A pilot forecasting system for epidemic thunderstorm asthma in south-eastern Australia

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Abstract

In November 2016, an unprecedented epidemic thunderstorm asthma event in Victoria, Australia, resulted in many thousands of people developing breathing difficulties in a very short period of time, including ten deaths, and created extreme demand across the Victorian health services. To better prepare for future events, a pilot forecasting system for epidemic thunderstorm asthma (ETSA) risk has been developed for Victoria. The system uses a categorical risk-based approach, combining operational forecasting of gusty winds in severe thunderstorms with statistical forecasts of high ambient grass pollen concentrations, which together generate the risk of epidemic thunderstorm asthma. This pilot system provides the first routine daily epidemic thunderstorm asthma risk forecasting service in the world that covers a wide area, and integrates into the health, ambulance and emergency management sector.

Epidemic thunderstorm asthma events have historically occurred infrequently, and no event of similar magnitude has impacted the Victorian health system since. However, during the first three years of the pilot, 2017-2019, two high asthma presentation events and four moderately high asthma presentation events were identified from public hospital emergency department records. The ETSA risk forecasts showed skill in discriminating between days with and without health impacts. However, even with hindsight of the actual weather and airborne grass pollen conditions, some high asthma presentation events occurred in districts that were assessed as low risk for ETSA, indicating the challenge of predicting this unusual phenomenon.

Capsule: A newly developed pilot forecasting system for epidemic thunderstorm asthma is assisting the health sector in Victoria, Australia, to prepare for these rare but potentially deadly events.

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Introduction

Thunderstorm asthma is thought to be triggered by the combination of a high concentration of airborne allergens, such as grass pollen, and a thunderstorm with strong outflows (Marks et al. 2001). When a large number of people develop asthma symptoms over a short period of time as a result of this combined trigger, the term epidemic thunderstorm asthma (ETSA) is often used, particularly in cases where there is a rapid increase in demand for emergency healthcare that overwhelms usual health and emergency services (e.g., Bellomo et al. 1992, Erbas et al. 2012, Guest 2017). Worldwide, at least 22 ETSA events have been reported since 1983, with ten of them occurring in south-eastern Australia during late spring or early summer when the temperate grasses are flowering and there are high levels of airborne grass pollen (Davies et al. 2017). Epidemic thunderstorm asthma has also been reported in the United Kingdom (Dabrera et al. 2013), Europe (D'Amato et al. 2016), the Middle East (Yair et al. 2019, Ali et al. 2019), the United States (Grundstein et al. 2008) and Canada (Dales et al. 2003).

On the evening of 21 November 2016, the greater cities of Melbourne and Geelong in Victoria, Australia experienced an epidemic thunderstorm asthma event which was unprecedented in terms of scale and severity. It resulted in extreme demand across the health service system including 9,909 respiratory-related public hospital emergency department presentations in the 30 hours from 6 pm on 21 November (Guest 2017, Thien et al. 2018). 814 cases were recorded by Ambulance Victoria in the first six hours, with most patients identifying as having a "breathing problem" (Guest 2017). Ten deaths were attributed to this event (Victorian Coroner 2018), an extraordinary toll given that previously only one death in Melbourne and two deaths in the United Kingdom had been noted in the medical literature

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as being associated with a thunderstorm asthma event (Bellomo et al. 1992; Venables et al. 1997; Pulimood et al. 2007).

The spring leading up to the November 2016 event was cooler and wetter than average with relatively lush pasture growth in regional Victoria. November 21 was the first very hot day of the season with northerly winds and temperatures in the mid-high 30's Celsius over most of the state. In the afternoon, a cold front approached Melbourne and the neighboring city of Geelong from the west, generating a north-south line of severe thunderstorms with a pronounced gust front ahead of the storms. Although the thunderstorms themselves dissipated in the western suburbs of Melbourne, the gust front passed over the metropolitan area between about 1700 and 1900 Australian Eastern Daylight Time (AEDT) before decaying to the east of the city (Figure 1). Associated with the passage of the gust front were 10-20 minutes of strong gusty winds with peak speeds ranging from 17-26 m s^{-1}. Extreme grass pollen concentrations exceeding 100 grains per cubic meter of air were measured in Melbourne and Burwood. Further information on this event and its impacts is available in IGEM (2017), Guest (2017) and Thien et al. (2018).

The causal mechanisms for thunderstorm asthma are poorly understood. Its study is hampered by both its rarity and the difficulties in observing the causal chain. Even in south-eastern Australia, a relative "hot spot" for thunderstorm asthma, most thunderstorms occurring during the grass pollen season do not result in ETSA events. In a carefully controlled study using health and weather data, Marks et al. (2001) demonstrated a link between epidemics of asthma and thunderstorm outflows. They proposed that strong gust fronts associated with thunderstorm outflows could collect aeroallergens such as pollen, some of which may be ruptured into tiny allergenic starch granules and concentrate them near ground level where they can be breathed into the lower airways and affect susceptible people. In the

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New South Wales city of Wagga Wagga (population 56,000), ryegrass (*Lolium perenne*) pollen was implicated in a 1997 ETSA event that sent more than 200 people to the emergency department (Girgis et al. 2000, Marks et al. 2001). Other factors, many of which are consistent with thunderstorm outflows, have been proposed to contribute to ETSA including lightning, rapid temperature and moisture changes, and the presence of fungal spores and/or air pollution (for a comprehensive review see Davies et al. 2017).

Predicting the risk of ETSA occurring would be beneficial to the population and health and emergency sectors in those places where it is known to be a risk. Most recently, Silver et al. (2018) tested statistical approaches for predicting the risk of asthma occurrence as a function of weather, pollen, and temporal (season, day of week) data. Although they found asthma to be more likely on days when both thunderstorms and high grass pollen concentrations (daily average >50 grains m^{-3}) occurred, they found little skill in directly predicting thunderstorm asthma events. They noted difficulties in establishing the most appropriate thunderstorm-related indicator. Using the November 2016 Victorian event as a case study, Grundstein et al. (2017) suggested that diagnostics for predicting strong downdraft winds from thermodynamic soundings and numerical model output could assist in predicting enhanced ETSA risk.

The lack of clear understanding of the thunderstorm asthma mechanism has discouraged the development of ETSA early warning or forecasting systems (Dabrera et al. 2013). Newson et al. (1998) argued that the high rate of false alarms would render an early warning system ineffective. The few thunderstorm asthma warnings that do exist are informal and limited in scope. For example, Charles Sturt University in Wagga Wagga, Australia, operates a regional alert service for individuals based on local pollen counts and official thunderstorm warnings (CSU 2017). In the United Kingdom the Met Office and Public Health

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England confer on whether to issue advice to the health community when there could be an elevated risk of thunderstorm asthma (Y. Clewlow, personal communication). In neither case, however, have the protocols been published or evaluated in the literature.

Following the November 2016 ETSA event, the Victorian Department of Health and Human Services (DHHS) commissioned the Bureau of Meteorology (BoM) and research partners to develop a pilot ETSA forecasting system that would cover the entire population of the state. The primary aim of the forecast was to identify and be prepared for any subsequent ETSA events where health and ambulance services may be unable to meet demands, and patient care put in jeopardy. This was part of a broad public health response led by the DHHS to mitigate future epidemic thunderstorm asthma events through improved preparedness and response arrangements. Other components include enhanced monitoring and early detection capacity (such as real-time monitoring of emergency department presentations), improved communication and coordination within the health and emergency management sectors and public awareness and education programs (IGEM 2017, 2018).

The pilot ETSA forecasting system is based on forecasting a combination of gusty thunderstorm outflows and high ambient grass pollen concentrations, supported by data from an expanded pollen monitoring network. During the springtime grass pollen season in Victoria (October to December), BoM meteorologists examine forecasts for weather and pollen conditions and provide ETSA risk forecasts to DHHS for the current day and next two days. This allows DHHS to alert the community and the health and emergency response sectors to increased risks of this phenomenon so that they can appropriately prepare.

The pilot ETSA forecasting system commenced on 1 October 2017 and has now been running for 3 consecutive years. It is the first routine daily epidemic thunderstorm asthma risk forecast in the world that covers a wide area (Victoria, more than 200,000 km^2) (Kornei 2018),

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and remarkable for being developed and implemented in less than one year. It is one example of the type of impact-based early warning services that national meteorological services are developing to better communicate threat to partners and the community.

Foundation for an epidemic thunderstorm asthma risk matrix

Given tight time frames and scientific uncertainty concerning the processes linking thunderstorms, grass pollen, and epidemic thunderstorm asthma events, we chose to adopt a relatively simple forecasting approach. Daily forecasts for low, moderate, or high ETSA risk are made for each of the BoM's nine Victorian forecast districts (Figure 2) using a matrix approach that combines weather and grass pollen concentration. The decision to issue daily forecasts for districts is consistent with BoM's current thunderstorm forecast services.

An early task was to examine meteorological, environmental (grass pollen) and health data together to choose appropriate weather variables for the ETSA risk matrix. Following the methodology of Silver et al. (2018), using emergency department presentation data from October-December 1999-2016 from the Victorian Emergency Minimum Dataset (VEMD), seventeen days were identified for which the number of asthma presentations (identified using codes for 'asthma' and 'asthma, childhood') at one or more public hospitals in Melbourne and regional Victoria was at least 4.5 standard deviations (SD) more than the expected hospital daily average during October-December 1999-2015. 2016 was deliberately excluded since the 21 November event was an extreme outlier. Although pollen was not explicitly considered, these high asthma presentation days (HAPD) represent unusually high presentations of asthma, potentially related to environmental triggers such as high ambient grass pollen and thunderstorm activity. As such, HAPD were considered "event days" for the purposes of developing the matrix, even though they did not result in health and emergency

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services becoming overwhelmed due to sudden increased demand. Eight additional Melbourne days that had extreme grass pollen concentrations (daily mean >100 grains m^{-3}) but did not trigger the 4.5 SD asthma presentation threshold were used as a non-event dataset.

We analyzed both event and non-event days for common weather patterns using radar, lightning, automatic weather station (AWS) and air quality (particulates and ozone) observations, and to identify any consistent differences between events and non-events. Interestingly, four Melbourne HAPD showed no indication of the presence of thunderstorms (no lightning was observed). However, all HAPD for the Melbourne area contained visible convergence lines on the Melbourne radar data, identified as lines of enhanced radar returns from insects concentrated along the boundaries between winds of different directions. We also identified convergence lines for some of the regional HAPD, though the lack of adequate radar coverage or corroborating weather observations for all sites meant it was not possible to confirm convergence lines for all of those days. Six of the eight non-events had some indication of convergence lines, with two also having indications of thunderstorm activity. Air quality did not differ significantly between the two samples. Therefore, this first analysis of the data could find no conclusive difference in the weather trigger between events and non-events.

With a forecast service delivery date fast approaching, our best working hypothesis (similar to Marks et al. 2001) was that the convergence lines were a plausible mechanism to concentrate pollen and pollen fragments to increase the likelihood of ETSA occurrence. Indeed, a recent case-control study of convergence lines identified on radar imagery and asthma presentation data at Melbourne hospitals provides strong evidence for this hypothesis (Bannister et al. 2020). Also, a higher concentration of airborne grass pollen would

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likely be associated with an increased allergen concentration in these convergence lines. Lastly, the intensity or strength of these convergence lines, to a first approximation, can be linked to the strength of wind gusts associated with outflows from thunderstorms, showers and rain bands, or associated with other convergence line mechanisms such as cold fronts and sea breezes.

On the basis of these preliminary analyses, we developed the ETSA risk matrix shown in Figure 3. This risk matrix is based on a combination of forecasts for damaging wind gusts (generating convergence) and categories used in Australia for grass pollen severity (Ong et al. 1995; Table 1). The risk of epidemic thunderstorm asthma is considered "high" when forecasts for severe wind gusts of at least 25 ms^{-1} occur in combination with forecasts of high or extreme daily grass pollen concentrations. The gust threshold is identical to that used for issuing operational severe thunderstorm warnings at the Bureau of Meteorology (BoM 2020) and was pragmatically chosen. Two diagnostics derived from numerical weather prediction (NWP) output, namely the squall line potential (based on the derecho composite parameter of Coniglio et al. 2005) and the instantaneous contraction rate (ICON; Cohen and Schultz, 2005) provide extra guidance for predicting damaging winds. The lower thresholds for the medium weather category were estimated by experienced meteorologists.

Mechanisms that have been proposed for the rupture of pollen grains into respirable starch granules include osmotic shock (Suphioglu et al. 1992, Knox 1993), lightning (Newson et al. 1998), and wind-driven mechanical rupture (Visez et al. 2015). We did not include a mechanism for grass pollen rupture and release of allergenic starch granules, which cannot be easily measured, but rather assumed that high concentrations of ruptured pollen were unlikely to occur in the absence of high ambient concentrations of whole pollen grains. Given

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these events are infrequent, we did not attempt to quantify the ETSA risk levels; they are treated as relative rather than absolute.

Before system launch, we tested the matrix thresholds by hindcasting ETSA risk in the Central district (which includes Melbourne and Geelong) during 2006-2016. This process used the actual BoM thunderstorm forecasts issued during that period and recorded Melbourne grass pollen counts to represent Central district pollen forecasts.

During 2006-2016 there were eleven HAPDs in Melbourne (three of which have been documented in the academic literature or media as epidemic thunderstorm asthma events – the 2016 event, which caused widespread health and emergency services impacts, and two which did not overwhelm usual health and emergency services capability). According to the risk matrix the forecasts would have produced six next-day high ETSA risk alerts and 13 current-day high ETSA risk alerts (Table 2). Alerts would have been made for almost half of the ETSA events in the morning, but fewer than one fifth of the events would have had a full day of advanced warning. Around two thirds of ETSA high risk forecasts would have been false alarms (i.e. alert issued but no event occurred), and had they occurred during the pilot would likely have triggered further action by DHHS (see sidebar).

To put these results into context, the assessed ETSA forecast performance was similar to that of the BoM's severe thunderstorm warnings for Melbourne. These are optimistic figures (small sample size notwithstanding) since the forecasts assumed perfect knowledge of grass pollen conditions. Importantly, for the next-day and current-day forecast ranges, the 21 November 2016 event would have been successfully forecast with these thresholds.

Based on these initial results, we deemed the ETSA risk matrix approach to be suitable for use in the pilot starting in October 2017. The matrix was reviewed at the end of each

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pollen season and, in the absence of any compelling reason to change the approach or the thresholds, it has continued as the basis for ETSA risk forecasting.

In the absence of operational pollen forecasts, our initial concept was to use a persistence or human generated pollen forecast. However, at that point pollen monitoring had only been undertaken in Melbourne and Geelong, and there was no guarantee that the grass pollen levels in these areas would be applicable across Victoria. Therefore, a statistical model was developed from historical data that could predict the mean daily grass pollen concentrations on a regular latitude-longitude grid across south-eastern Australia, thus providing full coverage for Victoria.

The statistical model uses regression equations based on meteorological variables, grassland growth phase estimated from the satellite-derived enhanced vegetation index (EVI; Huete et al. 2002), and land-use parameters to model both the day-to-day variation and year-to-year variation of grass pollen concentration (Emmerson et al. 2019, Silver et al. 2020a). The statistical pollen model is briefly described in the Appendix, along with information on the new pollen monitoring capability that was implemented in Victoria to support the pilot ETSA forecast system.

The ETSA forecasting system in operation

Figure 4 summarizes the processes and data flows comprising the pilot ETSA forecasting system. Each morning, operational meteorologists at the BoM prepare and issue forecasts of ETSA risk for the remainder of the day, then in the afternoon they prepare and issue forecasts for the next two days. All ETSA risk advice is provided directly to DHHS for dissemination and possible action. In the case of rapidly developing severe weather where no

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high ETSA risk has been forecast, the BoM meteorologist contacts DHHS to inform decisions around issuing advice and warnings.

[Insert sidebar near here]

The weather component of the ETSA risk matrix follows standard operational practice for severe thunderstorm forecasting, with additional scrutiny for convergence lines and damaging winds associated with other mesoscale or synoptic scale weather. For the longer lead times the timing and extent of likely severe thunderstorms with damaging winds are assessed from the thunderstorm environment in medium-range NWP output using diagnostics such as downward convective available potential energy (DCAPE) and squall line potential. At shorter lead times high resolution (1.5 km) output from the Australian Community Climate and Earth System Simulator (ACCESS; Puri et al. 2013) NWP model provides more explicit information on storm characteristics, and meteorologists continually monitor observations from surface networks, soundings, radar and satellite for storm set-up, initiation and evolution.

The grass pollen forecasts required by the ETSA risk matrix are automatically generated using the statistical pollen model (see Appendix). Meteorologists, in consultation with the project team, could override the pollen forecast if they believed it was erroneous based on the trend of recent pollen measurements, but in practice they almost always used the automatic grass pollen forecast.

Given the novelty of the ETSA forecast, mitigating a false negative (missed event) was important. In the first year of operation, 2017, a forecast of moderate risk led to some scaling up of the health/emergency system and public communications in case it had identified an

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event. As we gained experience and as the health promotion and system changes in the health/emergency sector became better established, the response to a forecast of moderate risks was adjusted to a "heads up" position with good situational awareness across the sector and community. Formal scaling up was reserved for forecasts of high ETSA risk.

Evaluation of ETSA forecasts during 2017-2019

ETSA events are difficult to accurately measure, so we use the number of asthma presentations at public hospital emergency departments as an indicator for the health outcome. There are several challenges with this approach. Public hospitals represent only part of the health system, and emergency department presentations reflect only the most severely affected patients, with many patients instead seeking help from family doctors, local clinics and pharmacies. Although we do not know the actual number of affected individuals, the HAPD (at least 4.5 SD above expected asthma presentation levels for the 24 hour period from noon on the day of interest until noon the following day) should give the timing of possible ETSA events during the grass pollen season. "HAPD events" were those days or sequences of days (acknowledging some patients may delay presenting to hospital) for which HAPD occurred for a cluster of at least three public hospital emergency departments.

In keeping with the 1999-2016 rate of HAPDs during the grass pollen season, over the first three years of the pilot there were two HAPD events in Victoria. On both occasions, forecasts of at least moderate ETSA risk were issued.

The first HAPD event occurred on 15-16 November 2017 when two public hospitals in western Victoria and four in the Melbourne area reported much higher than expected numbers of asthma presentations (total of 54 asthma presentations compared to an expected

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7.4). One of the authors (JD) experienced asthma symptoms first-hand while visiting the Hamilton pollen monitoring site.

To illustrate the forecast process, Table 3 and Table 4 give the day 2 (two days ahead), day 1 (next day) and day 0 (current day) grass pollen and ETSA risk forecasts, respectively, valid on 15 November 2017. Two days ahead of time, extreme grass pollen concentrations were forecast throughout most of Victoria (Table 3). The forecaster judged that there was sufficient chance of thunderstorms meeting the medium weather category of the ETSA risk matrix to indicate moderate ETSA risk for five districts on day 2 (Table 4).

On the following day, the statistical pollen model continued to predict high to extreme grass pollen concentrations over most of Victoria. The corresponding thunderstorm forecast indicated possible severe thunderstorms in the west and southeast (Figure 5), and possible (non-severe) thunderstorms elsewhere. Meteorologists assigned a next-day forecast of moderate ETSA risk to most districts.

On the morning of 15 November, the updated ETSA risk remained the same, even though the thunderstorm risk had increased (Figure 5). This is because meteorologists considered it unlikely that the wind gusts would exceed severe thresholds (25 m s^{-1} for gusts) in those storms.

Analysis of the radar data showed a convergence line moving northwards through the whole of the Melbourne area during the afternoon. As the convergence line moved through the eastern suburbs, thunderstorms developed in the same area and moved down to the south. Other thunderstorms then developed to the north of Melbourne and moved southwards over the eastern suburbs (Figure 6). Maximum reported gusts in the Central district ranged from 10 to 20 m s^{-1} while daily average grass pollen measurements made at the four sites in the district ranged from 62 to 172 grains m^{-3}, suggesting that a forecast of

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moderate ETSA risk was warranted. At Hamilton, wind gusts did not exceed 16 m s^{-1} but the daily average grass pollen concentration was extremely high, 385 grains m^{-3}. This was the third highest grass pollen reading in Victoria during 2017-2019 and likely helped drive the spike in asthma presentations at hospitals in the western part of the state.

The second HAPD event on 25 November 2017 produced significant spikes in asthma presentations at four public hospitals, two in South West District and two in Central District, and is only briefly described here. The ETSA risk was forecast as moderate on day 2, low on day 1, and moderate on day 0. Severe thunderstorms affected both districts, including a squall line that passed through Central District in the late afternoon. The observed and forecast daily mean grass pollen concentrations were moderate to high and followed a few days with extreme grass pollen levels in western Victoria. High ETSA risk was erroneously forecasted for North Central district (due to human error) instead of South West district. In contrast to the 15-16 November 2017 case which featured extreme grass pollen concentrations, this HAPD event had somewhat lower pollen concentrations but a much stronger weather signal.

It is not possible to conclude very much about the performance of the forecasting system based on only two HAPD events. To increase the sample size, we lowered the health criterion to 3 SD over the expected daily hospital emergency department presentations, denoting these days as moderate asthma presentation days (MAPD). Again requiring at least three Victorian hospitals to reach this threshold on the same day, four additional MAPD events were identified on 29 October 2017, 20 November 2018, 30 October-2 November 2019 and 21 November 2019.

During 2017-2019 there were a total of 27 affected districts with MAPD and HAPD events, with eight out of the nine Victorian forecast districts affected at least once. Table 5 shows the distribution of low, moderate and high ETSA risk forecasts given that MAPD and

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HAPD events occurred. For the HAPD events (left side of Table 5) the forecasts were moderate or greater more often than not, while for both MAPD and HAPD events, forecasts of elevated risk occurred about a third of the time.

If we require five Victorian hospitals instead of three in order to count a HAPD (MAPD) as an event, then the HAPD results in Table 5 remain unchanged while the number of affected districts with MAPD is halved. However, the relative proportion of moderate forecasts for MAPD increases by 14% on day 0, signaling improved performance for bigger events. Conversely, removing the requirement for multiple hospitals increased the sample size but degraded the forecast performance.

To get a crude estimate of the likelihood of a MAPD or HAPD event that would be associated with each ETSA risk category we divide the values in Table 5 by the number of forecasts made for each risk category. The resulting estimates in Table 6 have extremely large uncertainties but nevertheless suggest a monotonic progression in quantitative ETSA risk from low (~1%) to moderate (~10%) to high (~20%), indicating that the ETSA risk forecasts behave as expected.

The false alarm ratio (FAR) of 80% (four out of five high risk forecasts were not associated with an event) is higher than the pre-pilot estimate (Table 2) and is comparable to values for tornado forecasts in the United States (Anderson-Frey et al. 2019). Concerns about false alarms include warning fatigue, cost for agencies, opportunity costs and loss in credibility, reducing the benefits of providing a warning. However, as discussed by Barnes et al. (2007) a high FAR may not reflect the value of the forecasts to the public who are tolerant to false alarms in warning systems. In this case a conservative system allows implementation of preparedness measures while waiting for additional evidence of high ETSA risk from

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weather observations and real-time monitoring of emergency department presentations and ambulance calls.

It is tempting to interpret the low ETSA risk forecasts in Table 5 as missed events, as no decision to warn the community would have been made based on those forecasts. This leads us to question to what extent these apparent missed events could be related to poor forecasting of the ETSA risk, and how "perfect" forecasts of ETSA risk (assessed from observed conditions) would have corresponded to the observed health outcomes.

To answer these questions, we first estimated the assessed ETSA risk category based on the observed weather and pollen conditions (c.f. Figure 3). Because grass pollen is only measured in four of the forecast districts (Figure 2) this ETSA hazard evaluation could only be completed in those districts. Central district contains the cities of Melbourne and Geelong and is the area of greatest concern in terms of population exposure, together housing over 80% of Victoria's population. With four pollen monitoring sites located in this district the average value should be a reasonable estimate of the Central district pollen conditions. There is greater uncertainty in the observed pollen category in the other three districts. The density of pollen monitoring sites within Victorian districts is sparse compared with Europe, North America and East Asia (Buters et al. 2018).

Victoria's storm spotter network is also sparse. To diagnose the weather category, we instead used the operational severe weather warnings for severe thunderstorms with damaging winds affecting at least one third of the district that were issued by the meteorologist based on expert interpretation of radar, satellite and AWS observations. In addition to the severe thunderstorm warning, at least one AWS gust measurement exceeding the threshold of 25 m s^{-1} for the highest weather category (or 18 m s^{-1} for the medium weather

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category) was required to confirm the weather rating. In the absence of a thunderstorm, a gust measurement in the district of at least 25 m s^{-1} indicated a medium weather rating.

During 2017-2019 there were a total of 1088 assessments of low, moderate and high ETSA risk in the four districts, with only 13 assessed as moderate risk and 5 assessed as high risk using this approach (Table 7). Five districts experienced HAPDs (i.e., the two November 2017 events described earlier), and a further 11 districts experienced MAPDs. Of the 16 HAPDs and MAPD districts, elevated ETSA risk was assessed from weather and pollen observations for five of those districts. This ratio of 5/16 is broadly consistent with Marks et al. (2001), who detected thunderstorm outflows in nearby AWS data on 48% of asthma epidemic days in late spring and summer. It also supports the finding of Bannister et al. (2020) that thunderstorms, *per se*, may not be required in order to produce epidemic asthma during the grass pollen season if convergence lines are present. Other factors such as time of day, population composition and density, and the presence of other environmental triggers for asthma may also play a role (Thien et al. 2017, Davies et al. 2017).

Notably, 13 out of 18 assessments of elevated ETSA risk were not associated with spikes in asthma presentations, indicating that even when the environmental conditions appear right for epidemic thunderstorm asthma it may not occur. We speculate this may be because sufficient concentrations of broken pollen grains (releasing respirable allergenic starch granules) were not present to cause significant health impacts. The quantitative risk values associated with each ETSA risk category are higher for the assessment than for the forecasts in Table 6, as would be expected, but these values cannot be taken at face value due to the extremely small sample size.

To gain further insight on how to improve the forecasts, we compare the forecast ETSA risk to the assessed ETSA risk, which is our best estimate of the actual risk on a given day.

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Contingency tables of forecast versus assessed ETSA risk for day 0, day 1 and day 2 forecasts (Table 8) shows that forecasts of moderate risk were significantly over-predicted at all lead times, while there were too few forecasts of high risk. Further examination revealed that the most common source of error was overestimation of the forecast weather category, reflecting both a conservative approach for severe thunderstorm forecasting and the sparsity of severe wind gust observations.

The forecasts were skillful according to the 3-category Gerrity score (GS) which rewards rare but correct (or close) forecasts and penalizes large categorical errors (Gandin and Murphy 1992, Jolliffe and Stephenson 2012). The GS has not been used very widely; to put these values into some context, Tam and Wong (2017) reported GS values of 0.27-0.56 for 4-category forecasts of sky cover over Hong Kong from the ECMWF Ensemble Prediction System. Even though Table 8 shows no correct high risk forecasts, the GS values of 0.27 (day 2) to 0.36 (day 0) reflect the ability to predict moderate risk when moderate or high risk occurs (rarely).

Based on the 2017-2019 evaluation it may be possible to tune the categorical thresholds to improve the future forecast performance. Many more cases will be required before we can reliably assign probabilities to the categorical risk forecasts.

Conclusions

The pilot Victorian epidemic thunderstorm asthma forecasting system was developed through an inter-sector partnership between state and federal governments and academia, and rapidly implemented in response to needs identified following the catastrophic ETSA event of November 2016. It exemplifies the recent rise of impact-based meteorological services relevant to the health sector, which also include forecasts for heatwaves, smoke,

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dust and ultraviolet radiation. The simple forecast framework could be adapted for use in other parts of the world, or for other combinations of weather and environmental hazards such as heat and air pollution.

Emerging hazard forecasts normally take decades to develop (e.g., Lechner et al. 2017, Sills and Joe 2019), and it is encouraging that these early results show significant skill for an uncommon hazard. As a pilot, the epidemic thunderstorm asthma forecasting system is part of an overall strategy in Victoria that includes strengthened health emergency preparedness and response arrangements, improved real-time monitoring and early detection, improved health emergency warning processes, and public health awareness and education programs for health professionals and communities (IGEM 2018). The forecasting system provides prompts for behavior change in susceptible individuals and an early warning system for the health sector, especially ambulance services, to have the capacity to scale up if required.

The forecast matrix approach, though relatively simple to implement and consistent with the Bureau of Meteorology's existing severe thunderstorm warning process, requires up to an hour per day of manual effort for a meteorologist. As NWP continues to improve, particularly in its representation of thunderstorms, it may be possible to automate the weather-related risk categorization for some lead times as suggested by Grundstein et al. (2017). Meteorological expertise and oversight will still be valuable as storms develop and propagate and convergence lines have the potential to interact with high grass pollen concentrations to enhance the risk of thunderstorm asthma.

The statistical pollen forecasts have improved with time but are specific to Victoria and southeastern Australia and there is limited scope for improvement using a statistical approach. Our recent research to improve ETSA forecasting is focusing on improving grass pollen forecasts through better knowledge of vegetation state (Tran et al. 2020), and

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implementing this new knowledge in pollen emission and dispersion forecasting to provide physically-based forecasts with higher temporal and spatial resolution (Emmerson et al. 2019). This offers the possibility to make hourly or finer forecasts for ETSA risk that combine diurnally and spatially varying pollen forecasts with observations and forecasts of convergence lines. Crowd-sourced allergic rhinitis symptoms also have potential to contribute to real-time pollen forecasts (e.g. Silver et al. 2020b).

Pollen rupture into respirable allergenic starch granules remains an intriguing and difficult part of the overall picture. The most accepted hypothesis is rupture results from osmotic shock in conditions of high humidity (Suphioglu et al. 1992). New laboratory work may clarify details of some of the rupture mechanisms. Emmerson et al. (2020) recently tested several proposed pollen rupture mechanisms including humidity, lightning, and wind friction in a pollen emission and dispersion model and found that no single rupture mechanism could explain the severity of health impacts in the November 21, 2016 thunderstorm asthma event in Melbourne. Validating model forecasts of ruptured pollen is difficult as measuring the concentrations of specific allergens in the air is a time-consuming and costly process (Buters et al. 2015) and unlikely to be widely possible any time soon.

The role of other allergens and irritants such as fungal spores, ozone and aerosol particles in thunderstorm asthma remains an open question. Identifying the "smoking gun" that is responsible for epidemic thunderstorm asthma is a continuing challenge.

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Data availability statement

The meteorological data, severe thunderstorm warnings and pilot ETSA forecasts used in this study are stored in the operational archives of the Bureau of Meteorology accessible to BoM staff. The grass pollen counts and forecasts are stored in the restricted access online

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aerobiology platform (http://portal.pollenforecast.com.au/) described in the Appendix. Due to ethical concerns the health data cannot be made publicly available.

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Appendix. Pollen monitoring and prediction

Since the presence of allergenic particles (normally pollen) in the air is a necessary ingredient for thunderstorm asthma, it is crucial to accurately monitor and predict pollen levels. Here we briefly describe the methodologies used to support the pilot ETSA forecasting system.

Pollen counting

Pollen is collected using a continuous flow volumetric impaction air sampler such as the Burkard Spore Trap shown in Figure 7. Air is drawn in at a constant rate where pollen and other particles impact onto a microscope slide with Sylgard adhesive beneath the orifice. This slide is changed daily, stained with fuchsin and examined under a microscope to manually identify and count pollen grains to estimate the ambient pollen concentration in grains per cubic meter of air. This practice is known as "pollen counting"; further details of best practice pollen counting are given by Beggs et al. (2018).

Pollen counting is generally done by university research teams rather than meteorological services or other operational agencies. Automatic pollen counting instrumentation is being developed and tested overseas (e.g. Crouzy et al. 2016) but is currently very expensive and not yet tested for use in Australia.

VicTAPS network

Scientists at The University of Melbourne (UoM) in Parkville have measured the concentration of grass and other pollens during the grass pollen season of October-December for more than 20 years, while Deakin University scientists at Burwood and Geelong have routinely measured pollen for the last 7 years. However, these three sites cannot provide sufficient information on the spatial variability of the grass pollen concentration across the

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state of Victoria, which is needed for monitoring ambient pollen concentrations and providing reference data to verify pollen forecasts.

To better understand sources and transport of airborne pollen, we established five new pollen monitoring sites in regional Victoria in September 2017 to augment the existing urban sites in Parkville (Melbourne), Burwood, and Geelong. With support from DHHS, The University of Melbourne purchased and installed Burkard spore traps at university campuses in Dookie, Bendigo, Creswick Churchill and a hospital in Hamilton, where facilities for slide counting and data transmission were available. The expanded network (Figure 2) is called the Victorian Thunderstorm Asthma Pollen Surveillance (VicTAPS) network. Pollen counters at the new monitoring sites received pre-season and in-season refresher training onsite from experts, supplemented by an online training module. The pollen counters were also trained in making manual ("curated") forecasts of pollen concentration based on recent measurements, modelled pollen and weather forecasts. In addition, the sites were audited annually during 2017-2019 to ensure quality control and consistency between all sites.

Near real-time surveillance measurements and forecasts of grass and total pollen concentration (grains m^{-3}) are made each morning at 9 am during pollen season. This information is sent by 10:30 am each morning to the UoM Aerobiology Platform (described below) and to the BoM's forecasters to assist them in ETSA risk forecasting. Partner websites at UoM and Deakin University (Melbourne Pollen 2020, Deakin AIRwatch 2020) display the pollen categories (low to extreme) to the public.

Quality assurance

To help assure the quality of the pollen counts, a new Australian Airborne Pollen and Spore Monitoring Network Interim Standard and Protocols was established (Beggs et al. 2018), reflecting to a large extent best practice in pollen counting described in the European

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and US protocols (e.g. European Committee for Standardization 2015). A simpler grass pollen surveillance standard was adapted from the Australian Standard for use in the VicTAPS network (Jones et al. 2017). The main differences are that the surveillance standard requires only grass and total pollen to be counted (as opposed to a variety of pollen taxa) and two transects of the slide (as opposed to four) are sampled to speed the counting process.

Since pollen counters at the new sites were still gaining experience and the grass pollen surveillance standard calls for reduced sampling, a second "quality assurance" count of all slides was conducted at the end of the week by experienced University of Melbourne and Deakin University scientists following the new Australian Standard. These quality assured (L2) values were available a week or two post real-time for use in verifying pollen forecasts and other scientific purposes. For all seasons, the correlation between the surveillance (L1) and quality assured (L2) time series ranged between 0.6 and 0.9 at many sites but there was a tendency for the L1 counts to underestimate the actual counts by about 20-30%. This means that the near real-time data capture the temporal behavior of the ambient pollen concentration, which is important for monitoring purposes, but the values have substantial uncertainty and may be biased low.

Further, during each pollen season an external audit was conducted by Queensland University of Technology at all VicTAPS sites to check adherence to standard pollen counting procedures and safety procedures. The audit recommended actions to improve processes and enhance consistency of the VicTAPS pollen monitoring. As pollen counters became more experienced as a result of the audits and ongoing refresher training, the overall accuracy of L1 pollen counts improved from 2017 to 2019.

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Aerobiology Platform

An online portal (http://portal.pollenforecast.com.au/) was developed at UoM to allow password-protected submission of pollen count and forecast data from the VicTAPS sites and statistical pollen forecasts generated in parallel by UoM and BoM. It also includes several useful analysis functions including comparison of L1 and L2 pollen counts, verification of the pollen forecasts at VicTAPS sites, and display of pollen and ETSA risk forecasts. The portal has been enhanced each year to better integrate the data submission, analysis and reporting functions and add new functionality. It has become an extremely useful resource for the Australian pollen community.

During the pollen season we consulted the Aerobiology Platform routinely. Being able to quickly see how the pollen forecasts were performing against pollen measurements added to the meteorologists' and other partners' confidence in using them to make real-time decisions about epidemic thunderstorm asthma risk.

Statistical pollen modelling

Pollen forecasts are typically based on persistence of the most recent pollen observations or simple meteorological typing methods (e.g. Schäppi et al. 1998, Met Office 2020). In some countries and regions, dynamical pollen forecasts are produced using pollen emission and dispersion modelling; examples include the System for Integrated modeLling of Atmospheric coMposition (SILAM) in Europe (Sofiev et al. 2013) and the Community Multiscale Air Quality (CMAQ)-pollen modelling system in the United States (Efstathiou et al. 2011).

At the time of the November 2016 ETSA event, scientists at UoM and Deakin University had been making daily pollen measurements and forecasts for three urban locations for some

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years using simple manual forecasting methods (Melbourne Pollen 2020, Deakin AIRwatch 2020). Even after augmenting the Victorian pollen monitoring network it was still not sufficiently dense to provide the desired spatial coverage for the whole state. Neither was it possible to develop dynamical pollen modelling capability in time for the start of the pilot ETSA forecast service. Therefore, a statistical model was developed to estimate mean daily (9 am to 9 am) grass pollen concentrations from gridded weather and environmental data to provide full coverage for Victoria (Emmerson et al. 2019, Silver et al. 2020a).

The model consists of two components: a 'seasonal' or 'phenology' term (representing a smooth rise and fall in the grass pollen) and a daily modulation around this term. The latter of these, representing day-to-day variation, used a long time series of pollen data from Melbourne during October-December 2000-2016 to develop the regression relationship for daily mean grass pollen concentration (the predictand). Independent predictors that were tested included meteorological variables measured at Melbourne Airport (temperature, wind speed and direction, relative humidity, and precipitation), a variety of drought indices, fractional coverage of pasture grass (sourced from Australian Land Use and Management Classification Version 7) in the upwind direction, and phenological information describing the pollen season. The previous day's grass pollen count was not included as this information would only be available at a small number of point locations and therefore could not be applied generally.

The model was built up incrementally using forward stepwise variable selection, following a resampling strategy so that the skill of the model was assessed on data not used to fit the model, and ceasing when adding further variables produced negligible gain. The model used generalized additive models (Wood 2006) to allow for non-linear influences of the predictor variables on the response variables. The two variables contributing most to the

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day-to-day variation were the phenology term (described below) and the mean daily surface air temperature, with lesser dependence on rainfall, relative humidity, and the fractional coverage of pasture grass in the upwind direction.

The phenology term is a smooth function of time, approximately following a Gaussian distribution, which at a given location is defined by the timing and magnitude of the peak of the pollen season. Fitting the seasonal time series from seventeen years of pollen data at Melbourne, Silver et al. (2020a) found the duration of the pollen season did not vary significantly from year to year and a Gaussian distribution with a standard deviation of 19 days could approximate the temporal evolution of the pollen. Sample phenology terms for two different pollen seasons are illustrated in Figure 8.

The onset of the release of pollen from pasturelands depends on its growth phase, which can be estimated from space (Devadas et al. 2018). The spatially varying timing and magnitude of the grass pollen season was modelled as a function of the satellite-derived enhanced vegetation index (EVI), a measure of the “greenness” of the landscape (Huete et al. 2002; NASA 2020). Using time series of co-located EVI data and daily grass pollen data from Melbourne (2000-2016), Wagga Wagga (2008, 2010-2016) and Canberra (2007-2009), linear models for the magnitude and timing of the peak in the pollen season were estimated, respectively, from the wintertime maximum EVI and the day-of-year when the EVI dropped a fixed amount (0.05) below its wintertime maximum, signifying drying off (refer to Silver et al. (2020a) for details).

For routine forecasting, the statistical pollen model uses three-day forecasts of temperature, wind, rainfall and humidity on a 0.11^{0} latitude-longitude grid from the 1800 UTC run of the regional model, ACCESS-R. The previous day's rainfall is sourced from an earlier model run. To estimate the phenology term, the 500m resolution MODIS Terra EVI product

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MOD13A1 (V006) is supplemented with the near real-time MODIS Terra EVI data (MOD13A4N V006), which provides daily updates of EVI from a backward-looking 8-day window.

We judged the performance of the statistical pollen model to be of sufficient quality for adoption in the ETSA risk matrix and it was implemented at BoM in time for the start of the 2017 pollen season on the first of October. At the end of each year the model was retuned, incorporating the additional grass pollen measurements from the VicTAPS network. The accuracy of the pollen forecasts affects the accuracy of the ETSA risk forecasts and was scrutinized regularly during the pollen seasons.

The model captured the time-varying behavior of the observed pollen concentration, with a median temporal correlation for all sites and years of 0.53. Figure 9 shows time series of observed and next-day forecast grass pollen at two locations from the versions of the statistical model that were in use during 2017, 2018 and 2019. In Hamilton, the westernmost monitoring site, the early season overestimation seen in 2017 was improved in subsequent years after retuning the model to include the previous year's VicTAPS data. The performance of the statistical model did not decrease much for longer lead times (not shown). This is likely because the main drivers of day-to-day variability in the model are the phenological and temperature terms; the former of these varies only slowly with time and the latter is generally well forecast by modern NWP systems.

Figure 10 shows the performance for next-day categorical forecasts of high to extreme grass pollen concentration at monitoring sites. The median probability of detection (POD) was better than 0.5 and false alarm ratio (FAR) lower than 0.4, with considerable variation in skill between sites and years. 2018 was a dry year with lower grass pollen concentrations measured at most sites, making the grass pollen signal harder to predict. The urban sites tended to have a lower POD than the rural locations. The performance of the statistical grass

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pollen model is similar to that of numerical predictions of ragweed and birch pollen in Europe (Zink et al. 2017, Siljamo et al. 2013).

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Sidebar

Communication of epidemic thunderstorm asthma risk

In Australia state government departments and agencies are responsible for providing information and warnings to the public of potential environmental health risks. In Victoria, since 1 October 2017, the public can view ETSA risk forecasts during the grass pollen season on the Vic Emergency website (https://emergency.vic.gov.au/prepare/#thunderstorm-asthma-forecast) and app. An example is shown in Figure 11 for 26 November 2017 showing moderate ETSA risk in three forecast districts and low ETSA risk elsewhere. Clicking on the district pops up additional information about the forecast. The public can also set up a 'watch zone' for their location through the Vic Emergency platform to receive automatic alerts on days of high ETSA risk, and warnings about potential or emerging ETSA events should they occur.

The development of the ETSA forecast forms part of wider program which aims to minimize the impact that any future epidemic thunderstorm asthma events may have on the community and the Victorian health system. The forecasting system enables health and emergency services to be suitably prepared on days of increased risk. It concurrently raises community awareness so that those at increased risk can take action to reduce their exposure, such as

- avoid exposure to any storms that may emerge, especially the wind gusts that precede them,
- have a reliever appropriately available,

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- remind themselves of their asthma action plan and have practical knowledge of asthma first aid

(State of Victoria, 2017).

The forecasting system supports a coordinated public health campaign and education program to raise awareness amongst the community and health professionals about epidemic thunderstorm asthma, and the steps that can be taken to reduce potential health impacts. The public health campaign and education program has a primary focus on good asthma and hay fever management, and to date has included digital communications (e.g., Figure 12), publications and resources (including updated clinical guidelines for health professionals), media and community events, and broader stakeholder engagement.

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Tables

Table 1. Average daily grass pollen levels and corresponding concentrations (Ong et al. 1995).

Grass pollen level	Grass pollen concentration range (grains m^{-3})
Low	0-19
Moderate	20-49
High	50-99
Extreme	100+

Table 2. Categorical performance of hindcasts for high ETSA risk for the Central district during 2006 to 2016.

	Current day	Next day
Total number of HAPDs (known or possible ETSA events)	11	11
Total number of ETSA forecasts for high risk (alerts)	13	6
Alerts warranted (event occurred)	5	2
False alarms (alert issued but event did not occur)	8	4
Probability of detection (alerts warranted / total events)	0.45	0.18
False alarm ratio (false alarms / total forecasts)	0.62	0.67

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Table 3. Forecast grass pollen category (daily mean pollen concentration in grains m^{-3}) valid on 15 November 2017 at lead times of 2, 1, and 0 days.

District	Day 2	Day 1	Day 0
Mallee	Moderate (38)	Moderate (35)	Low (16)
Wimmera	Extreme (103)	High (95)	Moderate (32)
Northern Country	Extreme (108)	High (87)	High (60)
North Central	Extreme (127)	Extreme (103)	High (76)
North East	Extreme (129)	Extreme (106)	High (65)
South West	Extreme (182)	Extreme (174)	Extreme (104)
Central	Extreme (121)	Extreme (131)	High (86)
West & South Gippsland	Extreme (119)	Extreme (141)	High (76)
East Gippsland	Moderate (45)	High (52)	Moderate (23)

Table 4. As in Table 3, for ETSA risk forecasts. Asterisks indicate the districts where HAPD were recorded at public hospitals.

District	Day 2	Day 1	Day 0
Mallee	Low	Low	Low
Wimmera*	Low	Low	Low
Northern Country	Low	Moderate	Moderate
North Central	Moderate	Moderate	Moderate
North East	Moderate	Moderate	Moderate
South West*	Low	Moderate	Moderate
Central*	Moderate	Moderate	Moderate
West & South Gippsland	Moderate	Moderate	Moderate
East Gippsland	Moderate	Low	Low

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Table 5. Number of low, moderate and high ETSA risk forecasts issued for districts that had MAPD and HAPD events during 2017-2019[1].

	HAPD events (n=9)			MAPD and HAPD events (n=27)		
Forecast	Low	Moderate	High	Low	Moderate	High
Day 0	4	4	1	15	11	1
Day 1	4	5	0	17	10	0
Day 2	4	5	0	20	7	0

Table 6. Number of forecasts issued and estimated likelihood (quantitative risk) of a MAPD or HAPD event for each forecast risk category, based on results from 2017-2019. The total number of forecasts differs for day 0, day 1 and day 2 because the first issue date for all forecasts was October 1.

	Day 0			Day 1			Day 2		
	Low	Mod	High	Low	Mod	High	Low	Mod	High
Number of forecasts issued	2377	102	5	2386	88	1	2409	57	0
HAPD likelihood	0.002	0.04	0.20	0.002	0.06	0.00	0.002	0.09	---
HAPD + MAPD likelihood	0.01	0.11	0.20	0.01	0.11	0.00	0.01	0.12	---

[1] In Table 5 the forecast of ETSA risk that should have been made for the South West district on November 25, 2017 but was not (due to human error) has been corrected to allow the validity of the ETSA risk matrix approach to be assessed.

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Table 7. Joint distribution of assessed ETSA risk category diagnosed from observed weather and pollen ratings in four districts with MAPD and HAPD events during 2017-2019. The quantitative risk is estimated as the fraction of ETSA risk assessments with MAPD and HAPD events.

		Event			Estimated quantitative risk
		None	MAPD	HAPD	
Assessed ETSA risk	Low	1059	7	4	0.01
	Moderate	10	2	1	0.23
	High	3	2	0	0.40

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Table 8. Joint distribution of forecast versus assessed risk of epidemic thunderstorm asthma in four districts for (a) day 0, (b) day 1, and (c) day 2 forecasts during 2017-2019. The Gerrity score (GS) for 3-category forecasts is also shown.

(a) Day 0

		Assessed ETSA risk			
		Low	Moderate	High	
Forecast ETSA risk	Low	1020	4	0	
	Moderate	49	7	5	GS=0.36
	High	1	2	0	

(b) Day 1

		Assessed ETSA risk			
		Low	Moderate	High	
Forecast ETSA risk	Low	1026	5	1	
	Moderate	40	8	4	GS=0.31
	High	0	0	0	

(c) Day 2

		Assessed ETSA risk			
		Low	Moderate	High	
Forecast ETSA risk	Low	1039	5	3	
	Moderate	23	8	2	GS=0.27
	High	0	0	0	

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Figures

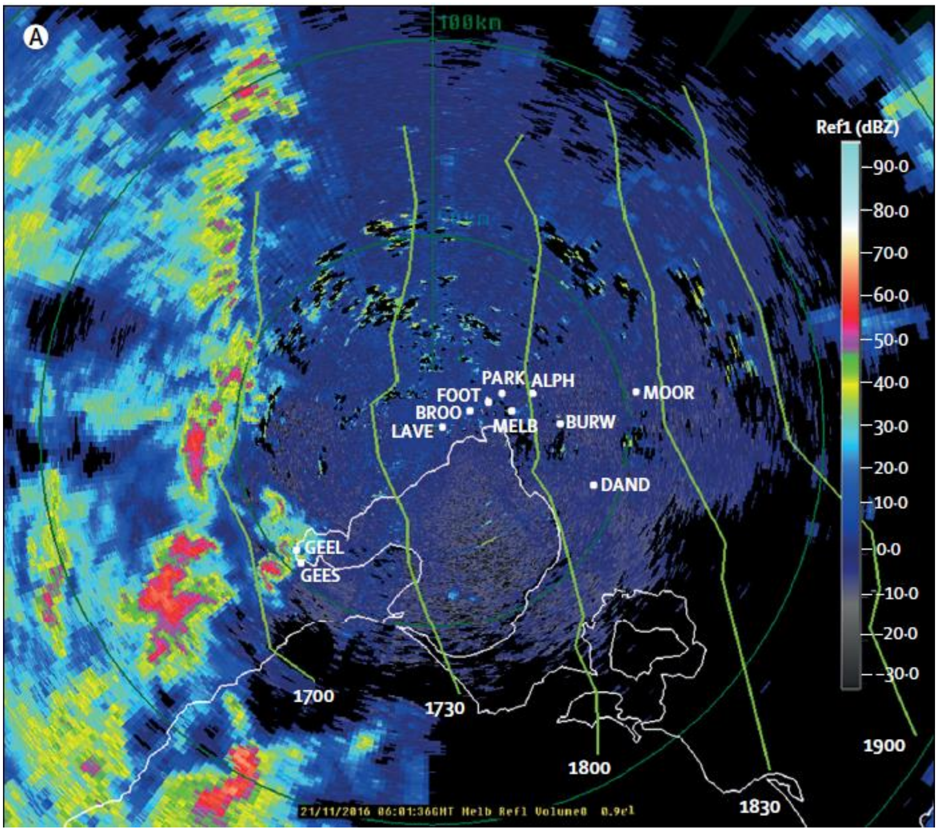

Figure 1. Radar image of the thunderstorm line (indicated by easternmost areas of red and yellow) at 1701 AEDT, with the associated (1700) and subsequent (1730–1900) gust front position indicated by the green lines. The locations of Geelong and Melbourne are indicated by GEEL and MELB, respectively (from Thien et al. (2018), reprinted with permission from The Lancet Planetary Health).

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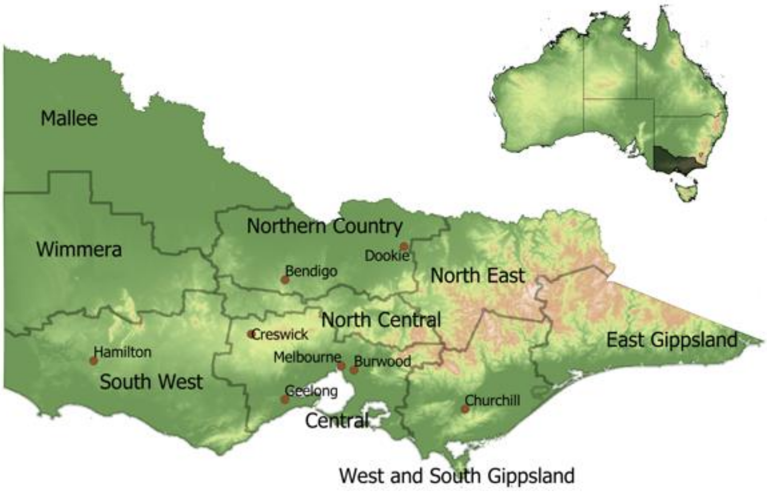

Figure 2. Victorian forecast districts showing the locations of the eight Victorian Thunderstorm Asthma Pollen Surveillance (VicTAPS) network pollen monitoring sites.

Weather category	Factors affecting at least one third of a forecast district			
High	**Likely** chance of thunderstorms causing gusts ≥ 25 m s^{-1}. Squall line potential ≥ 2 adds confirmation for gusts ≥ 25 m s^{-1}.	Low	Moderate	High
Medium	**Possible** chance of thunderstorms causing gusts ≥ 25 m s^{-1} *or* **likely** chance of thunderstorms causing gusts between 18 and 25 m s^{-1} *or* ICON ≥ 20.	Low	Low	Moderate
Low	**Possible** or **nil** chance of thunderstorms *and* ICON < 20.	Low	Low	Low
	District Pollen Forecast (grains m^{-3})	**Low (0-19)**	**Moderate (20-49)**	**High/Extreme (≥50)**
			Pollen category	

Figure 3. ETSA risk matrix used by BoM meteorologists in the pilot ETSA early warning service.

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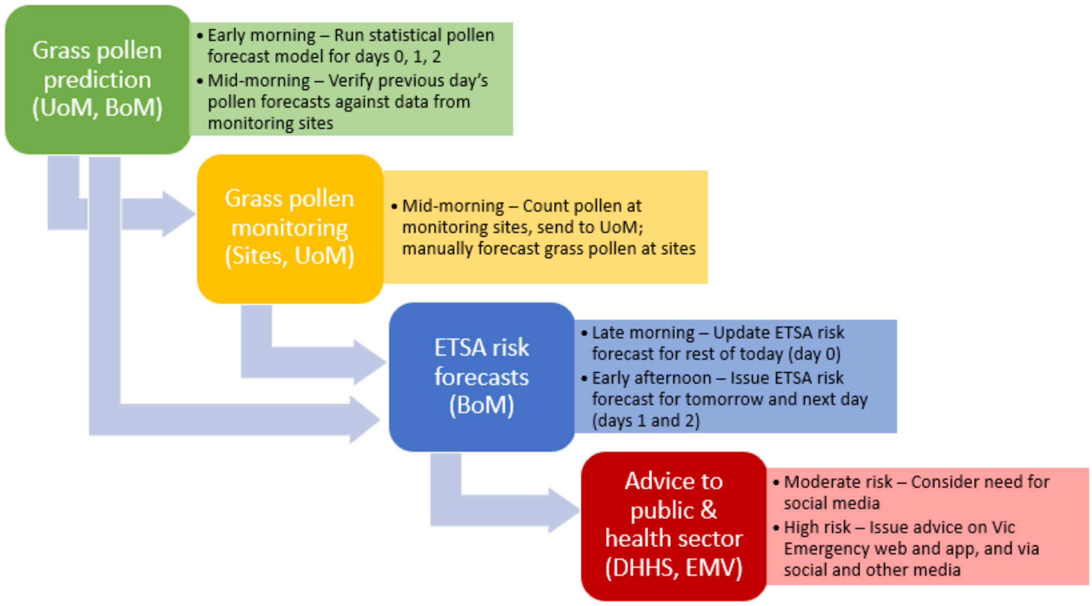

Figure 4. Schematic of the pilot epidemic thunderstorm asthma forecasting system. The pollen prediction and monitoring components are described in the Appendix.

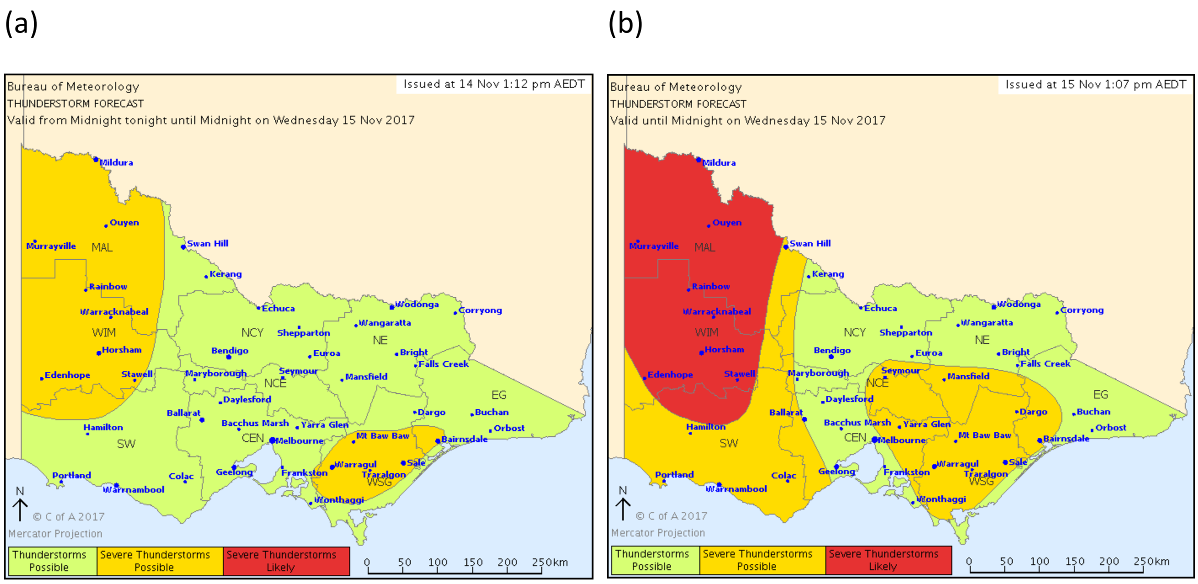

Figure 5. Graphical thunderstorm forecasts issued at (a) 1:12 pm 14 November 2017 (day 1) and 1:07 pm 15 November 2017 (day 0, at right) for 15 November 2017. The day 0 forecast is valid for the afternoon and evening period.

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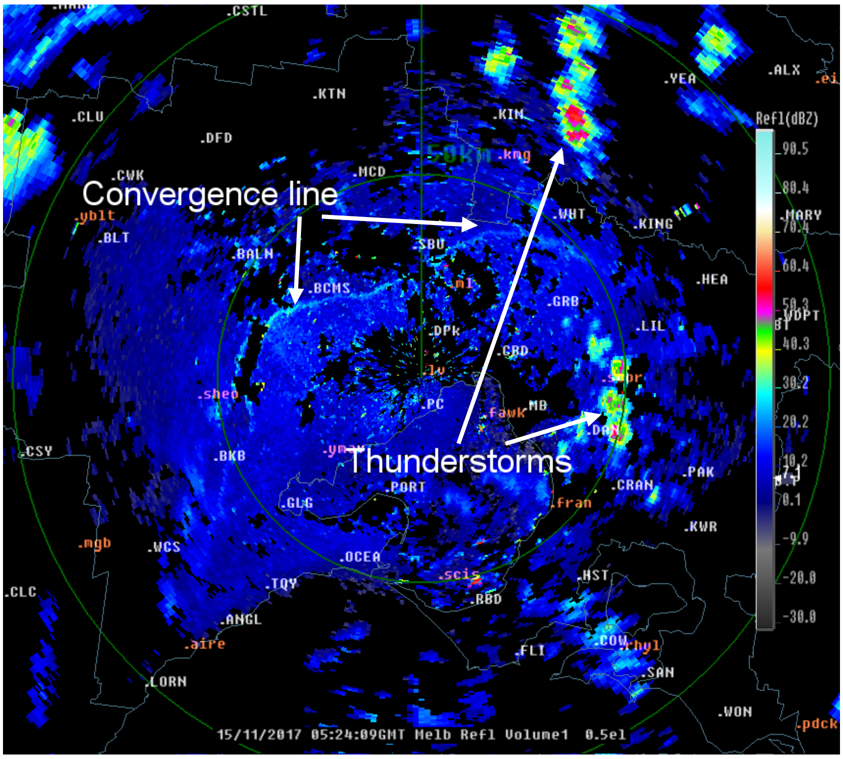

Figure 6. Image from Melbourne radar taken at 4.24pm AEDT 15 November 2017, indicating a convergence line and developing thunderstorms.

Figure 7. One of the authors (EL) installing and testing a Burkard volumetric pollen trap.

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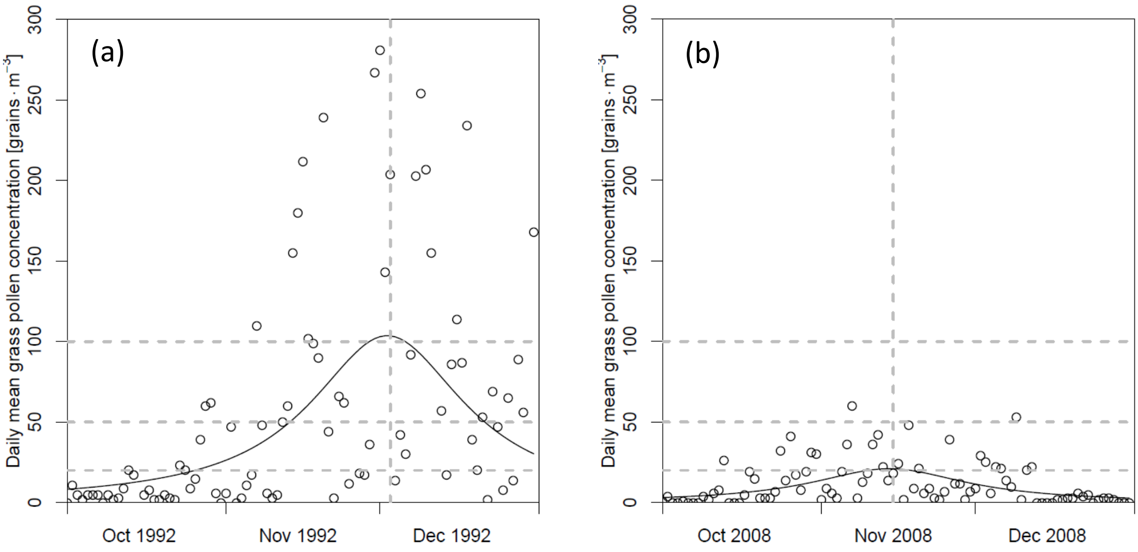

Figure 8. Melbourne pollen data and the associated fitted curves from (a) 1992, which had a very wet spring, and (b) 2008, which experienced an anomalously dry spring. The horizontal dashed lines indicate thresholds for moderate (20 grains m^{-3}), high (50 grains m^{-3}), and extreme (100 grains m^{-3}) grass pollen concentrations. The vertical dashed line indicates the date of peak pollen concentration.

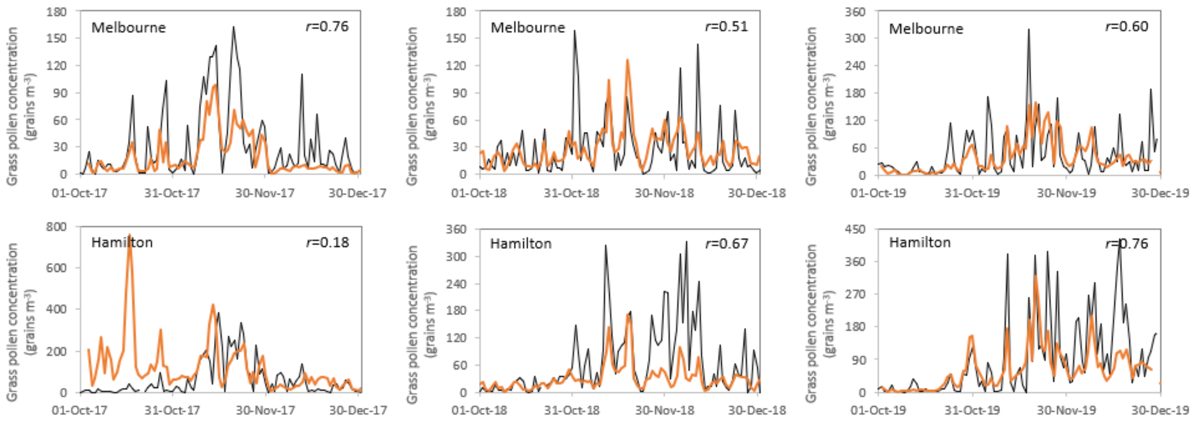

Figure 9. Observed (black line) and next-day statistical forecasts (orange line) of grass pollen concentration at Melbourne (top) and Hamilton (bottom) for 2017-2019. The forecasts correspond to that year's version of the statistical model. The Pearson correlation *r* measures of the correspondence of the forecast and observed time series.

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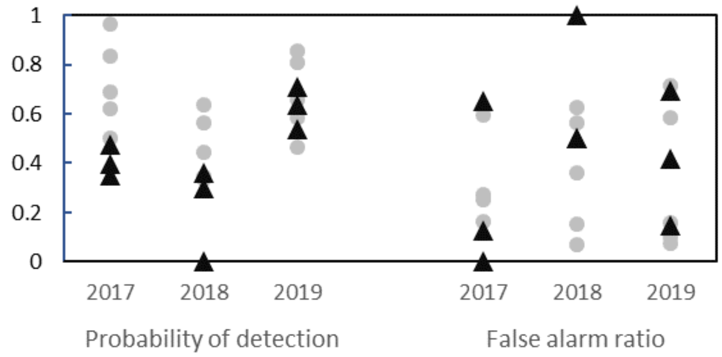

Figure 10. Probability of detection (POD) and false alarm ratio (FAR) for 1-day forecasts of daily grass pollen concentration exceeding 50 grains m^{-3}, the threshold required for high ETSA risk, for 8 monitoring sites in 2017-2019. The dark triangles indicate the urban sites of Melbourne, Burwood and Geelong and the grey circles the rural sites.

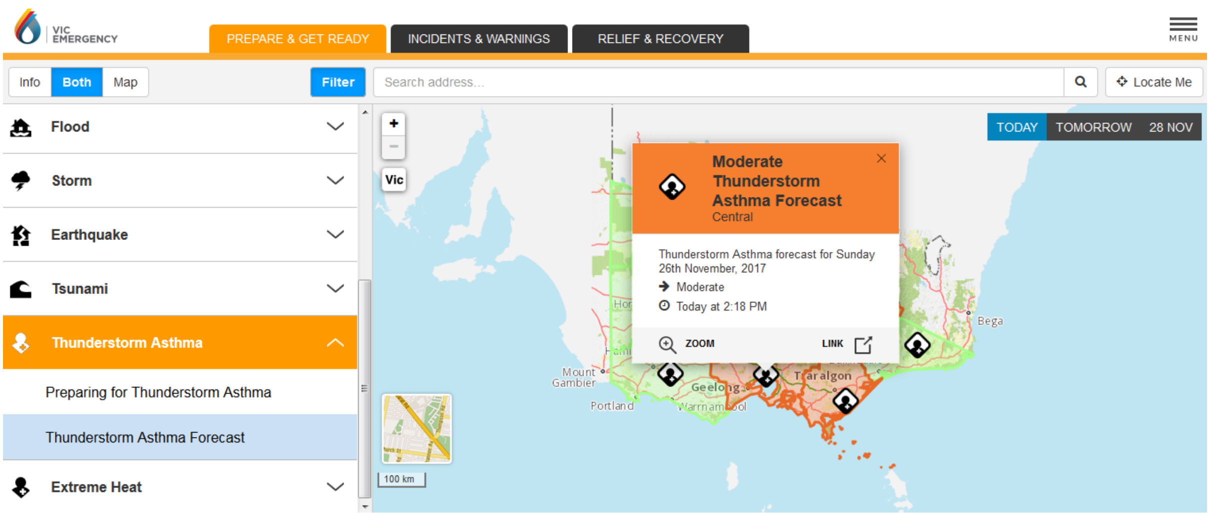

Figure 11. Sample forecast of epidemic thunderstorm asthma risk available to the public.

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Figure 12. Video explaining thunderstorm asthma risk and mitigation, which can be viewed at https://www.betterhealth.vic.gov.au/health/conditionsandtreatments/thunderstorm-asthma (Source: Better Health Channel, Department of Health and Human Services, Victoria)

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