The Role of Mesoscale-Convective Processes in Explaining the 21 November 2016 Epidemic Thunderstorm Asthma Event in Melbourne, Australia

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ABSTRACT

A major thunderstorm asthma epidemic struck Melbourne and surrounding Victoria, Australia, on 21 November 2016, which led to multiple deaths, a flood of residents seeking medical attention for respiratory problems, and an overwhelmed emergency management system. This case day had all the classic ingredients for an epidemic, including high rye grass pollen concentrations, a strong multicellular thunderstorm system moving across the region, and a large population of several million people in the vicinity of Melbourne. A particular characteristic of this event was the strong, gusty winds that likely spread the pollen grains and/or allergenic contents widely across the region to increase population exposure. This exploratory case study is the first to examine the usefulness of low-to-middle-atmospheric thermodynamic information for anticipating epidemic thunderstorm asthma outbreaks by allowing the forecast of strong downdraft winds. The authors investigated the utility of several mesoscale products derived from atmospheric soundings such as downdraft convective available potential energy (DCAPE) and indices for predicting surface wind gusts such as microburst wind speed potential index (MWPI) and a wind gust index (GUSTEX). These results indicate that DCAPE levels reached ''high'' to ''very high'' thresholds for strong downdraft winds in the lead-up to the thunderstorm, and the MWPI and GUSTEX indices accurately predicted the high maximum surface wind observations. This information may be useful for diagnostic and prognostic assessment of epidemic thunderstorm asthma and in providing an early warning to health practitioners, emergency management officials, and residents in affected areas.

1. Introduction

Thunderstorm asthma is a term used to describe the association between thunderstorm activity and increases in asthma exacerbation (Dabrera et al. 2013; Dales et al. 2003; D'Amato et al. 2007; Grundstein et al. 2008; Grundstein and Sarnat 2009; Nasser and Pulimood 2009). This phenomenon has important public health implications. Thunderstorms have been linked to asthma exacerbations of epidemic proportions, with five- to tenfold increases in the number of people seeking medical attention, thereby stressing the resources of local emergency departments (EDs) and other healthcare providers (Bellomo et al. 1992; Higham et al. 1997; Packe and Ayres 1985). The rapid influx of patients during a thunderstorm asthma event near London on 25 June 1994, for instance, caught many EDs unprepared and resulted in insufficient quantities of medication, nebulizers, and other supplies needed to treat respiratory ailments (Murray et al. 1994). This particular epidemic also resulted in an estimated 1500 additional calls by asthma sufferers to their general care practitioners by that evening (Higham et al. 1997; Venables et al. 1997).

It is hypothesized that some combination of rainfall, winds, and lightning from thunderstorms work in conjunction with bioaerosols such as pollen grains or mold spores to exacerbate asthma (Knox 1993; Suphioglu 1998; Taylor et al. 2007). The rainfall and high-humidity environment of the thunderstorm are thought to rupture bioaerosols, particularly rye grass pollen grains, into respirable-sized granules. It is also proposed that pollen and pollen particles may serve as cloud condensation and/or ice nuclei, which can release respirable-sized

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particles from splashing when droplets impact surfaces (Beggs 2017). Electrical activity during a thunderstorm may further contribute to pollen fragmentation (Taylor et al. 2007; Vaidyanathan et al. 2006). The strong, gusty winds produced by thunderstorm outflow boundaries may spread the pollen granules many kilometers ahead of the storm (Taylor and Jonsson 2004) and explain why some individuals experience asthma symptoms prior to the occurrence of rainfall (Nasser and Pulimood 2009). Indeed, Marks et al. (2001) observed anomalously high emergency department attendances for asthma on days with thunderstorm outflows in the spring and summer. For these events to reach ''epidemic'' proportions, Marks and Bush (2007) indicate that several factors must occur in combination, including the formation of small micron-size particles from pollen grain or fungal spore fragmentation resulting in high atmospheric concentrations of respirable allergenic biologic material, strong thunderstorm outflows to spread the particles over a large regional area, and exposure of large numbers of sensitive individuals.

A recent thunderstorm asthma epidemic that occurred in Melbourne and surrounding Victoria, Australia, on 21 November 2016 provides an excellent case study for examining the physical mechanisms associated with these events. The health impact of this event exceeds any previous thunderstorm asthma incident in the Melbourne area or internationally. It led to at least nine deaths, thousands of patients seeking medical care for respiratory distress, and a strained emergency medical system (Inspector-General for Emergency Management 2017). Call volumes to the Emergency Services Telecommunications Authority (ESTA) reached an unprecedented level, including a 12-h period (1800–0600) during which 2332 emergency ambulance calls were received, and demand for care at many local area hospitals increased by at least 50% relative to the same period in the previous week (Inspector-General for Emergency Management 2017).

This event matched the preconditions listed by Marks and Bush (2007) for a thunderstorm asthma epidemic including high pollen concentrations, thunderstorm activity, and a large population center in the Melbourne metropolitan area with over 4 million residents. As thunderstorms and high grass pollen levels are not uncommon in this area, a key question is what made this particular event so severe? It is clear that rye grass pollen levels were sufficiently high on this day, reaching 102 grains per cubic meter (Whelan 2016), which is classified as extreme (Asthma Australia 2016). Further, the thunderstorms moved through the area between 1700 and 1800 local time when more residents were likely to be outside after leaving work or school, possibly increasing exposure. While these are important conditions for the occurrence of thunderstorm asthma, they are not necessarily sufficient conditions for the magnitude of thunderstorm asthma that the Melbourne population experienced on this day.

Previous attempts to model and forecast thunderstorm asthma have been limited both by data (i.e., pollen and fungal spore) and by an incomplete understanding of the precise mechanisms by which thunderstorms interact with allergenic particles to exacerbate asthma (Dabrera et al. 2013). A model developed by Newson et al. (1998), for instance, was impractical as part of a public health warning system because it produced high false alarm rates. A better understanding of the physical processes associated with these events may help to refine our ability to provide accurate advance warnings. Here, we argue that the mesoscale environment may be of particular importance in explaining this epidemic. Thunderstorm outflows or gust fronts are generated from downdraft winds that diverge when reaching the surface. These outflows are mesoscale processes, which are typically characterized by spatial scales on the order of 5 to a few hundred kilometers (Fujita 1986). While Marks et al. (2001) observed a strong association between thunderstorm outflows and epidemic-level increases in asthma across Australia, no study to our knowledge has investigated in the context of thunderstorm asthma the mesoscale preconditions that may lead to strong downdraft winds and associated outflows, which we believe was a key factor in making this such a severe thunderstorm asthma event. The need for developing better diagnostic and prognostic tools is echoed by a report prepared in the aftermath of this epidemic by the Inspector-General for Emergency Management for the Victoria State Government, which notes that ''identifying meaningful indicators for predicting thunderstorm asthma remains a key priority'' (Inspector-General for Emergency Management 2017, p. 3). Thus, we present an exploratory case study of the 21 November 2016 epidemic to investigate the effectiveness of several mesoscale products for predicting strong, downdraft winds from thunderstorms.

2. Data and methods

We reconstructed the meteorological conditions for 21 November 2016 using a combination of surface weather observations from stations in the vicinity of the Melbourne area, synoptic maps, and both observed and modeled sounding data. Hourly surface weather data were obtained for the Melbourne International Airport (37.67°S, 144.83°E) and the Avalon Airport (38.03°S, 144.48°E) located approximately 70 km to the southwest.

Atmospheric sounding data, derived from balloon-borne instrumentation, collected prior to the thunderstorm activity at 0000 UTC [1100 Australian eastern daylight time (AEDT)] were obtained for the Melbourne International Airport (YMML) from the website maintained by the University of Wyoming Department of Atmospheric Sciences (http://weather.uwyo.edu/upperair/sounding.html). A synoptic weather map for Australia was obtained from Australian Bureau of Meteorology Analysis Chart Archive.

Because the line of thunderstorms impacted the Melbourne area several hours after the YMML radiosonde was launched, forecast soundings from the 0000 UTC 21 November 2016 forecast fields of the Global Forecast System (GFS) were rendered for +3 and +6 h (1400 and 1700 AEDT) at the location of the Melbourne International Airport. The GFS is an ~28-km global numerical weather model with 64 hybrid sigma-pressure levels operated by the U.S. National Centers for Environmental Prediction (NCEP). Initialized four times daily (0000, 0600, 1200, and 1800 UTC), the 0000 and 1200 UTC initializations of the GFS assimilate observations from the globally coincident radiosonde launches. The Melbourne forecast soundings were generated using output from 21 pressure levels spaced every 50 hPa between ground level and 100 hPa. Although the GFS is a coarse, global-scale model, it is nonetheless capable of resolving the basic features used by forecasters to predict convective wind potential.

Several indices, derived from soundings using the Sounding and Hodograph Analysis and Research Program in Python (SHARPpy) software package (Halbert et al. 2015), were used to characterize the mesoscale environment that would impact downdraft winds from thunderstorm activity, including downdraft convective available potential energy (DCAPE), microburst wind speed potential index (MWPI), and a wind gust index (GUSTEX). DCAPE (Molinari et al. 2013; Emanuel 1994) is a metric of the maximum energy available to a parcel of air that is descending. It is commonly used within the field of mesoscale meteorology to estimate the potential strength of downdrafts. DCAPE was computed by first identifying the downdraft parcel source found in the lowest 400 hPa of the sounding, defined as the minimum 100-hPa-layer averaged θ_e. This parcel is then lowered moist adiabatically to the surface (without virtual temperature correction) and DCAPE is equal to the accumulated energy. The U.S. National Weather Service (NWS 2016) has established the following broad criteria for DCAPE:

- Values > 800 J kg^{-1} are nominal to high.
- Values > 1200 J kg^{-1} are very high.

MWPI was derived to assess storm environments favorable for downdrafts and strong surface wind gusts (Pryor 2015). It is computed as follows:

$$\mathrm{MWPI} = (\mathrm{CAPE}/1000\,\mathrm{J\,kg^{-1}}) + \{\Gamma/5°\mathrm{C\,km^{-1}} + [(T - T_d)_{850} - (T - T_d)_{670}]/5°\mathrm{C}\}, \quad (1)$$

where convective available potential energy (CAPE) is an indicator of atmospheric instability (J kg^{-1}), Γ is the temperature lapse rate (°C km^{-1}) between the 850- and 670-hPa levels, and $[(T - T_d)_{850} - (T - T_d)_{670}]$ is the dewpoint depression (DD) difference between two layers and a measure of the relative dryness in the lower-tropospheric layers of interest. MWPI yields a unitless value that ranks wind gust potential from 1 (lowest) to 5 (highest). In Pryor's work, the two most favorable conditions included the presence of a large CAPE value and surface-based or elevated mixed layers with a large temperature lapse rate. Pryor (2015) further developed regression equations to relate the MWPI to surface wind gusts based on data from Oklahoma–Texas and the mid-Atlantic regions in the United States:

$$\mathrm{WS}_1 = 0.3163\mathrm{MWPI} + 33.766\ (\text{Oklahoma–Texas}) \quad \text{and} \quad (2)$$

$$\mathrm{WS}_2 = 3.775\mathrm{MWPI} + 29.9639\ (\text{mid-Atlantic}), \quad (3)$$

where WS is wind speed in knots (kt; 1 kt = 0.51 m s^{-1}).

We also employ a more regional approach for estimating downdraft-related surface wind gusts. Mills and Colquhoun (1998) suggested the use of wind index (WINDEX) for predicting thunderstorms in Australia with microbursts. However, Geerts (2001), using data collected in New South Wales, Australia, found more accurate results by combining downdraft spreading (i.e., gust front) quantified in WINDEX with the vertical transfer of horizontal momentum as indicated by 500-hPa wind speeds. This hybrid index, called GUSTEX, is used in this study. WINDEX is first computed as

$$\mathrm{WINDEX} = 5[H_m R_q(\Gamma^2 - 30 + q_1 - 2q_m)]^{0.5}, \quad (4)$$

where H_m is the height (km) of the melting level above the ground, Γ is the lapse rate (K km^{-1}) from the surface to the freezing level, q_1 is the average mixing ratio in the lowest 1 km above the surface (g kg^{-1}), q_m is the mixing ratio at the melting level (g kg^{-1}), and $R_q = q_1/12$ but is not greater than 1. Using WINDEX, GUSTEX (kt) is calculated as

$$\mathrm{GUSTEX} = \alpha\mathrm{WINDEX} + 0.5U_{500}, \quad (5)$$

where α is a unitless constant best estimated by Geerts (2001) at 0.6 and U_{500} is the 500-hPa wind speed (kt).

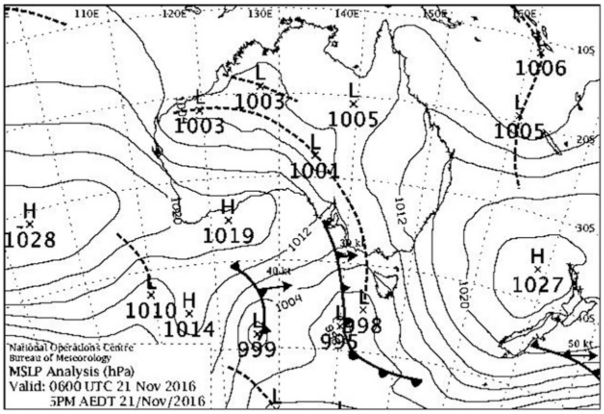

FIG. 1. Weather map for Australia at 0600 UTC (1700 AEDT) 21 Nov 2016.

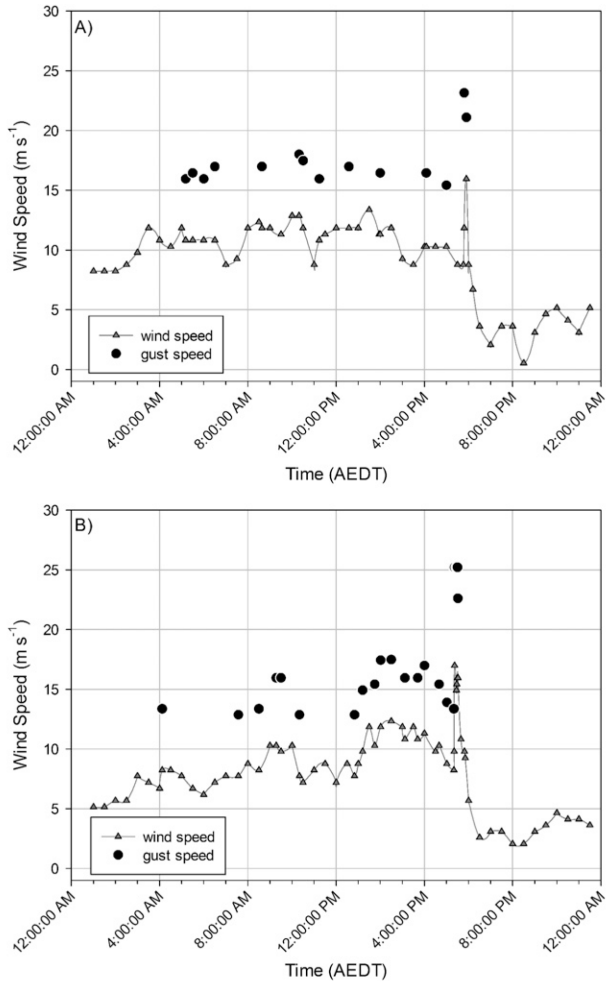

FIG. 2. Wind speeds and wind gusts for (a) Melbourne International Airport and (b) Avalon Airport on 21 Nov 2016. Thunderstorm activity occurred between 1700 and 1800 AEDT.

3. Results

The synoptic weather configuration on the day of the 2016 epidemic was very similar to conditions present in two previous thunderstorm epidemics in 1987 and 1989 in the Melbourne area (Bellomo et al. 1992). On 21 November 2016, a cold front pushed in from the west and a strong pressure gradient over eastern Australia directed northerly winds ahead of the cold front, which swept rye grass pollens from surrounding pastures into Melbourne and surrounding Victoria (Fig. 1). Ahead of the cold front, a squall-line thunderstorm moved across the region between 1700 and 1800 AEDT. A notable feature of this system was the strong wind gusts at the surface during this time, indicative of powerful downdraft winds (Fig. 2). Indeed, surface wind speeds from two sample stations at Melbourne International Airport and Avalon Airport had peak wind speeds exceeding 15.9 m s^{-1} and gusts over 23 m s^{-1} during the thunderstorm.

Atmospheric soundings from 0000 UTC (1100 AEDT) prior to thunderstorm activity reveal the potential for strong downdrafts that occurred (Fig. 3a). One of the most apparent meteorological features in the sounding is the presence of a dry layer between 1000 and 700 hPa. The spacing between the temperature profile (right) and the dewpoint temperature (left) is directly related to the dryness of the atmosphere. Greater (lesser) spacing is indicative of a relatively dry (moist) layer. The dryness of the atmosphere is a key measure incorporated into the indices for predicting downdraft potential shown in section 2. The DCAPE from approximately 800 hPa in the 0000 UTC Melbourne sounding was 719 J kg^{-1} (Table 1). This value is close to the marginal indicator (800 J kg^{-1}) for downdraft activity and is coupled with a very dry layer that is supportive of increased evaporation of precipitation, another mechanism that intensifies potential downdrafts.

To investigate further, we employed GFS model data to identify conditions closer to when the thunderstorm occurred. The zero-hour forecast sounding shows that the model reasonably depicts the observed YMML sounding with the elevated mixed layer seen in the observed profile as well as the dry layer near 400 hPa (Figs. 3a,b). Additionally, the GFS first produces rain in the model field at 0600 UTC corresponding to the observed onset at YMML. Thus, the overall similarity of the YMML observations and 0000 UTC GFS solution increases the credibility of the GFS's near-term forecast conditions for Melbourne on 21 November 2016. However, relative to the observed sounding, the 0000 UTC GFS zero-hour forecast is too moist near 850 hPa causing the layer of minimum θ_e to be placed at 550 hPa, and DCAPE to be overestimated (1035 vs 719 J kg^{-1}; Table 1). Low-level temperature and moisture representation can be problematic in both coarse- and

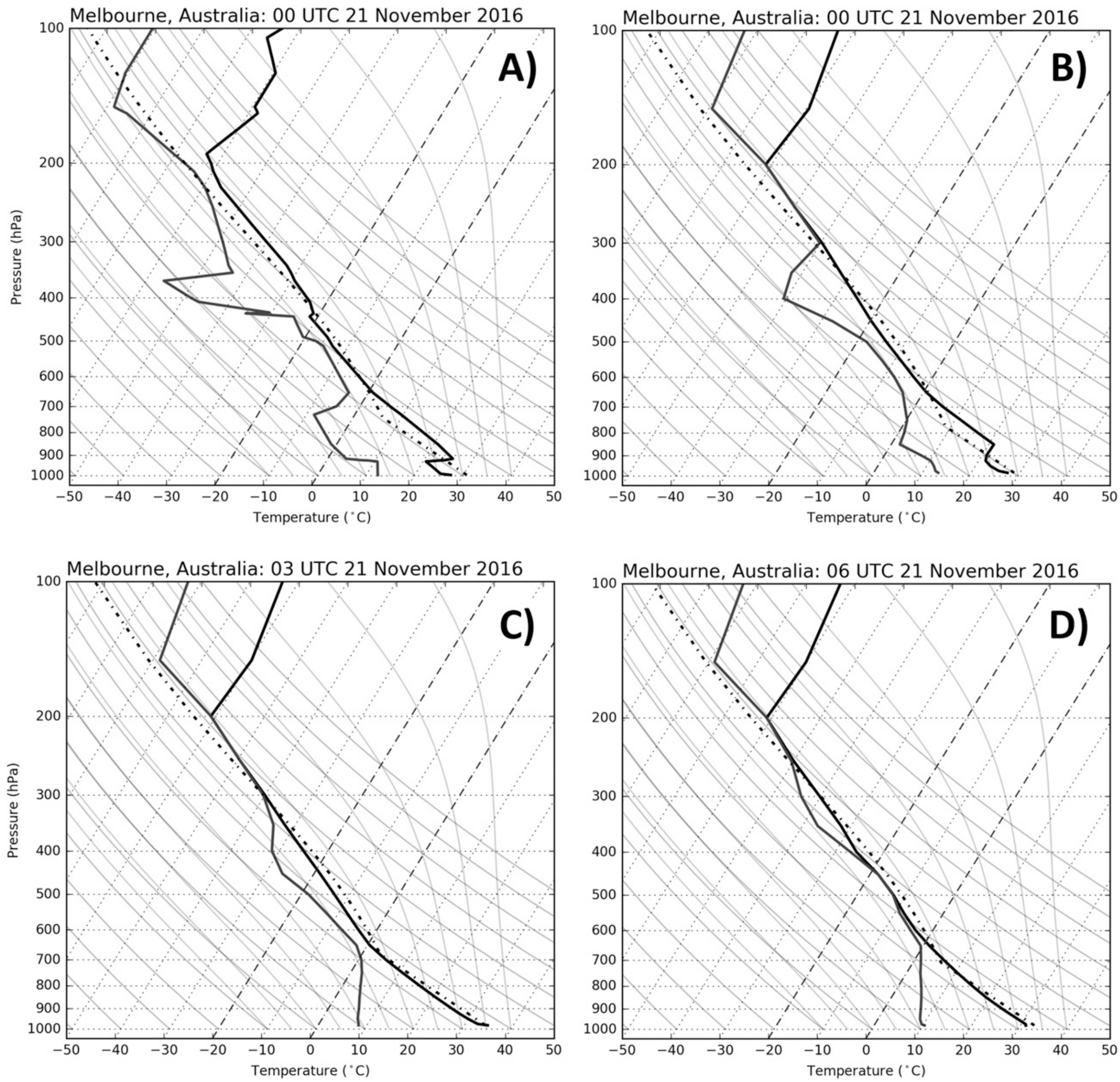

FIG. 3. (a) Observed 0000 UTC sounding on 21 Nov 2016 at the Melbourne Airport as well as (b) the GFS-resolved sounding for the same time and location based on the 0000 UTC 21 Nov 2016 initialization. The GFS forecast soundings for (c) 0300 and (d) 0600 UTC 21 Nov 2016 are also provided.

high-resolution models, and is magnified by measures of CAPE (Thompson et al. 2003; Gensini et al. 2014).

The predicted increase in DCAPE over time, combined with the drying of the near-surface layer suggests that the atmosphere was becoming increasingly unstable to descending air parcels as the day progressed. During the 3-h period following the observed sounding, turbulent mixing yielded a nearly dry adiabatic layer between ~650 hPa and the surface. This evolved near-surface layer is warmer and drier than at 0000 UTC, supporting a greater potential for evaporative cooling and downdraft acceleration. Both the forecast soundings and the diurnal evolution of the lower atmosphere are similar to the cases of microburst activity described by Wakimoto (1985). The forecast sounding for 0300 UTC, then, yields a DCAPE value of 1157 J kg^{-1}, a value approaching the "very high" threshold according to the U.S. National Weather Service (Fig. 3c). By 0600 UTC, the GFS has begun indicating precipitation, and the subsequent moistening in the midlevels decreases DCAPE relative to 0000 and 0300 UTC. Nonetheless, the

TABLE 1. DCAPE calculations and estimated wind gust potential from the observed 0000 UTC sounding at Melbourne International Airport on 21 Nov 2016 and forecast GFS soundings.

	Index	0000 UTC observed	0000 UTC GFS	0300 UTC GFS	0600 UTC GFS
	DCAPE (J kg^{-1})	719	1035	1157	921
Pryor (2015)	MWPI	4.81	4.70	4.50	4.03
	WS_1 [m s^{-1} (kt)]	18.2 (35.3)	18.2 (35.3)	18.1 (35.2)	18.0 (35.0)
	WS_2 [m s^{-1} (kt)]	24.7 (48.1)	24.5 (47.7)	24.2 (47.0)	23.3 (45.2)
Geerts (2001)	GUSTEX [m s^{-1} (kt)]	17.2 (33.5)	16.5 (32.1)	22.3 (43.4)	20.5 (39.9)

favorability of the atmosphere for descending air parcels is captured at 0600 UTC with a DCAPE exceeding the threshold of 800 J kg^{-1}.

The other indices examined, MWPI and GUSTEX, are consistent with the DCAPE results of strong downdraft potential and strong surface wind gusts. The observed MWPI value at 0000 UTC was 4.81 out of 5, indicating great potential for strong downdraft winds (Table 1). Regression equations linking MWPI to gust speeds indicate estimated gusts of 18.2 and 24.7 m s^{-1} (35.3 and 48.1 kt, respectively) for the two models. GUSTEX estimated gusts of 17.2 m s^{-1} (33.5 kt). The GFS, then, replicates the gust estimates to within 5% at 0000 UTC (Table 1). Given this good performance, MWPI and GUSTEX are calculated for the 0300 and 0600 UTC GFS soundings. While the regression-predicted gust potential is not as strong during the ensuing 6 h, the values remain high. The GFS MWPI never falls below 4.0, and the weakest gust estimated by any of the tested methods at any timeframe is still strong at 18.0 m s^{-1} (35.0 kt). Further, the estimated gusts at 0600 UTC, near the time of the storm, ranged from 18 to 23.3 m s^{-1} (35–45.3 kt) and closely match the magnitude of the observed gusts recorded at Melbourne International Airport of 15.4–23.2 m s^{-1} (29.9–45.1 kt).

4. Conclusions

This thunderstorm asthma epidemic has been defined as the most severe to ever strike the region (Inspector-General for Emergency Management 2017). A distinct characteristic of the event was the very strong downdraft winds that led to a gust front and the spreading of pollen fragments across the region. We believe this was a critical component in explaining the magnitude of the event and may be useful in the development of advance warning systems aimed at the medical and public health communities as well as susceptible members of the population. As such, our study investigated the mesoscale weather conditions that produced these strong winds. We found that the thermodynamic configuration on the day of the epidemic as indicated by both the observed and forecast soundings created a favorable environment for strong downdraft winds and associated gust fronts to be produced from the thunderstorm system that moved through the Melbourne area. In particular, our results show robust results from several indices that used different input variables from sounding data. An important point is that the signature of possible strong downdraft winds we identified can be assessed with observed soundings and forecast model output and used as a prognostic aid. We did observe some previously documented issues with representations of temperature and moisture at the low levels of the atmosphere in our model output that particularly influenced DCAPE. Higher-resolution, convection-resolving models may be able to address this issue and further improve model performance. In conclusion, our findings are promising but a more in-depth follow-up study with a larger sample of events and the use of higher-resolution models is needed to verify that our results apply more broadly to other thunderstorm asthma events.

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