50 grains/m³) the day before the thunderstorm and after 4pm on thunderstorm day. Asthma admissions relative risk (95% CI) for every 100 pollen grains/m³ increase the day before the thunderstorm: ● Norfolk/Suffolk/Cambridgeshire = 0.85 (0.72–1.01), p-value = 0.0688 ● Trent = 0.86 (0.73–1.02), p-value = 0.0819 ● Combined = 0.87 (0.75–0.99), p-value = 0.0434 Fungi: Levels of spores were above threshold up to two days before the thunderstorm. The previous day's broken <i>Alternaria</i>, <i>Cladosporium</i> and <i>Didymella</i> species counts were significantly associated with asthma admissions. Results for the relative risk (95% CI) are as follows: - Broken <i>Alternaria</i> (per 10 increase/m³) ● Norfolk/Suffolk/Cambridgeshire = 2.36 (1.54–3.66), p-value = < 0.0001 ● Trent = 2.10 (1.34–3.28); p-value = 0.001 ● Combined = 2.21 (1.51–3.27), p-value = < 0.0001 <i>Cladosporium</i> (per 10,000 increase/m³) ● Norfolk/Suffolk/Cambridgeshire = 1.47 (1.15–1.86), p-value = 0.002 ● Trent = 1.53 (1.22–1.92), p-value = 0.0002 ● Combined = 1.47 (1.20–1.79), p-value = 0.0002 <i>Didymella</i> (per 10,000 increase/m³) ● Norfolk/Suffolk/Cambridgeshire = 1.68 (1.43–2.01), p-value = < 0.0001 ● Trent = 1.60 (1.34–1.90), p-value = < 0.0001 ● Combined = 1.65 (1.42–1.90), p-value = < 0.0001 Pollen: There was a high concentration of grass pollen (~140 grains/l) 9 h before the thunderstorm asthma epidemic (24–25 June 1994). Graphical analysis provided. Three-hourly pollen count data from asthma epidemic (relative risks of asthma (95% CI)): > 74 grains/l = 0.18 (0.07–0.49), p-value: < 0.01 29–74 grains/l = 0.26 (0.12–0.56), p-value: < 0.01 1–28 grains/l = 0.29 (0.09–0.98), p-value: 0.05 0 grains/l = 1.00 (baseline) > 30 grains/l fall compared to 9 h before = 2.50 (1.36, 4.59), p-value: < 0.01 > 30 grains/l rise compared to 9 h before = 0.83 (0.42, 1.67), p-value: 0.61	Seasonal factors, temperature	Rainfall
Pulimood et al., 2007	Number of asthma admission rates by using ICD10 codes	Pollen: Levels of grass pollen in Derby, UK was intermittently above the threshold (i.e. 50 grains/m³) the day before the thunderstorm and after 4pm on thunderstorm day. Asthma admissions relative risk (95% CI) for every 100 pollen grains/m³ increase the day before the thunderstorm: ● Norfolk/Suffolk/Cambridgeshire = 0.85 (0.72–1.01), p-value = 0.0688 ● Trent = 0.86 (0.73–1.02), p-value = 0.0819 ● Combined = 0.87 (0.75–0.99), p-value = 0.0434 Fungi: Levels of spores were above threshold up to two days before the thunderstorm. The previous day's broken <i>Alternaria</i>, <i>Cladosporium</i> and <i>Didymella</i> species counts were significantly associated with asthma admissions. Results for the relative risk (95% CI) are as follows: - Broken <i>Alternaria</i> (per 10 increase/m³) ● Norfolk/Suffolk/Cambridgeshire = 2.36 (1.54–3.66), p-value = < 0.0001 ● Trent = 2.10 (1.34–3.28); p-value = 0.001 ● Combined = 2.21 (1.51–3.27), p-value = < 0.0001 <i>Cladosporium</i> (per 10,000 increase/m³) ● Norfolk/Suffolk/Cambridgeshire = 1.47 (1.15–1.86), p-value = 0.002 ● Trent = 1.53 (1.22–1.92), p-value = 0.0002 ● Combined = 1.47 (1.20–1.79), p-value = 0.0002 <i>Didymella</i> (per 10,000 increase/m³) ● Norfolk/Suffolk/Cambridgeshire = 1.68 (1.43–2.01), p-value = < 0.0001 ● Trent = 1.60 (1.34–1.90), p-value = < 0.0001 ● Combined = 1.65 (1.42–1.90), p-value = < 0.0001 Pollen: There was a high concentration of grass pollen (~140 grains/l) 9 h before the thunderstorm asthma epidemic (24–25 June 1994). Graphical analysis provided. Three-hourly pollen count data from asthma epidemic (relative risks of asthma (95% CI)): > 74 grains/l = 0.18 (0.07–0.49), p-value: < 0.01 29–74 grains/l = 0.26 (0.12–0.56), p-value: < 0.01 1–28 grains/l = 0.29 (0.09–0.98), p-value: 0.05 0 grains/l = 1.00 (baseline) > 30 grains/l fall compared to 9 h before = 2.50 (1.36, 4.59), p-value: < 0.01 > 30 grains/l rise compared to 9 h before = 0.83 (0.42, 1.67), p-value: 0.61	None tested	None tested
Celenza et al., 1996	Presentation of asthma to ED department	Pollen: There was a high concentration of grass pollen (~140 grains/l) 9 h before the thunderstorm asthma epidemic (24–25 June 1994). Graphical analysis provided. Three-hourly pollen count data from asthma epidemic (relative risks of asthma (95% CI)): > 74 grains/l = 0.18 (0.07–0.49), p-value: < 0.01 29–74 grains/l = 0.26 (0.12–0.56), p-value: < 0.01 1–28 grains/l = 0.29 (0.09–0.98), p-value: 0.05 0 grains/l = 1.00 (baseline) > 30 grains/l fall compared to 9 h before = 2.50 (1.36, 4.59), p-value: < 0.01 > 30 grains/l rise compared to 9 h before = 0.83 (0.42, 1.67), p-value: 0.61	Rainfall, temperature, air pressure, humidity, air pollutants (ozone, sulphur dioxide, nitrogen dioxide)	None tested

Fungi: No reports on fungi.

(continued on next page)

Table 4 (continued)

Author(s) (Year)	Outcome definition	Findings	Confounders	Interactions
Lewis et al., 2000	Daily asthma admissions and attendances at ED departments using ICD-9493, ICD-10 J45.9 & J46 or main diagnosis of asthma	Pollen: Grass pollen, thunderstorms & asthma admissions: - Grass pollen count is slightly reduced on thunderstorm day but it peaks days prior to the thunderstorm (no numerical value) - Grass pollen count is not associated with number of ED attendance on dry days, but is positively associated on stormy or wet days ($p = 0.02$) - Increase in grass pollen count is most significant on light rainfall days: - Adjusted relative risk (95% CI): 2.1 (1.4,3.3) of ED attendances for ≥ 50 vs < 10 grains/m³ - Strongest effect seen at lag 2 days preceding the thunderstorm - Birch pollen, thunderstorms and asthma admissions: - Birch pollen only had an effect on ED attendances on wet days ($p = 0.1$). - The interaction between birch pollen and rainfall was not statistically significant (provided graphical analysis). Fungi: <i>Cladosporium</i> and <i>Didymella</i> counts rose sharply with the occurrence of a thunderstorm but there was no evidence of interaction (statistical nor graphical) by thunderstorms or rainfall. Pollen: Thunderstorms with high pollen counts are at least 10 times more likely to cause epidemics (RR (95% CI): 98.37 (10.92, 422.98) but out of the 13 predicted epidemics, only 2 were followed by actual epidemics. The probability of severe thunderstorms and high pollen count causing an epidemic for either age group is between 2% and 45%. Fungi: No reports on fungi. Pollen: Relative risk (RR) of asthma admissions (high pollen count ≥ 50 Gr/m³/day & with sferics compared to zero/low/moderate pollen count & with sferics): - Children (0–14) = 1.16 (1.04,1.31) - Adults (15+) = 1.47 (1.32,1.64) - All ages = 1.31 (1.21, 1.42) Fungi: No reports on fungi. Pollen: Asthma consultation relative risk (95% CI) for every 100 grains/m³ increase in grass pollen: - All ages: 1.17 (1.06, 1.29), p-value = 0.0013 - Children: 1.21 (1.03, 1.41), p-value = 0.0257 - Adults: 1.31 (1.16, 1.47), p-value = < 0.0001 - Elderly: 0.81 (0.60, 1.09), p-value = 0.1507 Asthma consultation relative risk (95% CI) for every 100 grains/m³ increase in grass pollen + dummy variable of thunderstorm asthma event (25 June): - All ages: 1.01 (0.92, 1.11), p-value = 0.1637 - Children: 1.09 (0.92, 1.31), p-value = 0.2905 - Adults: 1.11 (0.96, 1.27), p-value = 0.1623 - Elderly: 0.73 (0.63, 0.85), p-value = 0.0439 Association between grass pollen and admission counts is not statistically significant when dummy variable (25 June 1994- TA event) is incorporated into the model Levels of nettle (89 grains/m³) and grass (258 grains/m³) pollens were extremely high 3 days before TA event. After adjusting for confounders, nettle was not significantly associated with asthma consultations. Fungi: The levels of allergenic fungi were not high, but the concentrations of some damp air spores may have increased during and after the thunderstorm (no numerical data provided). Pollen: Daily pollen count exceeded 100 grains/m³ (extreme) up to 4 days before (15, 18, Nov 19, 2003) thunderstorm asthma event (Nov 20, 2003) Asthma admissions peaked on Nov 20, 2003 (i.e. 70 visits per day) Fungi: No reports on fungi.	Long-term time trends, humidity, temperature, day of the week and influenza epidemics	Air pollutants (nitrogen dioxide, ozone, black smoke), rainfall
Newson et al., 1998	Number of asthma admissions corresponding to a combination of admission date, age group and Regional Health Authority (RHA)	Pollen: Thunderstorms with high pollen counts are at least 10 times more likely to cause epidemics (RR (95% CI): 98.37 (10.92, 422.98) but out of the 13 predicted epidemics, only 2 were followed by actual epidemics. The probability of severe thunderstorms and high pollen count causing an epidemic for either age group is between 2% and 45%. Fungi: No reports on fungi.	Seasonal factors, regional variation	None tested
Newson et al., 1997	Daily number of asthma admissions	Pollen: Relative risk (RR) of asthma admissions (high pollen count ≥ 50 Gr/m³/day & with sferics compared to zero/low/moderate pollen count & with sferics): - Children (0–14) = 1.16 (1.04,1.31) - Adults (15+) = 1.47 (1.32,1.64) - All ages = 1.31 (1.21, 1.42) Fungi: No reports on fungi.	Seasonal factors (weekly cycle and long term trends)	None tested
Hajat et al., 1997	Daily number of asthma consultations using ICD code 493	Pollen: Asthma consultation relative risk (95% CI) for every 100 grains/m³ increase in grass pollen: - All ages: 1.17 (1.06, 1.29), p-value = 0.0013 - Children: 1.21 (1.03, 1.41), p-value = 0.0257 - Adults: 1.31 (1.16, 1.47), p-value = < 0.0001 - Elderly: 0.81 (0.60, 1.09), p-value = 0.1507 Asthma consultation relative risk (95% CI) for every 100 grains/m³ increase in grass pollen + dummy variable of thunderstorm asthma event (25 June): - All ages: 1.01 (0.92, 1.11), p-value = 0.1637 - Children: 1.09 (0.92, 1.31), p-value = 0.2905 - Adults: 1.11 (0.96, 1.27), p-value = 0.1623 - Elderly: 0.73 (0.63, 0.85), p-value = 0.0439 Association between grass pollen and admission counts is not statistically significant when dummy variable (25 June 1994- TA event) is incorporated into the model Levels of nettle (89 grains/m³) and grass (258 grains/m³) pollens were extremely high 3 days before TA event. After adjusting for confounders, nettle was not significantly associated with asthma consultations. Fungi: The levels of allergenic fungi were not high, but the concentrations of some damp air spores may have increased during and after the thunderstorm (no numerical data provided). Pollen: Daily pollen count exceeded 100 grains/m³ (extreme) up to 4 days before (15, 18, Nov 19, 2003) thunderstorm asthma event (Nov 20, 2003) Asthma admissions peaked on Nov 20, 2003 (i.e. 70 visits per day) Fungi: No reports on fungi.	Size of general practices, humidity, air temperature, pollutants, weekday effects, flu epidemics and long-term cycles	None tested
Erbas et al., 2012	Daily asthma presentations at ED using ICD10-AM, J45 and J46 codes	Pollen: Daily pollen count exceeded 100 grains/m³ (extreme) up to 4 days before (15, 18, Nov 19, 2003) thunderstorm asthma event (Nov 20, 2003) Asthma admissions peaked on Nov 20, 2003 (i.e. 70 visits per day) Fungi: No reports on fungi.	Daily relative humidity, rainfall, maximum temperature, seasonality, day of the week effects	Airborne particle index (API), nitrogen dioxide

(continued on next page)

Table 4 (continued)

Author(s) (Year)	Outcome definition	Findings	Confounders	Interactions
Silver et al., 2018	Daily number of asthma admissions using ICD-9 code 493 and ICD-10 codes J45, J46	Pollen: Grass pollen, asthma admissions and thunderstorms: -Without pollen, thunderstorms led to a fall in asthma admission rates -High concentrations of grass pollen up to three days before the thunderstorm were associated with a rise in asthma admission rates Effect size (i.e. an estimate of the number of daily asthma admissions associated with a variable, assuming a population of 4.0 million) (95% CI): ● Thunderstorm only: -1.35 (-3.84, 1.13), p-value: 0.277 ● Grass at lag 0 and thunderstorm (interaction): -1.77 (-6.77, 3.22), p-value: 0.478 ● Non-grass at lag 0 and thunderstorm (interaction): 2.02 (-1.01, 5.04), p-value: 0.183 ● Grass at lag 3 and thunderstorm (interaction): 7.02 (1.36, 12.69), p-value: 0.013 ● Non-grass at lag 3 and thunderstorm (interaction): 0.16 (-2.28, 2.60), p-value: 0.896 Fungi: No reports on fungi. No epidemic thunderstorm asthma events during the 14.5-year study period. Pollen: Thunderstorm gust events commonly occurred during winter, which was outside the peak grass pollen season. The standardised risk assessment of weather and pollen data against the Tasmanian State Natural Disaster Risk Assessment (TSNDRA) (Hayes et al., 2012) framework suggests that the probability of thunderstorm gust events with peak grass pollen season occurring in a susceptible population is very low. Fungi: No reports on fungi. Pollen: Thunderstorm days (n = 151): ● Tree: 86 grains/m³ (p = 0.14) ● Grass: 22 grains/m³ (p = 0.82) ● Weed: 92 grains/m³ (p = 0.83) Non- thunderstorm days (n = 919): ● Tree: 125 grains/m³ (p = 0.14) ● Grass: 23 grains/m³ (p = 0.82) ● Weed: 87 grains/m³ (p = 0.83) Fungi: The concentrations of fungi i.e. <i>Cladosporium</i> and ascomycetes almost doubled during thunderstorms: ● <i>Cladosporium</i>: from 1259 to 2419/m³ ● Ascomycetes: from 263 to 492/m³	Temperature, relative humidity, seasonality, precipitation, wind speed, weekday effects, air pollutants (ozone and PM_{2.5})	None tested
Campbell et al., 2019	Number of asthma exacerbation epidemic days	Fungi: No reports on fungi. No epidemic thunderstorm asthma events during the 14.5-year study period. Pollen: Thunderstorm gust events commonly occurred during winter, which was outside the peak grass pollen season. The standardised risk assessment of weather and pollen data against the Tasmanian State Natural Disaster Risk Assessment (TSNDRA) (Hayes et al., 2012) framework suggests that the probability of thunderstorm gust events with peak grass pollen season occurring in a susceptible population is very low. Fungi: No reports on fungi. Pollen: Thunderstorm days (n = 151): ● Tree: 86 grains/m³ (p = 0.14) ● Grass: 22 grains/m³ (p = 0.82) ● Weed: 92 grains/m³ (p = 0.83) Non- thunderstorm days (n = 919): ● Tree: 125 grains/m³ (p = 0.14) ● Grass: 23 grains/m³ (p = 0.82) ● Weed: 87 grains/m³ (p = 0.83) Fungi: The concentrations of fungi i.e. <i>Cladosporium</i> and ascomycetes almost doubled during thunderstorms: ● <i>Cladosporium</i>: from 1259 to 2419/m³ ● Ascomycetes: from 263 to 492/m³	None tested	None tested
Dales et al., 2003	Presentation to ED with principal diagnosis of asthma (ICD 493)	Fungi: No reports on fungi. Pollen: Thunderstorm days (n = 151): ● Tree: 86 grains/m³ (p = 0.14) ● Grass: 22 grains/m³ (p = 0.82) ● Weed: 92 grains/m³ (p = 0.83) Non- thunderstorm days (n = 919): ● Tree: 125 grains/m³ (p = 0.14) ● Grass: 23 grains/m³ (p = 0.82) ● Weed: 87 grains/m³ (p = 0.83) Fungi: The concentrations of fungi i.e. <i>Cladosporium</i> and ascomycetes almost doubled during thunderstorms: ● <i>Cladosporium</i>: from 1259 to 2419/m³ ● Ascomycetes: from 263 to 492/m³	Climate, air pollutants (ozone, nitrogen dioxide, sulphur dioxide, coefficient of haze and sulfate), viral epidemics, humidity, a day-of-the-week effect	None tested

have a higher collection efficiency compared to the Rotorod (Crisp et al., 2013).

Several studies (Celenza et al., 1996; Lewis et al., 2000; Newson et al., 1997; Silver et al., 2018) found positive associations between the lagged effects of pollen and thunderstorm asthma. Celenza et al. (1996) found that when grass pollen counts fell by more than 30 grains/m³ during the thunderstorm compared to 9 h before, the relative risk (95% CI) of asthma presentations was 2.5 (1.36, 4.59). Newson et al. (1997) found that a thunderstorm (measured by sferics, which are electromagnetic signals emitted during lightning discharges (Anto and Sunyer, 1997)) with high grass pollen count up to four days before was associated with increased asthma admissions in children (adjusted RR [95% CI]: 1.16 [1.04, 1.31]) and adults (adjusted RR [95% CI]: 1.47 [1.32, 1.64]) compared to a thunderstorm of the same magnitude but with an average grass pollen count of moderate, low or zero.

Similarly, Silver et al. (2018) fitted an interaction between thunderstorms and grass pollen and found that increased grass pollen levels were significantly associated with an increase in asthma admission rates but only at lag three days (effect size [95% CI]: 2.57 [1.19, 3.95], p-value < 0.001). Without a high level of grass pollen, thunderstorms were not associated with asthma admission rates (effect size [95% CI]: -1.35 [-3.84, 1.13], p-value = 0.28). Lewis et al. (2000) found that only the interaction between grass pollen and thunderstorms on ED attendances was significant (p = 0.02). ED attendances were unrelated to grass pollen levels on dry days but were positively associated on stormy days (adjusted RR for 50 vs. < 10 grass pollen grains/m³ [95% CI]: 2.1 [1.4, 3.3]) (Lewis et al., 2000). Graphical analysis showed that the strongest effects between grass pollen counts and asthma admissions were seen at lag two days preceding the thunderstorm (Lewis et al., 2000). Although the levels of *Cladosporium* and *Didymella* spores rose sharply during the thunderstorm, there was no evidence of an interaction by rainfall or thunderstorms with respect to asthma admissions (Lewis et al., 2000).

There were also studies (Anderson et al., 2001; Campbell et al., 2019; Newson et al., 1998; Hajat et al., 1997; Erbas et al., 2012; Dales et al., 2003) that found little to no association between pollen exposure (same-day or lagged), thunderstorms and asthma admissions. Anderson and colleagues (Anderson et al., 2001) presented graphical analysis to show that asthma admissions did increase during thunderstorms. However, it was unlikely to be explained by an increase in pollen counts because no significant correlation was found between pollen and asthma admissions (r = -0.07). There was also no evidence of interaction between rainfall and grass pollen or total pollen counts with respect to asthma admissions. The same was reported for fungi. Hajat et al. (1997) found no significant association between grass pollen and admission counts for all ages except in the elderly (65+) when they incorporated a dummy variable of the thunderstorm asthma event into the model. Only when the dummy variable was removed was there a significant association for the other age groups. In addition, the authors reported that the concentrations of damp air spores (species not specified) may have increased during and after the thunderstorm but no numerical data were presented.

Newson and colleagues (Newson et al., 1998) reported that thunderstorms with high (> 50 grains/m³) pollen counts up to four days before were at least 10 times more likely to cause epidemics (i.e. an asthma admission count which exceeded the predicted count by at least 4 coefficients of variation) (adjusted RR [95% CI]: 98.4 [10.9, 423]). However, this model would result in an unacceptable high false alarm rate: out of the 13 predicted epidemics, only two were followed by actual epidemics. Similarly, Campbell et al. (2019) conducted a standardised risk assessment of weather and pollen data against the Tasmanian State Natural Disaster Risk Assessment (TSNDRA) (White et al., 2016) and found that the probability of thunderstorm gust events with peak grass pollen season resulting in an epidemic thunderstorm asthma event (epidemic: daily presentations of asthma exceeding four standard deviations from expected value) was low.

Dales et al. (2003) reported that daily asthma admissions did increase during thunderstorm days compared to non-thunderstorm days but no significant increases were found in the concentrations of pollen during thunderstorm days (p = 0.14, 0.82, 0.83 for trees, grass and weed, respectively). The concentrations of fungal spores instead, specifically Ascomycetes (p < 0.001), doubled during days with thunderstorms. One study (Erbas et al., 2012) in Melbourne simply modelled the thunderstorm asthma event as a sensitivity analysis and found that thunderstorms in Melbourne did not accentuate the estimated effects of grass pollen on asthma admissions in children during the 2003 grass pollen season. However, the counts were reported to exceed 100 grains/m³ up to five days before the 2003 thunderstorm asthma event. Similar lagged effects of pollen were observed in eight other studies (Packer and Ayres, 1985; Davidson et al., 1996; Venables et al., 1997; Howden et al., 2011; Celenza et al., 1996; Lewis et al., 2000; Newson et al., 1997; Silver et al., 2018).

Only the study by Pulimood et al. (2007) found a protective effect of grass pollen on thunderstorm asthma. Their combined (Norfolk, Suffolk, Cambridgeshire and Trent Strategic Health Authorities (SHA)) analyses showed that the previous day's grass pollen was associated with a decrease in asthma admissions (RR [95% CI]: 0.87 [0.75, 0.99]). The opposite was observed for fungi. The previous day's broken *Alternaria* (RR [95% CI]: 2.21 [1.51, 3.27], *Cladosporium* (RR [95% CI]: 1.47 [1.20, 1.79]) and *Didymella* (RR [95% CI]: 1.65 [1.42, 1.90]) species were associated with a significant increase in asthma admissions.

4.3. Quality assessment

The quality of the included studies is summarised in Tables S1 and S2. The scores ranged between 9 and 15.5 out of 17, with a median score of 14. Possible limitations and biases of the studies included mainly arose from differences or lack of information in exposure measurements (Thien et al., 2018; Anderson et al., 2001; Campbell et al., 2019; Marks et al., 2001; Lee et al., 2017; Venables et al., 1997; Darvall et al., 2018; Howden et al., 2011; Celenza et al., 1996; Newson et al., 1997, 1998; Erbas et al., 2012; Dales et al., 2003) (measurement bias); lack of adjustment for confounders such as humidity (Anderson et al., 2001; Pulimood et al., 2007; Newson et al., 1997, 1998), temperature (Pulimood et al., 2007; Newson et al., 1997, 1998), air pollutants (Anderson et al., 2001; Pulimood et al., 2007; Newson et al., 1997, 1998) and seasonality (Pulimood et al., 2007; Celenza et al., 1996) in the analyses (confounding bias); limited statistical power (Anderson et al., 2001; Marks et al., 2001; Lee et al., 2017; Lewis et al., 2000; Silver et al., 2018) and inclusion of children less than five years old in whom asthma would be difficult to diagnose (Thien et al., 2018; Packer and Ayres, 1985; Andrew et al., 2017; Newson et al., 1997, 1998; Hajat et al., 1997; Erbas et al., 2012; Silver et al., 2018) (misclassification bias).

5. Discussion

This is the first review to systematically synthesize and critically appraise the studies in the current literature to better understand the role of outdoor pollen exposure in thunderstorm asthma and to identify what role fungi may have on these associations. This review showed that high grass pollen levels were important in thunderstorm asthma events and that there were lagged relationships with high pollen levels of up to four days preceding the thunderstorm associated with increased risk of asthma exacerbations. The important point here is the duration of pollen exposure. Thunderstorm asthma events almost always occur during pollen seasons. This means that the pollen levels and possibly other aeroallergens such as fungi are already high preceding the event, so susceptible individuals are already exposed and sensitised. The length of high pollen exposure prior to the thunderstorm event appears to "prime" individuals to respond dramatically to thunderstorms. Therefore, when pollen ruptures into hundreds of tiny starch

granules during thunderstorms, it is believed to cause a more severe asthmatic response not only to susceptible individuals but also to others considered as “low-risk” previously (i.e. no history of diagnosed asthma or rhinitis). However, this does not appear to be enough to induce a thunderstorm asthma event as some studies show presence of low levels of pollen but with other important environmental changes occurring such as high levels of fungi, humidity and thunderstorm activity.

Nonetheless, almost all observational case report studies (Thien et al., 2018; Marks et al., 2001; Lee et al., 2017; Andrew et al., 2017; Darvall et al., 2018) conducted in Australia reported high grass pollen counts on the day of the thunderstorm. This could be because thunderstorm asthma events in Australia are seasonal and occur during the peak grass pollen seasons (Marks and Bush, 2007).

Of the studies (Anderson et al., 2001; Campbell et al., 2019; Pulimood et al., 2007; Celenza et al., 1996; Lewis et al., 2000; Newson et al., 1997, 1998; Hajat et al., 1997; Silver et al., 2018) that conducted statistical analyses to investigate the association between grass pollen and thunderstorm asthma, four (Celenza et al., 1996; Lewis et al., 2000; Celenza et al., 1996; Silver et al., 2018) found a positive association. These studies investigated four different events, but a common feature was the investigation of important lagged effects of grass pollen, ranging from four days and up to 9 h prior to the occurrence of thunderstorm.

Some studies (Anderson et al., 2001; Dales et al., 2003) found low to moderate counts of intact pollen during the thunderstorm. Since pollen is hypothesised to rupture into respirable particles upon contact with water during a thunderstorm event, pollen grains may rupture and no longer be detectable. The resultant particles may instead be classified as particulate matter (PM_{2.5} or PM₁₀). If pollen measurements were made the morning of, or the day before a thunderstorm, intact pollen will be measured and reflect the high pollen season counts. To support this hypothesis, some of the observational case report studies (Packer and Ayres, 1985; Davidson et al., 1996; Venables et al., 1997; Howden et al., 2011) reported that the concentrations of grass pollen were high days before the thunderstorm asthma event, but the concentrations remained high only until the onset of thunderstorms.

Only one study (Pulimood et al., 2007) which considered modelling of lag effects showed a protective effect of the previous day's grass pollen on asthma admissions. However, this study had several methodological limitations. The presentation data were collated from four sites in the UK but only one pollen trap was used to assess pollen exposure. The trap was located at Derby, UK, which was 110 miles from Cambridgeshire, 120 miles from Norfolk, 148 miles from Suffolk and 189 miles from Trent. Another possible explanation is that while Norfolk/Suffolk/Cambridge were combined in the analysis, the storm occurred in the evening for Cambridge but not in the other areas.

Of all the pollen families, grass pollen seems to be the most important trigger in relation to thunderstorm asthma events, especially in Australia. Grasses possess the most potent allergens and upon contact with water, grass pollen grains can rupture and release approximately 700 starch granules (Singh et al., 2017; Suphioglu, 1998; Sofiev and Bergmann, 2013). It is also hypothesised that the electrical ions from the thunderstorms could enhance the rupturing of pollen by attaching to the pollen particles and augmenting bronchial hyperresponsiveness (D'Amato et al., 2016). These granules contain the major allergen, Lol p 5, that could trigger IgE-mediated responses demonstrated both *in-vivo* and *in-vitro* (Suphioglu, 1998). Not all studies investigated tree and weed pollen, so we were unable to determine the significance of these pollen families in thunderstorm asthma events. Nevertheless, of the studies that did investigate other pollen taxa (i.e. tree (Hirst et al., 1967; Newson et al., 1998); weed (Newson et al., 1998; Hajat et al., 1997); and non-grass pollen (Silver et al., 2018)), they found no significant association with thunderstorm asthma.

Nevertheless, it should be noted that high counts of grass pollen accompanied by thunderstorms may not always be sufficient to cause thunderstorm asthma events. This can be observed from the study by

Newson et al. (1998). An early warning system solely based on high sferics and high pollen counts will likely lead to “alarm fatigue” if used as a public health warning system. Moreover, epidemic thunderstorm asthma events in Australia seem to be seasonal, but the Tasmanian study (Campbell et al., 2019) showed that there was no occurrence of thunderstorm asthma events during that State's peak grass pollen seasons in the 14.5-year study period. This highlights the need for ongoing research to develop a sensitive and specific prediction tool for thunderstorm asthma events. It is also important to consider the spatial and temporal scales when assessing such associations. All studies included in this review have assessed grass pollen temporally using standard methods (i.e. hourly) which have limited temporal precision. In addition, spatial variations are also important. On a spatial scale, the variations are quite stark from small ruptured grass pollen grains (which are difficult to measure and seldom measured (Schäppi et al., 1999)) upon contact with the thunderstorm to larger distances depending on wind speed and severity of the thunderstorm. All these factors need to be considered when assessing the impacts on affected individuals during the timing of thunderstorm asthma events.

There were studies (Thien et al., 2018; Packer and Ayres, 1985; Davidson et al., 1996; Venables et al., 1997; Darvall et al., 2018; Pulimood et al., 2007; Lewis et al., 2000; Hajat et al., 1997; Dales et al., 2003) that reported increased concentrations of fungi during a thunderstorm asthma event, but none examined the interactions between pollen and fungi. On average, fungal spores have sizes between 2 and 10 µm (Simon-Nobbe et al., 2008), so they are generally smaller than grass pollen grains (> 20 µm). They are also more abundant in the air (Simon-Nobbe et al., 2008; Tham et al., 2017), so their effects on the respiratory tract may be stronger when coupled with high levels of grass pollen. Although it is hypothesised that fungal spores of respirable sizes can be released into the atmosphere upon contact with wind or the vibrations of impacting raindrops (Taylor and Jonsson, 2004), this proposed mechanism is understudied, therefore it is not yet fully known. Hence, fungi do have the potential to be a critical effect modifier of the association between grass pollen and thunderstorm asthma, but this is yet to be explored. Other synergistic environmental effects may also be necessary to cause thunderstorm asthma. For example, a sudden drop in temperature, high humidity and the presence of storm outflows seem to be important in creating “the perfect storm” because they not only facilitate the rupturing of pollen grains and possibly fungal spores, but they also increase the risk of asthma exacerbations (Taylor and Jonsson, 2004; Cong et al., 2017; Hayes et al., 2012). A drop in temperature can cause airway dysfunction while an increase in humidity can cause bronchoconstriction, both of which are underlying mechanisms for exacerbations of asthma (Cong et al., 2017; Hayes et al., 2012).

Certain limitations need to be acknowledged when considering the results of this systematic review. The methodological approaches between studies were very diverse, so the findings were not directly comparable. Since a meta-analysis was not possible, we were unable to provide a pooled estimate of risk. Our search also focused only on the associations between pollen and thunderstorm asthma, so any findings on other factors, including fungi were limited by this search. Numerous challenges arise when studying rare phenomenon such as thunderstorm asthma events. The exposure period is short and spikes in respiratory-related outcomes occur. Therefore, we are limited in statistical power to study these events with precision and reliability. These limitations are inherent in most, if not all studies considered in this review. Nevertheless, this review provides a critical discussion of the available studies investigating pollen-thunderstorm asthma associations as well as identifying shortcomings of past research in the assessment of thunderstorm asthma events.

6. Conclusion

In conclusion, our narrative synthesis of current evidence suggests

that outdoor levels of grass pollen in the days preceding a thunderstorm is a necessary ingredient for a thunderstorm asthma epidemic event. However, these two factors (grass pollen and thunderstorm) do not always result in a thunderstorm asthma event, suggesting that other factors may also be important. There is a need to further investigate the role of fungi and other environmental factors such as air quality in predicting thunderstorm asthma events. It is imperative to have a better understanding of the correlations of thunderstorm asthma so that preventive strategies can be adopted, and the health burden of future thunderstorm asthma events significantly reduced.

Credit Author Statement

Nur Idrose: Investigation, Writing- Original Draft. Shyamali Dharmage: Conceptualization, Writing- Review & Editing, Supervision. Adrian Lowe: Writing- Review & Editing. Katrina Lambert: Investigation. Caroline Lodge: Writing- Review & Editing. Michael Abramson: Writing- Review & Editing. Jo Douglass: Writing- Review & Editing. Ed Newbigin: Writing- Review & Editing. Bircan Erbas: Conceptualization, Investigation, Writing- Review & Editing, Supervision

Funding sources

A.J.L., C.J.L. and S.C.D. hold funding from the National Health & Medical Research Council (NHMRC) of Australia.

Declaration of competing interest

Michael Abramson holds investigator-initiated grants from Pfizer and Boehringer-Ingelheim for unrelated research. He has also undertaken an unrelated consultancy for Sanofi.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envres.2019.108911>.

References

- Anderson, W., Prescott, G.J., Packham, S., Mullins, J., Brookes, M., Seaton, A., 2001. Asthma admissions and thunderstorms: a study of pollen, fungal spores, rainfall, and ozone. *QJM: Int. J. Med.* 94 (8), 429–433. <https://doi.org/10.1093/qjmed/94.8.429>.
- Andrew, E., Nehme, Z., Bernard, S., Abramson, M.J., Newbigin, E., Piper, B., et al., 2017. Stormy weather: a retrospective analysis of demand for emergency medical services during epidemic thunderstorm asthma. *BMJ* 359, j5636. <https://doi.org/10.1136/bmj.j5636>.
- Anto, J.M., Sunyer, J., 1997. Thunderstorms: a risk factor for asthma attacks. *Thorax* 52 (8), 669–670. <https://doi.org/10.1136/thx.52.8.669>.
- Campbell, S.L., Fox-Hughes, P.D., Jones, P.J., Remenyi, T.A., Chappell, K., White, C.J., et al., 2019. Evaluating the risk of epidemic thunderstorm asthma: lessons from Australia. *Int. J. Environ. Res. Public Health* 16 (5), 837. <https://doi.org/10.3390/ijerph16050837>.
- Celenza, A., Fothergill, J., Kupek, E., Shaw, R.J., 1996. Thunderstorm associated asthma: a detailed analysis of environmental factors. *BMJ* 312 (7031), 604–607. <https://doi.org/10.1136/bmj.312.7031.604>.
- Cong, X., Xu, X., Zhang, Y., Wang, Q., Xu, L., Huo, X., 2017. Temperature drop and the risk of asthma: a systematic review and meta-analysis. *Environ. Sci. Pollut. Res. Int.* 24 (28), 22535–22546. <https://doi.org/10.1007/s11356-017-9914-4>.
- Crisp, H.C., Gomez, R.A., White, K.M., Quinn, J.M., 2013. A side-by-side comparison of Rotorod and Burkard pollen and spore collections. *Ann. Allergy Asthma Immunol.: Off. Publ. Am. Coll. Allergy Asthma Immunol.* 111 (2), 118–125. <https://doi.org/10.1016/j.anai.2013.05.021>.
- D'Amato, G., Baena-Cagnani, C.E., Cecchi, L., Annesi-Maesano, I., Nunes, C., Ansotegui, I., et al., 2013. Climate change, air pollution and extreme events leading to increasing prevalence of allergic respiratory diseases. *Multidiscip. Respir. Med.* 8 (1), 12. <https://doi.org/10.1186/2049-6958-8-12>.
- D'Amato, G., Vitale, C., D'Amato, M., Cecchi, L., Liccardi, G., Molino, A., et al., 2016. Thunderstorm-related asthma: what happens and why. *Clin. Exp. Allergy: J. Br. Soc. Allergy Clin. Immunol.* 46 (3), 390–396. <https://doi.org/10.1111/cea.12709>.
- Dales, R.E., Cakmak, S., Judek, S., Dann, T., Coates, F., Brook, J.R., et al., 2003. The role of fungal spores in thunderstorm asthma. *Chest* 123 (3), 745–750. <https://doi.org/10.1378/chest.123.3.745>.
- Darvall, J.N., Durie, M., Pilcher, D., Wigmore, G., French, C., Karalapillai, D., et al., 2018. Intensive care implications of epidemic thunderstorm asthma. *Crit. Care Resusc.: J. Australas. Acad. Crit. Care Med.* 20 (4), 294–303.
- Davidson, A.C., Emberlin, J., Cook, A.D., Venables, K.M., 1996. A major outbreak of asthma associated with a thunderstorm: experience of accident and emergency departments and patients' characteristics. *Thames Regions Accident and Emergency Trainees Association. BMJ (Clin. Res. ed)* 312 (7031), 601–604. <https://doi.org/10.1136/bmj.312.7031.601>.
- Davies, J., Erbas, B., Simunovic, M., Al Kouba, J., Milic, A., 2017. Literature review on thunderstorm asthma and its implications for public health advice [Internet]. *Www2.health.vic.gov.au* Available from: <https://www2.health.vic.gov.au/about/publications/researchandreports/thunderstorm-asthma-literature-review-may-2107>, Accessed date: 21 April 2019.
- Erbas, B., Akram, M., Dharmage, S.C., Tham, R., Dennekamp, M., Newbigin, E., et al., 2012. The role of seasonal grass pollen on childhood asthma emergency department presentations. *Clinical and Experimental Allergy: J. Br. Soc. Allergy Clin. Immunol.* 42 (5), 799–805. <https://doi.org/10.1111/j.1365-2222.2012.03995.x>.
- Erbas, B., Jazayeri, M., Lambert, K.A., Katelaris, C.H., Prendergast, L.A., Tham, R., et al., 2018. Outdoor pollen is a trigger of child and adolescent asthma emergency department presentations: a systematic review and meta-analysis. *Allergy* 73 (8), 1632–1641. <https://doi.org/10.1111/all.13407>.
- Hajat, S., Goubet, S.A., Haines, A., 1997. Thunderstorm-associated asthma: the effect on GP consultations. *The British journal of general practice: J. R. Coll. Gen. Pract.* 47 (423), 639–641.
- Hayes, D., Collins, P.B., Khosravi, M., Lin, R.-L., Lee, L.-Y., 2012. Bronchoconstriction triggered by breathing hot humid air in patients with asthma. *Am. J. Respir. Crit. Care Med.* 185 (11), 1190–1196. <https://doi.org/10.1164/rccm.201201-0088OC>.
- Hirst, J.M., Stedman, O.J., Hurst, G.W., 1967. Long-distance spore transport: vertical sections of spore clouds over the sea. *Microbiology* 48 (3), 357–377. <https://doi.org/10.1099/00221287-48-3-357>.
- Howden, M.L., McDonald, C.F., Sutherland, M.F., 2011. Thunderstorm asthma—a timely reminder. *Med. J. Aust.* 195 (9), 512–513. <https://doi.org/10.5694/mja11.11044>.
- Lee, J., Kronborg, C., O'Hehir, R.E., Hew, M., 2017. Who's at risk of thunderstorm asthma? The ryegrass pollen trifecta and lessons learnt from the Melbourne thunderstorm epidemic. *Respir. Med.* 132, 146–148. <https://doi.org/10.1016/j.rmed.2017.10.012>.
- Lewis, S.A., Corden, J.M., Forster, G.E., Newlands, M., 2000. Combined effects of aerobiological pollutants, chemical pollutants and meteorological conditions on asthma admissions and A & E attendances in Derbyshire UK, 1993–96. *Clin. Exp. Allergy* 30 (12), 1724–1732. <https://doi.org/10.1046/j.1365-2222.2000.00947.x>.
- Lindstrom, S.J., Silver, J.D., Sutherland, M.F., Treloar, A.B.A., Newbigin, E., McDonald, C.F., et al., 2017. Thunderstorm asthma outbreak of November 2016: a natural disaster requiring planning. *Med. J. Aust.* 207 (6), 235–237. <https://doi.org/10.5694/mja17.00285>.
- Marks, G.B., Bush, R.K., 2007. It's blowing in the wind: new insights into thunderstorm-related asthma. *J. Allergy Clin. Immunol.* 120 (3), 530–532. <https://doi.org/10.1016/j.jaci.2007.07.012>.
- Marks, G.B., Colquhoun, J.R., Girgis, S.T., Koski, M.H., Treloar, A.B., Hansen, P., et al., 2001. Thunderstorm outflows preceding epidemics of asthma during spring and summer. *Thorax* 56 (6), 468–471. <https://doi.org/10.1136/thorax.56.6.468>.
- Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Med.* 6 (7), e1000097. <https://doi.org/10.1371/journal.pmed.1000097>.
- Newson, R., Strachan, D., Archibald, E., Emberlin, J., Hardaker, P., Collier, C., 1997. Effect of thunderstorms and airborne grass pollen on the incidence of acute asthma in England, 1990–94. *Thorax* 52 (8), 680–685. <https://doi.org/10.1136/thx.52.8.680>.
- Newson, R., Strachan, D., Archibald, E., Emberlin, J., Hardaker, P., Collier, C., 1998. Acute asthma epidemics, weather and pollen in England, 1987–1994. *Eur. Respir. J.* 11 (3), 694–701.
- Packe, G.E., Ayres, J.G., 1985. Asthma outbreak during a thunderstorm. *Lancet* 2 (8448), 199–204. [https://doi.org/10.1016/s0140-6736\(85\)91510-7](https://doi.org/10.1016/s0140-6736(85)91510-7).
- Pearce, T., 2017. Review of response to the thunderstorm asthma event of 21–22 November 2016. [Internet]. *Igem.vic.gov.au Insp. Gen. Emerg. Manag* Available from: https://www.igem.vic.gov.au/sites/default/files/embridge_cache/emshare/original/public/2017/07/80/c414fe2ba/ReviewofemergencyresponsetoNovember2016thunderstormasthmaeventfinalreport.pdf, Accessed date: 25 April 2019.
- Pulimood, T.B., Corden, J.M., Bryden, C., Sharples, L., Nasser, S.M., 2007. Epidemic asthma and the role of the fungal mold *Alternaria alternata*. *J. Allergy Clin. Immunol.* 120 (3), 610–617. <https://doi.org/10.1016/j.jaci.2007.04.045>.
- Schäppi, G.F., Taylor, P.E., Staff, I.A., Rolland, J.M., Suphioglu, C., 1999. Immunologic significance of respirable atmospheric starch granules containing major birch allergen Bet v 1. *Allergy* 54 (5), 478–483. <https://doi.org/10.1034/j.1398-9995.1999.00838.x>.
- Silver, J.D., Sutherland, M.F., Johnston, F.H., Lampugnani, E.R., McCarthy, M.A., Jacobs, S.J., et al., 2018. Seasonal asthma in Melbourne, Australia, and some observations on the occurrence of thunderstorm asthma and its predictability. *PLoS One* 13 (4), e0194929. <https://doi.org/10.1371/journal.pone.0194929>.
- Simon-Nobbe, B., Denk, U., Pöll, V., Rid, R., Breitenbach, M., 2008. The spectrum of fungal allergy. *Int. Arch. Allergy Immunol.* 145 (1), 58–86. <https://doi.org/10.1159/000107578>.
- Singh, N., Singh, U., Singh, D., Daya, M., Singh, V., 2017. Correlation of pollen counts and number of hospital visits of asthmatic and allergic rhinitis patients. *Lung India: Off. Organ Indian Chest Soc.* 34 (2), 127–131. <https://doi.org/10.4103/0970-2113.201313>.
- Sofiev, M., Bergmann, K.-C., 2013. Allergenic Pollen: A Review of the Production,

- Release, Distribution and Health Impacts.
- Suphioglu, C., 1998. Thunderstorm asthma due to grass pollen. *Int. Arch. Allergy Immunol.* 116 (4), 253–260. <https://doi.org/10.1159/000023953>.
- Suphioglu, C., Singh, M.B., Taylor, P., Bellomo, R., Holmes, P., Puy, R., et al., 1992. Mechanism of grass-pollen-induced asthma. *Lancet* 339 (8793), 569–572. [https://doi.org/10.1016/0140-6736\(92\)90864-y](https://doi.org/10.1016/0140-6736(92)90864-y).
- Taylor, P.E., Jonsson, H., 2004. Thunderstorm asthma. *Curr. Allergy Asthma Rep.* 4 (5), 409–413.
- Tham, R., Vicendese, D., Dharmage, S.C., Hyndman, R.J., Newbiggin, E., Lewis, E., et al., 2017. Associations between outdoor fungal spores and childhood and adolescent asthma hospitalizations. *J. Allergy Clin. Immunol.* 139 (4), 1140–1147. <https://doi.org/10.1016/j.jaci.2016.06.046>. e4.
- Thien, F., Beggs, P.J., Csutoros, D., Darvall, J., Hew, M., Davies, J.M., et al., 2018. The Melbourne epidemic thunderstorm asthma event 2016: an investigation of environmental triggers, effect on health services, and patient risk factors. *The Lancet Planet. Health* 2 (6), e255–e263. [https://doi.org/10.1016/S2542-5196\(18\)30120-7](https://doi.org/10.1016/S2542-5196(18)30120-7).
- Venables, K.M., Allitt, U., Collier, C.G., Emberlin, J., Greig, J.B., Hardaker, P.J., et al., 1997. Thunderstorm-related asthma – the epidemic of 24/25 June 1994. *Clin. Exp. Allergy* 27 (7), 725–736. <https://doi.org/10.1046/j.1365-2222.1997.790893.x>.
- White, C., Remenyi, T., McEvoy, D., Trundle, A., Corney, S., 2016. *Tasmanian State Natural Disaster Risk Assessment 2016*.
- Zaza, S., Wright-De Agüero, L.K., Briss, P.A., Truman, B.I., Hopkins, D.P., Hennessy, M.H., et al., 2000. Data collection instrument and procedure for systematic reviews in the guide to community preventive services. Task force on community preventive services. *Am. J. Prev. Med.* 18 (1 Suppl. 1), 44–74. [https://doi.org/10.1016/S0749-3797\(99\)00122-1](https://doi.org/10.1016/S0749-3797(99)00122-1).
- Zink, K., Pauling, A., Rotach, M.W., Vogel, H., Kaufmann, P., Clot, B., 2013. Empol 1.0: a new parameterization of pollen emission in numerical weather prediction models. *Geosci. Model Dev. (GMD)* 6 (6), 1961–1975. <https://doi.org/10.5194/gmd-6-1961-2013>.

Table S1. Quality assessment of observational case report studies using Zaza et al. (2000) framework.

	Overall score (out of 17)	Possible limitations & biases
Observational case report studies		
Packe et al. (1985)	10	• Did not model the association between pollen and outcome • Did not conduct statistical testing • Did not state type of pollen family assessed**** • Included children less than 5 years of age****
Marks et al. (2001)	14	• Did not provide age & gender of participants • Did not model the association between pollen and outcome • Lack of detail on how thunderstorm was measured* • Limited power
Davidson et al. (1996)	14	• Did not provide age of participants • Did not model the association between pollen and outcome • 57/640 patients' records could not be found***
Lee et al. (2017)	9	• Lack of detail on how and where exposure was measured* • Did not model the association between pollen and outcome • Did not conduct statistical testing • Only 85/243 people participated in study***
Venables et al. (1997)	10	• Did not provide age & gender of participants • Lack of detail on how and where exposure was measured* • Did not model the association between pollen and outcome • Did not conduct statistical testing
Andrew et al. (2017)	13	• Unable to confirm the asthma diagnosis patients received at the hospital*** • Did not model the association between pollen and outcome

		• Included children less than 5 years of age****
Thien et al. (2018)	14.5	• Lack of detail on how thunderstorm was measured* • Did not model the association between pollen and outcome • Included children less than 5 years of age****
Darvall et al. (2018)	14	• Lack of detail on how thunderstorm was measured* • Lack of detail on how and where exposure was measured* • Did not model the association between pollen and outcome
Howden et al. (2011)	12.5	• Did not provide age & gender of participants • Lack of detail on how exposure was measured* • Did not model the association between pollen and outcome • Lack of detail on how acute asthma was diagnosed**** • Did not state type of pollen family assessed**** • Did not conduct statistical testing

*=measurement bias, **=confounding bias, ***=selection bias, ****= misclassification bias

Table S2. Quality assessment of time-series studies using Zaza et al. (2000) framework.

	Overall score (out of 17)	Possible limitations & biases
Time-series studies		
Anderson et al. (2001)	13.5	• Did not provide age & gender of participants • Lack of detail on how and where exposure was measured* • Did not account for air pollutants & humidity** • Limited power
Pulimood et al. (2007)	14	• Did not provide gender of participants • Did not mention adjustments for any confounders**
Celenza et al. (1996)	15.5	• Lack of detail on how exposure was measured* • Did not account for seasonal factors**
Lewis et al. (2000)	14.5	• Did not provide gender of participants • Limited power
Newson et al. (1998)	13.5	• Did not provide gender of participants • Lack of detail on how and where exposure was measured* • Did not adjust for humidity, temperature and air pollutants** • Included children less than 5 years of age****
Newson et al. (1997)	13.5	• Did not provide gender of participants • Lack of detail on where exposure was measured* • Did not specify which volumetric trap was used to measure pollen* • Did not adjust for humidity, temperature and air pollutants** • Included children less than 5 years of age****
Hajat et al. (1997)	14.5	• Did not provide gender of participants • Lack of detail on how and where exposure was measured*

		• Included children less than 5 years of age****
Erbas et al. (2012)	14	• Did not provide gender of participants • Lack of detail on how exposure was measured* • Did not model the association between pollen and outcome • Included children less than 5 years of age****
Silver et al. (2018)	15	• Limited power • Included children less than 5 years of age****
Campbell et al. (2019)	14	• Did not provide age & gender of participants • Did not specify where pollen data was obtained from* • Lack of detail on how exposure was measured* • Pollen data did not cover the 14.5-year study period***
Dales et al. (2003)	14.5	• Did not provide age & gender of participants • Use of Rotorod (less sensitive in collecting particles)* • Did not model the association between pollen and outcome

*=measurement bias, **=confounding bias, ***=selection bias, ****= misclassification bias

Table S3. Classification of pollen species based on D’Amato et al. (2007).

Family	Species
Grass	• <i>Secale cereal</i> (rye)
	• <i>Phleum pratense</i> (Timothy)
Tree	• <i>Betula</i> (birch)
	• <i>Tilia</i> (lime)
	• <i>Sambucus</i> (elder)
	• <i>Quercus</i> (oak)
	• <i>Castanea</i> (sweet chestnut)
Weed	• <i>Urticaceae</i> (nettle)
	• <i>Rumex</i> (dock)
	• <i>Plantago</i> (plantain)
	• <i>Ambrosia</i> (ragweed)

References

D'Amato, G., Cecchi, L., Bonini, S., Nunes, C., Annesi-Maesano, I., Behrendt, H., et al., 2007. Allergenic pollen and pollen allergy in Europe. *Allergy* 62(9), 976-990. doi:10.1111/j.1398-9995.2007.01393.x.

Zaza, S., Wright-De Agüero, L. K., Briss, P. A., Truman, B. I., Hopkins, D. P., Hennessy, M. H., et al., 2000. Data collection instrument and procedure for systematic reviews in the Guide to Community Preventive Services. Task Force on Community Preventive Services. *Am. J. Prev. Med.* 18(1 Suppl), 44-74. doi:10.1016/s0749-3797(99)00122-1.